

**SCUOLA SUPERIORE MERIDIONALE**

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**DOCTORAL THESIS**

*in Modeling and Engineering Risk and Complexity*

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**FRISE: Feedback-based Risk Integration for Safety and  
Sustainability in Engineering**

*A holistic risk and safety framework for complex engineering systems*

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## Abstract

The present doctoral research develops, applies, and validates the FRISE (*Feedback-based Risk Integration for Safety and Sustainability in Engineering*) framework—a systemic model that integrates risk, safety, and sustainability through feedback-based reasoning. FRISE is founded on the Three-Paradigm (3P) model, merging Sustainability, Complexity, and Systems Thinking into a coherent methodological and theoretical structure. It consists of five interlinked modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—connected through a Systemic Glue Layer that captures the dynamic interactions and feedback loops among them.

The framework was developed and validated across three major domains: hydrogen safety and sustainability, fire safety engineering, and the hydrogen economy. Using a hybrid methodology combining Causal Loop Diagrams (CLDs), System Dynamics (SD), and Graph-Theoretic (GT) analysis, FRISE demonstrated structural coherence, behavioral realism, and cross-domain transferability. The results revealed recurring system archetypes (e.g., Limits to Growth, Shifting the Burden, Success to the Successful) and universal sustainability drivers such as trust, adaptive learning, and financial elasticity.

Beyond methodological innovation, this research establishes FRISE as a multi-scale systemic architecture capable of guiding adaptive governance and decision-making under uncertainty. It bridges technical and socio-environmental perspectives, showing that safety and sustainability emerge as interdependent properties of complex adaptive systems. The thesis concludes by positioning FRISE as both a validated modeling framework and a conceptual cornerstone for the emerging discipline of Systemic Sustainability Engineering, where feedback management and dynamic adaptation define the foundations of future resilient and sustainable societies.

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## Chapter 1 – Introduction

This chapter establishes the motivation, context, and research rationale of the thesis. It identifies the limitations of traditional Risk Assessment and Safety Management (RA–SM) approaches in addressing dynamic, socio-technical, and sustainability-related challenges within chemical, energy, and fire safety systems. The chapter introduces the need for an integrated, feedback-based framework capable of capturing interdependencies, feedback loops, and long-term trade-offs among economic, environmental, and social dimensions. In response, it presents the FRISE Framework (*Feedback-based Risk Integration for Safety and Sustainability in Engineering*) as the core methodological contribution of the research. It also defines the research objectives, questions, and structure of the thesis, positioning the study within the broader paradigms of Sustainability, Complexity, and Systems Thinking. The chapter thus provides the conceptual foundation and motivation for the theoretical integration developed in Chapter 2.

### 1.1 - Motivation: complexity in chemical, energy, and fire safety systems

Industrial, energy, and fire safety systems represent some of the most challenging socio-technical domains due to their intrinsic complexity and their potential to cause severe societal, environmental, and economic consequences. Traditional risk assessment (RA) and safety management (SM) approaches in these sectors have generally been reductionist, static, and event-oriented. They often neglect feedback effects, time delays, and systemic interdependencies that shape the long-term dynamics of accidents and safety performance (Dueñas Santana, Di Benedetto, González Gómez, et al., 2024; Lane & Sterman, 2011; Sterman, 2000, 2002). As a result, risk assessments are frequently limited to linear cause–effect chains, overlooking emergent behaviors, domino effects, and cross-sectoral sustainability implications.

In the chemical industry, accident scenarios such as fires, explosions, and toxic releases demonstrate how cascading failures and domino effects can escalate into major disasters (Cozzani & Reniers, 2021; Khan & Abbasi, 1998). The European Commission has identified research into domino-effect prediction models as an important challenge for future safety policy (Poljanšek, 2017). Yet, most RA methodologies used in safety reports still neglect the temporal dimension and the dynamic evolution of safety barriers, resource allocation, and organizational culture. Such limitations hinder the capacity of industry to proactively anticipate

risks and to optimize safety management strategies under constrained budgets and societal expectations.

The energy sector is undergoing a rapid transformation towards sustainability, with hydrogen emerging as a key enabler of decarbonization. However, this transition introduces new complexities. Hydrogen technologies pose inherent hazards such as high flammability, wide flammability limits, low ignition energy, and material embrittlement (Najjar, 2013; Rivkin et al., 2015). Moreover, hydrogen infrastructure development interacts with economic feasibility, environmental impacts, public acceptance, and regulatory frameworks. These interdependencies make the hydrogen economy a paradigmatic case of a complex adaptive system, where technological, social, and political factors are tightly coupled (Laimon et al., 2022). Traditional static RA methods cannot adequately capture these cross-cutting dynamics.

Similarly, in fire safety engineering (FSE), the complexity of modern buildings and urban infrastructures challenges conventional safety models. Static or linear models typically analyze fire growth or evacuation in isolation, but fail to represent their interactions or the uncertainties in occupant behavior (Gehandler, 2017). Recent research highlights the necessity of system-based approaches that integrate technical, human, and organizational elements as interacting subsystems (Meacham, 2022). For example, trade-offs between fire safety and sustainability—such as the increased use of combustible eco-materials—exemplify the competing objectives faced by modern designers and regulators (Van Coile, Hopkin, et al., 2019).

A further motivation arises from the societal dimension of safety. Public perception, risk communication, and acceptance of novel energy technologies play a critical role in shaping adoption pathways and regulatory decisions. In the context of sustainability, safety cannot be decoupled from economic viability, environmental protection, and social acceptance—the three pillars of the “Three Paradigm” (3P) (Sustainability–Complexity–Systems Thinking) proposed in recent works (Dueñas Santana, Di Benedetto, González Gómez, et al., 2024; Sterman, 2002).

Altogether, these motivations emphasize the urgent need for a holistic RA–SM framework capable of:

- capturing dynamic feedbacks, delays, and interdependencies,

- integrating safety with sustainability assessment (economic, environmental, and social pillars), and
- providing actionable insights for policymakers, industry stakeholders, and engineers.

Such an integrated framework promises not only to improve the reliability of safety assessments but also to enable more sustainable and societally acceptable decisions in the energy transition and in fire safety practice. This Ph.D. project is motivated by precisely this need: to extend RA and SM beyond their traditional static and siloed boundaries, and to embed them within a systemic, sustainability-oriented perspective.

This doctoral research therefore proposes the **FRISE** framework (*Feedback-based Risk Integration for Safety and Sustainability in Engineering*) as the methodological core of this thesis. FRISE unifies Risk Assessment, Safety Management, and sustainability analysis into a single feedback-driven system capable of capturing the dynamic behavior of complex engineering domains.

The FRISE Framework integrates five modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—within a feedback-based system that links safety performance with sustainability outcomes.

## **1.2- Limitations of traditional RA–SM approaches**

Risk Assessment (RA) and Safety Management (SM) have long been cornerstones of engineering practice in the chemical, energy, and fire safety sectors. Classical approaches typically rely on HAZOP, probabilistic risk assessment (PRA), event tree/fault tree analyses, and deterministic consequence models. These methods have been invaluable in identifying hazards and quantifying risks in industrial contexts. However, their usefulness is increasingly constrained when facing complex, dynamic, and socio-technical systems, such as hydrogen infrastructures, interconnected chemical plants, or modern sustainable buildings (Cozzani & Reniers, 2021; Dueñas Santana et al., 2025; Sterman, 2002).

### **1.2.1- Static and linear nature**

Traditional RA techniques generally assume static failure probabilities and linear cause–effect chains. For instance, equipment failure rates are often modeled as constant values, neglecting the reality of time-dependent degradation phenomena such as corrosion, fatigue, or hydrogen

embrittlement (Najjar, 2013; Salzano et al., 2014). This assumption disregards the dynamic evolution of risks, particularly in infrastructures where hazard exposure, material properties, and operational conditions change over time.

Similarly, accident modeling is often restricted to linear sequences of events. In practice, however, accident escalation frequently involves non-linear feedbacks, cascading failures, and domino effects (Cozzani & Reniers, 2021; Khan & Abbasi, 1998). The inability of classical RA methods to represent these interactions results in underestimation of systemic vulnerabilities and inadequate prevention strategies.

### **1.2.2- Neglect of feedbacks and delays**

Another major limitation is the neglect of feedback mechanisms and delays that govern safety performance. For example, budget cuts in maintenance may initially improve short-term profitability but gradually erode safety culture, leading to higher accident probabilities in the long run (Bouloiz et al., 2013). Similarly, safety investments often face delays before their benefits materialize, while organizational learning from accidents may decay over time if not continuously reinforced. These systemic dynamics cannot be captured by conventional static analyses, which treat risk as a fixed quantity rather than an evolving property of the system.

### **1.2.3- Fragmented treatment of sustainability**

Traditional RA–SM frameworks also tend to isolate safety from broader sustainability dimensions. Economic cost–benefit analyses are often performed separately from risk assessments, while environmental and societal consequences (e.g., emissions, downtime of critical infrastructures, loss of societal trust) are rarely integrated into decision-making (Dueñas Santana, Di Benedetto, & Salzano, 2024; Dueñas Santana, Di Benedetto, González Gómez, et al., 2024; Dueñas Santana et al., 2025). This siloed perspective ignores critical trade-offs. For example, certain fire safety measures may be rejected due to upfront costs without accounting for their long-term benefits in terms of reduced damage, environmental protection, or improved resilience (Mohan et al., 2021; Van Coile, Hopkin, et al., 2019).

### **1.2.4- Limited socio-technical scope**

Risk analysis tools historically emphasize technical failures, giving less attention to human, organizational, and social factors. However, safety is increasingly recognized as a property of socio-technical systems, where culture, trust, and regulatory frameworks are as important as technical reliability (Ibrahim Shire et al., 2018; Meacham & McNamee, 2023). Traditional RA approaches rarely model these “soft” dimensions or their feedback with technical performance.

As a result, they struggle to anticipate phenomena such as public resistance to hydrogen adoption, loss of organizational resilience, or erosion of trust in fire safety institutions.

### **1.2.5- Communication and policy gaps**

Finally, classical RA–SM outputs are often difficult to communicate to decision-makers. Event trees or risk indices do not easily convey how safety evolves dynamically under different policies. This hampers transparent, evidence-based decision-making at the policy level. For example, the As Low As Reasonably Practicable (ALARP) principle requires balancing costs and benefits of safety measures over time, but traditional cost–benefit analyses are static and fail to visualize how these trade-offs might shift over the lifetime of an installation (Van Coile, Jomaas, et al., 2019).

### **1.2.6- Toward a new approach**

Given these limitations, there is a strong need for dynamic, integrated, and interdisciplinary approaches that:

- I. Capture time-dependent risk evolution and domino effects;
- II. Incorporate systemic feedbacks and delays;
- III. Integrate sustainability dimensions into safety assessments;
- IV. Expand the scope to socio-technical systems; and
- V. Provide clear, dynamic tools for communication and policy support.

System Dynamics (SD) and Systems Thinking (ST) approaches provide a promising pathway to overcome these shortcomings. By explicitly modeling stocks, flows, and feedback loops, SD enables the analysis of complex system behaviors over time, while ST offers a framework to integrate interdisciplinary perspectives (Bouloiz et al., 2013; Sterman, 2000, 2002). This thesis responds to these gaps by proposing the FRISE Framework, a modular RA–SM–sustainability approach capable of informing cleaner and safer technological transitions.

## **1.3- Objectives of the research**

The motivation for this research arises from the increasing complexity of risk and safety challenges in chemical, energy, and fire safety systems, and from the shortcomings of traditional Risk Assessment (RA) and Safety Management (SM) methods (Dueñas Santana, Di Benedetto, González Gómez, et al., 2024; Yuan et al., 2022). Current approaches often neglect feedback mechanisms, time delays, systemic interdependencies, and sustainability trade-offs, thereby limiting their capacity to inform robust and adaptive decision-making. This thesis is



driven by the need to establish a holistic, modular, and interdisciplinary framework that integrates RA and SM with the broader pillars of sustainability: economic viability, environmental protection, and societal acceptance.

The overarching goal of this PhD project is therefore to develop, validate, and apply the FRISE framework capable of addressing the complexity of socio-technical systems across multiple engineering domains. This framework is anchored in the Three-Paradigm (3P) model—Sustainability, Complexity, and Systems Thinking (Dueñas Santana, Di Benedetto, González Gómez, et al., 2024)—and aims to extend conventional RA–SM beyond its traditional technical scope to embrace economic, environmental, and societal perspectives.

More specifically, the objectives of this thesis are:

I. Conceptual development

- a. To design a modular RA–SM framework that captures feedbacks, delays, and interdependencies between technical, economic, environmental, and societal dimensions.
- b. To embed the framework within the 3P paradigm, ensuring that complexity, sustainability, and systemic feedbacks are explicitly considered.

II. Methodological innovation

- a. To integrate graph-theoretical approaches (influence matrices, centrality metrics) with Systems Thinking tools (Causal Loop Diagrams, System Dynamics) for analyzing cross-modular interactions.
- b. To incorporate decision anchors from established safety and sustainability practices, namely:
  - i. ALARP (As Low As Reasonably Practicable) for risk reduction,
  - ii. Cost–Benefit Analysis (CBA) for economic evaluation,
  - iii. Environmental Index (EI) for environmental impact evaluation, and
  - iv. Life Quality Index (LQI) for evaluating societal well-being.

III. Application and validation

- a. To demonstrate the applicability of the proposed framework in two engineering domains:
  - i. Hydrogen safety and sustainability, including hydrogen enrichment of methane and hydrogen storage pathways (GH<sub>2</sub> vs NH<sub>3</sub>).

- ii. Fire Safety Engineering, including evacuation dynamics, structural fire safety, and trade-offs between safety and sustainability in building design.
  - b. To validate the framework through simulation, scenario testing, and comparison with literature and case studies.
- IV. Policy and decision-making relevance
- a. To identify policy archetypes and leverage points that shape safety and sustainability outcomes across different systems.
  - b. To provide a decision-support dashboard integrating ALARP, CBA, EI, and LQI, thereby translating the research into actionable insights for regulators, industry stakeholders, and policymakers.

### **1.3.1- Expected contributions**

By achieving these objectives, this thesis seeks to deliver the following contributions:

- I. A theoretical contribution, through the integration of Sustainability, Complexity, and Systems Thinking into a unified FRISE framework.
- II. A methodological contribution, by combining dynamic simulation, graph theory, and multi-criteria indices for holistic safety management.
- III. An applied contribution, through case studies in hydrogen safety and fire safety engineering, demonstrating transferability to other domains such as energy infrastructures and civil engineering.

Ultimately, the thesis aspires to support the design of engineering systems that are not only safer but also sustainable, societally accepted, and resilient in the face of emerging global challenges.

### **1.4- Research questions**

The motivation and objectives outlined above lead to a set of research questions that guide the development of this thesis. These questions reflect the need to overcome the limitations of traditional RA–SM approaches, to integrate sustainability dimensions, and to provide interdisciplinary insights for engineering risk management.

The central research question is: *Can a framework (the FRISE framework), grounded in Sustainability, Complexity, and Systems Thinking, be developed and applied to address the dynamic challenges of hydrogen safety, energy sustainability and fire safety engineering?*

This overarching question is addressed through the following sub-questions:

*Conceptual questions*

- I. Framework design – What are the essential modules and cross-modular linkages required to build a generic RA–SM framework (FRISE) that integrates technical, economic, environmental, and social dimensions?
- II. Paradigm integration – How can the Three-Paradigm (3P) model (Sustainability–Complexity–Systems Thinking) provide a unifying conceptual foundation for advancing RA–SM beyond traditional boundaries?

*Methodological questions*

- III. Dynamic modeling – How can Systems Thinking and System Dynamics be employed to capture feedbacks, delays, and emergent behaviors in complex socio-technical systems?
- IV. Quantitative integration – In what ways can graph-theoretical tools (e.g., influence matrices, centrality metrics) complement system dynamics to identify dominant loops, policy leverage points, and systemic vulnerabilities?
- V. Decision anchors – How can established policy anchors—ALARP, CBA, Environmental Index (EI), and Life Quality Index (LQI)—be consistently embedded within the modular framework to support evidence-based decision-making?

*Application questions*

- VI. Hydrogen safety and sustainability – How can the proposed framework be applied to:
  - a. evaluate the risks of hydrogen enrichment of methane,
  - b. compare the safety and sustainability of hydrogen storage pathways (GH<sub>2</sub> vs NH<sub>3</sub>), and
  - c. explore long-term adoption scenarios in the hydrogen economy?
- VII. Fire safety engineering – How can the framework be applied to fire safety challenges, such as evacuation dynamics, probabilistic occupant risk, and trade-offs between safety and sustainability in building design?

*Validation and policy questions*

- VIII. Validation – How can the framework’s outputs be validated against literature, case studies, and empirical data to ensure reliability and transferability?

- IX. Policy insights – Which systemic archetypes and leverage points emerge from the integrated RA–SM framework, and how can these inform more effective policies for safe and sustainable engineering systems?

#### *Alignment with objectives*

These research questions map directly to the objectives of the thesis: questions I–II support conceptual development; questions III–V address methodological innovation; questions VI–VII cover application and case studies; and questions VIII–IX target validation and policy relevance. Together, they establish a coherent path from theory to practice, ensuring that the contributions of the thesis are both scientifically rigorous and practically meaningful.

### **1.5- Overview of Publications and Conferences within the FRISE Framework**

During the Ph.D. research, several peer-reviewed publications and international conferences progressively developed and disseminated the modules of the FRISE framework. Table 1.1 summarizes all publications and international conferences derived from this PhD project. Each work corresponds to a specific domain of the framework — from Risk Assessment and Safety Management to Environmental, Economic, and Social sustainability — and demonstrates the incremental construction of the integrated Systems Thinking approach applied to hydrogen safety and fire safety engineering.

### **1.6- Structure of the thesis**

This thesis is organized into ten chapters that progressively develop, apply, and validate the FRISE Framework. Each chapter contributes to the overall objective of establishing a holistic, feedback-oriented methodology for integrating risk, safety, and sustainability across complex engineering systems.

**Chapter 1 – Introduction.** This current chapter presents the motivation, context, and research rationale of the study. It introduces the gaps identified in traditional Risk Assessment–Safety Management (RA–SM) approaches, outlines the research objectives and questions, and formally defines the FRISE Framework as the core methodological contribution of the thesis. It also positions the research within the broader context of sustainability, complexity, and systems thinking.

**Chapter 2 – Conceptual and Theoretical Foundations** elaborates the theoretical paradigms underpinning the FRISE Framework. It discusses the three fundamental pillars—Sustainability,

Complexity, and Systems Thinking—and how they collectively support a feedback-based understanding of risk and safety.

**Chapter 3** – *Systematic Literature Review of Fire Safety Engineering: Systems Thinking and Sustainability Trade-offs* presents a detailed systematic literature review of the Fire Safety Engineering domain. It outlines the review methodology, including databases, keywords, and inclusion criteria, and analyzes trends in systems-based and sustainability-oriented research. Quantitative and qualitative results are discussed to identify how systems thinking has been applied to fire safety, how sustainability metrics have been incorporated, and where significant research gaps remain. The findings demonstrate the limited integration of feedback-based modeling in Fire Safety Engineering and motivate the need for a broader, systemic approach.

**Chapter 4**– *Comparative Literature Review: Risk and Safety Modeling in Complex Engineering Systems* broadens the perspective to other sectors, including chemical, energy, and hydrogen systems. It synthesizes advances in risk assessment, safety management, and sustainability integration across these domains. By comparing the lessons learned and identifying cross-sectoral limitations, the chapter defines the overarching research gaps that justify the development of the FRISE Framework as a unifying approach for systemic safety and sustainability modeling.

**Chapter 5** – *The FRISE Research Framework* details the methodological design and structure of the FRISE Framework. It explains its five modular components—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—and describes how they are interconnected through feedback relationships. The methodological tools adopted, including System Dynamics modeling, Causal Loop Diagrams, and Graph Theory metrics, are introduced, together with data sources and validation procedures.

**Chapter 6** – *FRISE Core Model Development* describes the development of each FRISE module in detail, outlining their internal structures, feedback loops, and interactions. The cross-modular integration is established through an overarching causal network, which captures the dynamic interplay between risk control, safety culture, economic performance, environmental compliance, and social trust. This network forms the operational backbone of the framework used in the subsequent application chapters.

**Chapter 7** – *Application I: Hydrogen Safety and Sustainability* provides the first application of the FRISE Framework focusing on hydrogen safety systems. It models dynamic interactions between process safety, safety management investment, and sustainability factors during

hydrogen enrichment and storage. The analysis demonstrates the framework's ability to capture feedback-driven behaviors and policy sensitivities in emerging energy technologies.

**Chapter 8 – Application II: Fire Safety Engineering** applies FRISE to the domain of fire safety engineering. It combines literature-derived feedback structures with new dynamic models addressing evacuation, building design, and safety–sustainability trade-offs. The analysis highlights the systemic dependencies between safety performance, resource allocation, and societal acceptance, demonstrating FRISE's transferability to complex socio-technical safety problems.

**Chapter 9 – Application III: Energy Sustainability and Hydrogen Economy** extends the framework to macro-scale sustainability challenges, modeling the hydrogen economy as a complex socio-technical system. It explores how feedbacks among economic, environmental, and social subsystems which influence large-scale energy transition pathways, policy delays, and public acceptance. The results provide strategic insights into balancing energy security, safety, and sustainability under systemic constraints.

Finally, **Chapter 10 – Validation, Discussion, and Comparative Insights** validates the FRISE Framework across domains, assessing its structural coherence, behavioral realism, and applicability. Comparative insights highlight recurring feedback patterns and sustainability drivers. Finally, the chapter presents the general conclusions, practical and research recommendations, and a comprehensive summary of the entire thesis, highlighting how the research objectives were achieved and how FRISE contributes to the advancement of systemic sustainability engineering.

Figure 1.1 illustrates the logical organization and progression of the thesis, structured around four main research stages. The first stage, *Introduce and contextualize the research problem* (Chapters 1–4), establishes the motivation, theoretical foundations, and literature analyses that reveal existing gaps in risk and safety modeling within complex engineering systems. The second stage, *develop the FRISE Framework* (Chapters 5–6), presents the conceptual and methodological design of the Feedback-based Risk Integration for Safety and Sustainability in Engineering (FRISE) model and details its core modular structure. The third stage, *demonstrate its application in complex domains* (Chapters 7–9), applies the framework to hydrogen safety, fire safety engineering, and energy sustainability, validating its adaptability across socio-technical systems. The final stage, *validate the framework and extract comparative insights*

(Chapter 10), synthesizes results, assesses cross-domain feedback patterns, and formulates conclusions and recommendations for future research and policy.

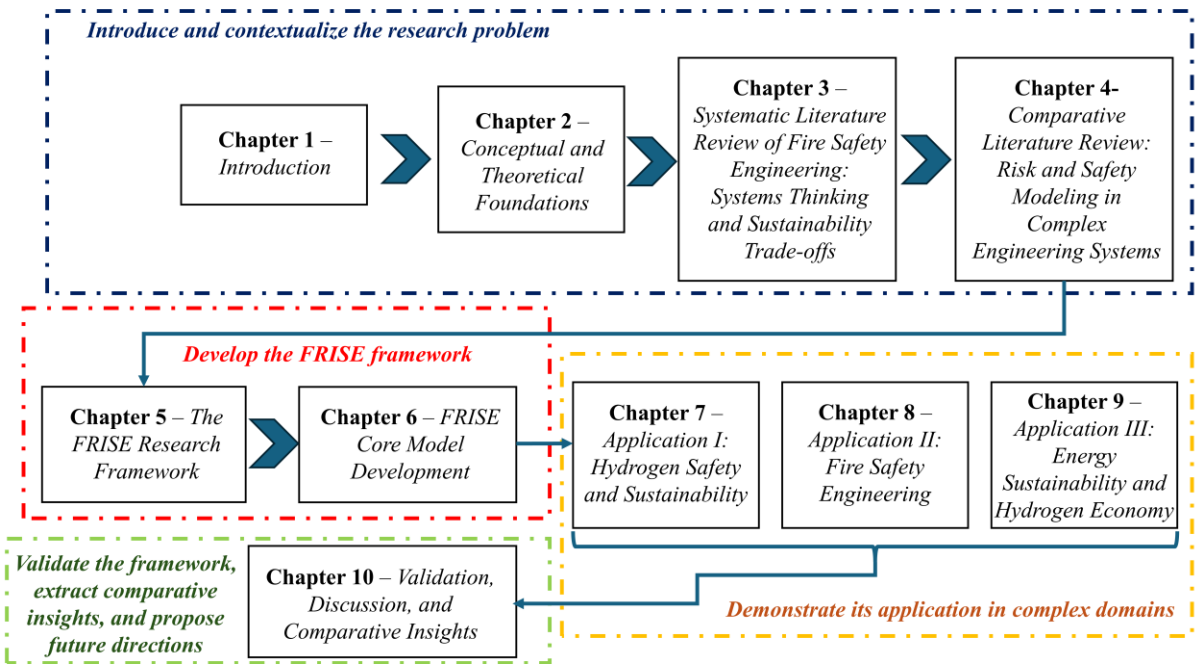


**Fig. 1.1- Thesis roadmap and structure of the research**

Overall, the thesis progresses from theoretical and methodological foundations to model construction, domain applications, and integrated analysis. The structure reflects the evolution of the research—from conceptual development to empirical validation—culminating in the establishment of FRISE as a robust, transferable framework for addressing complexity, sustainability, and resilience in engineering systems.

**Table 1.1- Publications and Conferences within the FRISE Framework (2022–2025)**

| <b>Year</b> | <b>FRISE Module / Theme</b>                           | <b>Type</b>               | <b>Title &amp; Venue</b>                                                                                                                                                                                                     | <b>Relevance / Contribution to the FRISE Framework</b>                                                         |
|-------------|-------------------------------------------------------|---------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|
| 2022        | RA / ECO                                              | Journal                   | Fire and Explosion Economic Losses (FEEL) Index: A new approach for quantifying economic damages due to accidents in hydrocarbon storage sites. Process Safety and Environmental Protection, DOI: 10.1016/j.psep.2022.07.007 | Established the Economic (ECO) foundation of the FRISE model by quantifying industrial accident losses.        |
|             | RA                                                    | Conference                | 14th ISHPMIE 2022 – Probabilistic Risk Assessment for Domino Effect due to Vapor Cloud Explosions using an Integrated Petri–Bayesian Network Approach, Braunschweig, Germany.                                                | Early exploration of Risk Assessment (RA) dynamics in process safety.                                          |
| 2023        | SM / SOC                                              | Conference                | CCS/Italy 2023 – Italian Chapter of the Complex Systems Society. Using a Systems Thinking Approach for Hydrogen Safety Management, Naples, Italy.                                                                            | First presentation of Systems Thinking (ST) as a tool for Safety Management (SM) and hydrogen safety.          |
| 2024        | ENV / ECO / SOC (Core Theory)                         | Journal                   | Towards Sustainable Hydrogen Production: An Integrated Approach for Sustainability, Complexity, and Systems Thinking in the Energy Sector. Journal of Cleaner Production, DOI: 10.1016/j.jclepro.2024.141751                 | Defined the Three-Paradigm (Sustainability–Complexity–ST) theoretical base for FRISE; cornerstone publication. |
|             | RA / SM / ENV                                         | Journal                   | An Integrated Systems Thinking Approach for Assessing and Comparing the Safety of Hydrogen and Ammonia Storage. Chemical Engineering Transactions, DOI: 10.3303/CET24111065                                                  | Integrated Environmental (ENV) and Safety Management (SM) modules; validated dynamic interdependencies.        |
|             | RA / SM                                               | Journal                   | Systems Thinking for Explosion Safety Management. Journal of Loss Prevention in the Process Industries, DOI: 10.1016/j.jlp.2025.105621                                                                                       | Developed System Dynamics (SD) model for explosion risk; strengthened RA–SM interface.                         |
|             | SM / FSE                                              | Conference                | ISHPMIE 2024 – International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions. Systems Thinking for Explosion Safety Management, Naples, Italy.                                                      | Disseminated SD–based explosion model; connected FRISE to the industrial safety community.                     |
|             | RA / ENV                                              | Conference                | CISAP 11 – International Conference on Safety & Environment in Process & Power Industry. An Integrated Systems Thinking Approach for Assessing and Comparing the Safety of Hydrogen and Ammonia Storage, Naples, Italy.      | Introduced comparative SD analysis of hydrogen and ammonia storage; RA–ENV coupling.                           |
|             | SM / FSE                                              | Conference                | ESFSS 2024 – 4th European Symposium on Fire Safety Science. Using System Dynamics for Cost–Benefit Analysis of Fire Safety Engineering Features, Barcelona, Spain.                                                           | First Fire Safety Engineering (FSE) application of SD; linked SM to FRISE framework.                           |
| 2025        | Cross–Modular Integration / FRISE Framework Synthesis | Journal (to be submitted) | FRISE: Feedback-based Risk Integration for Safety and Sustainability in Engineering. A holistic risk and safety framework for complex engineering systems. Reliability Engineering & System Safety (Submission 2025).        | Capstone paper integrating all FRISE modules (RA–SM–ECO–ENV–SOC); defines and validates the full framework.    |



| Year                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | FRISE Module / Theme                         | Type                      | Title & Venue                                                                                                                                                                        | Relevance / Contribution to the FRISE Framework                                                 |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| 2025 (cont.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | RA / SM Dynamic Modelling                    | Journal                   | Using a Systems Thinking Approach for a Dynamic Hydrogen Risk Assessment. Chemical Engineering Transactions, DOI: 10.3303/CET25116028.                                               | Quantitative dynamic modelling of hydrogen risk; consolidates RA–SM feedback loops.             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | SOC / FSE                                    | Journal (to be submitted) | Modeling Occupant Risk during Fire Growth and Evacuation Using a System Dynamics Approach. Journal of Loss Prevention in the Process Industries.                                     | Represents the Social (SOC) layer through occupant evacuation modelling.                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | FSE / Complexity                             | Journal (under review)    | Exploring Systems Thinking and System Dynamics in Fire Safety Engineering: A Literature Review. Fire Technology (Springer Nature).                                                   | Theoretical expansion of FRISE principles into Fire Safety Engineering research.                |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | FSE / SOC / ENV                              | Journal                   | A Systems Thinking Approach to Balancing Fire Safety and Sustainability in Building Design. Journal of Physics: Conference Series (IOP), 2025.                                       | Integrates FSE–Sustainability–Social modules, demonstrating cross-sector adaptability of FRISE. |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Cross–Modular Validation                     | Conference                | ISFEH 2025 – International Symposium on Fire Engineering and Human Behavior. Modeling Occupant Risk during Fire Growth and Evacuation Using a System Dynamics Approach, Rome, Italy. | Application of FRISE–SOC modules to human behavior and evacuation.                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Cross–Sector Application / RA–SM Integration | Conference                | Loss Prevention 2025 – AIDIC Conference. Using a Systems Thinking Approach for a Dynamic Hydrogen Risk Assessment, Bologna, Italy.                                                   | Validation of RA–SM module and dissemination to process safety community.                       |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Cross–Field Integration (Chemical / Civil)   | Conference                | GRICU Congress 2025 – Challenging Chemical Engineering. A Generic System Dynamics Model for Integrated Risk Assessment and Safety Management in Chemical Engineering, Ischia, Italy. | Presentation of unified RA–SM–Cross Modular model for chemical systems.                         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | FSE / Sustainability                         | Conference                | ESFSS 2025 – 5th European Symposium on Fire Safety Science. A Systems Thinking Approach to Balancing Fire Safety and Sustainability in Building Design, Slovenia.                    | Expanded validation of FSE–Sustainability interactions; feedback to FRISE.                      |
| <p>Acronyms: FRISE – Feedback-based Risk Integration for Safety and Sustainability in Engineering; RA – Risk Assessment; SM – Safety Management; ECO – Economic; ENV – Environmental; SOC – Social; FSE – Fire Safety Engineering; ST – Systems Thinking; SD – System Dynamics; CBA – Cost–Benefit Analysis; ISHPMIE – Int. Symposium on Hazards, Prevention &amp; Mitigation of Industrial Explosions; CISAP – Int. Conf. on Safety &amp; Environment in Process &amp; Power Industry; ESFSS – European Symposium on Fire Safety Science; ISFEH – Int. Symposium on Fire Engineering &amp; Human Behavior; LP – Loss Prevention Conference; GRICU – <i>Gruppo Ricercatori di Ingegneria Chimica Universitari</i>; CCS/Italy – Italian Chapter of the Complex Systems Society; JCP – Journal of Cleaner Production; JLPPI – Journal of Loss Prevention in the Process Industries; CET – Chemical Engineering Transactions; PSEP – Process Safety and Environmental Protection; RESS – Reliability Engineering &amp; System Safety. <i>Journal paper status updated October 31<sup>st</sup>, 2025.</i></p> |                                              |                           |                                                                                                                                                                                      |                                                                                                 |

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## **Chapter 2 – Conceptual & Theoretical Foundations**

This chapter develops the theoretical basis of the thesis by integrating three complementary paradigms—Sustainability, Complexity, and Systems Thinking—into a unified conceptual model. It analyzes how these paradigms jointly support dynamic decision-making and holistic system representation in engineering risk and safety contexts. Systems Thinking and System Dynamics are introduced as methodological instruments for modeling feedback loops, interdependencies, and delays, while Graph Theory is presented as a complementary structural analysis tool. Together, these concepts form the Three-Paradigm (3P) model, which underpins the design of the FRISE Framework. The chapter demonstrates how the 3P model operationalizes feedback-based reasoning and interdisciplinary integration, thereby linking abstract theory with the methodological architecture elaborated in Chapter 3 and beyond.

### **2.1- Introduction**

The dynamic nature of the world, shaped by emerging situations and unforeseen events, needs a consideration of these factors in endeavors toward sustainable development. Effectively addressing the complex challenges is essential for comprehending, describing, and studying the intricacies of our global environment. Despite the awareness of living in a complex world, conventional decision-making has often relied on static, narrow, and reductionistic mental models (Ball & Wietschel, 2009). In other words, to propose an effective decision-making approach, it is needed to provide a holistic perspective considering dynamic complexity.

The global energy sector constitutes a dynamically complex system (Birol, 2022), suggesting that its behavior is influenced not only by its independent components but also by the emergent behavior arising from its agent interactions (Laimon et al., 2022). Due to this fact, there are several and crucial limitations of previous approaches (Nanjundaswamy Vasist & Krishnan, 2023) for addressing the sustainability challenge of the energy sector (Zhao et al., 2023). At the same time, it is important to highlight that sustainability includes environmental protection, societal advancements, but also, economic development (Meraj et al., 2023). For this reason, the proposed solutions must be economically viable, otherwise, it is not possible to talk about real sustainable development.

Therefore, with regard to the energy sector, it is of paramount importance to propose a holistic framework which integrates the following aspects for sustainable development: (1) an effective decision-making process, (2) the dynamic behavior of the energy sector, and (3) the complexity linked to the sustainability of the energy sector. Additionally, there is a gap in integrating into

the same approach the complex interdependencies among technical issues and social, economic, and political decisions related to the energy sector which need to be studied and modeled in order to adopt the right policies in the long-term run. For this purpose, it is needed to propose effective ways of intervention in a given complex system (as is the energy sector), but how to do so?

A possible answer to this concern is that changing paradigms and changing the way of adopting them could lead to achieving actual changes in a given complex system. According to Meadows, (2008) the most effective places to intervene in a system are (1) the power to transcend paradigms, (2) the mindset or paradigm from which the system arises; and (3) the goals of the system. “There is yet one leverage point that is even higher than changing a paradigm” (D. Meadows, 1999). Therefore, nowadays the integration of new predominant paradigms in order to provide a unified framework could aim at this actual transformation looking for a sustainable future.

The second question to be addressed is which paradigms really need to be integrated for this purpose. The complexity paradigm allows to identify the interactions and interdependencies among the economy, the environment, and the society. A Systems Thinking approach leads to adopt an effective decision-making process consistent with the complex causalities identified (Delikhoon et al., 2022). Finally, sustainability naturally emerged as the result of combining these paradigms.

This chapter aims to fill the aforementioned gaps by developing a new unified framework for the integration of the following three paradigms: (1) *Sustainability*, (2) *Complexity*, and (3) *Systems Thinking*. For this purpose, it is crucial to analyze the multiple and complex interdependencies among the economy, the environment, and the society. Hence, the novelty of this integration results from the development of a new framework for integrating three paradigms into the same approach: (1) *Sustainability*, (2) *Complexity*, and (3) *Systems Thinking*.

By providing a holistic perspective through the integration of the aforementioned paradigms it is expected to consider the multiple and complex interdependencies among economy, environment, society, sustainability, and safety within the FRISE framework. At the same time, integrating these paradigms will contribute to adopting long-term solutions in the near future by assuring the effectiveness of these policies.

Additionally, the conceptual models developed as well as the proposed guidelines will allow to analyze the dynamic behavior of the energy sector and fire safety engineering by studying the effectiveness of different policies.

## **2.2- Why is a Systems Thinking approach chosen?**

### **2.2.1- Theoretical overview**

This section provides a theoretical overview of ST, SD, and STS theory to establish the conceptual foundation for the literature review (Chapters 3-4). These frameworks are presented as established methodologies rather than being subjects of critical examination. Exploring alternative or complementary perspectives to ST and SD could be a valuable direction for future research. Additionally, the tools that can be used within an ST framework are explained, such as the CLD, SAs, and SD.

ST encompasses a range of philosophical and methodological perspectives that vary in their emphasis on qualitative or quantitative analysis. Two influential perspectives are often highlighted:

- Soft / phenomenological systems approaches – Exemplified by the work of (Checkland, 1981), this perspective emphasizes understanding systems through the lens of stakeholders' perceptions, experiences, and values. Known as Soft Systems Methodology (SSM), this approach focuses on clarifying complex, ill-structured problems by engaging stakeholders in iterative learning processes. It is particularly suited for situations where problem boundaries and objectives are contested or evolving.
- Hard / quantitative systems approaches – Represented by Forrester's System Dynamics (Forrester, 1961), this perspective is grounded in formal modeling and simulation of feedback processes. It seeks to capture the structure and behavior of systems through quantifiable variables, causal relationships, and time delays. This approach is effective in contexts where system boundaries can be defined and sufficient data exist to support modeling.

Other foundational contributions to ST include von Bertalanffy's (von Bertalanffy, 1968) General System Theory, which provided the theoretical basis for viewing systems holistically; Meadows' (Meadows, 2008) articulation of feedback loops and leverage points in Thinking in Systems; and Senge's (Senge, 1990) integration of ST into organizational learning.

In this research, both perspectives are relevant: the soft systems view offers insight into socio-technical and stakeholder dimensions of fire safety, while the hard systems view informs quantitative modeling through tools such as SD. Integrating these perspectives enables a more comprehensive approach to complex problems, where both stakeholder engagement and quantitative analysis are often necessary.

It is important to clarify the boundaries of ST when combining it with other analytical approaches. As Leveson (Leveson, 2011) notes, ST analyses focus on understanding system structure, feedback loops, and interdependencies, whereas traditional risk analyses quantify probabilities and consequences, often within a predefined event space. ST-based tools are understood to include SD, CLDs, and SAs. Non-ST tools such as CBA, Probabilistic Risk Assessment (PRA), or Bayesian Networks can complement ST when carefully integrated—for example, using SD to map dynamic interactions and PRA to quantify specific risk pathways. Such combinations can provide a more comprehensive view of system performance, but also introduce methodological challenges, including the need to reconcile qualitative causal mapping with quantitative statistical modeling. Recognizing these boundaries helps prevent the misconception of ST as a ‘theory of everything’ and ensures its application remains problem-focused and evidence-based.

### 2.2.2- Comparing Complex Adaptive Systems Theory, Soft Systems Modeling, and Systems Thinking approaches

In this section the three most important approaches are compared: Complex Adaptive Systems Theory (CAS), Soft Systems Modeling (SSM), and the Systems Thinking (ST) approach. Table 2.1 shows a brief comparison of these methods.

**Table 2.1: Comparison among the CAS Theory, SSM, and Systems Thinking approach**

| Parameter         | CAS Theory                                                           | SSM                                                           | ST                                                      |
|-------------------|----------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------|
| Scope             | Primarily focused on complex adaptive systems in nature and society. | Primarily applied to human activity systems.                  | Applicable across a wide range of systems.              |
| Approach          | Emphasizes adaptability and emergence.                               | Human-centric and emphasizes stakeholder perspectives.        | Holistic approach considering system interdependencies. |
| Modeling          | Focuses on understanding and describing system behavior.             | Involves creating rich pictures and conceptual models.        | Involves system diagrams and feedback loops.            |
| Applicability     | Well-suited for natural and social systems.                          | Effective for addressing unstructured human activity systems. | Applicable across various domains and industries.       |
| <i>References</i> | (Holden, 2005; Holland, 1992)                                        | (Hindle, 2011)                                                | (Martinez & Richardson, 2009; Sterman, 2002)            |

In general, these paradigms offer different lenses for understanding and solving complex problems. The choice of the adopted approach will depend on the nature of the problem, the context, and the specific factors that need attention. In this research a Systems Thinking approach is adopted due to its ability to capture the interdependencies of a given system, considering their dynamic evolution and possible interactions. This comparative assessment establishes the rationale for adopting Systems Thinking as the foundational paradigm of the FRISE framework, as detailed in the following sections.

### **2.3- Systems Thinking approach and interactions with Complexity and Sustainability paradigms**

ST can be understood at the philosophical level as the holistic conceptual framework for analyzing systems by recognizing feedback loops, interdependencies, and emergent properties (Checkland, 1981; D. H. Meadows, 2008; von Bertalanffy, 1968). ‘System Dynamics’ (SD), developed by Forrester (Forrester, 1961), is a quantitative simulation method within the ST paradigm (i.e., the methodological level of ST), translating conceptual models into computational representations to test policies over time. SAs represent recurrent behavioral patterns in systems (Senge, 1990) (toolset level of ST), while STS theory views systems as the product of interactions between social and technical components (Emery & Trist, 1960).

Thus, while ST is a broad conceptual framework for understanding the interconnections within complex systems, SD is a specific methodological tool within that framework. ST helps identify relationships, feedback loops, and leverage points conceptually, often using qualitative tools like CLD. In contrast, SD takes this a step further by translating these relationships into quantitative models that simulate system behavior over time. In other words, ST frames the problem and structure, while SD allows for computational modeling and scenario testing.

For example, consider an FSE scenario involving an automatic sprinkler system in a commercial building. A ST approach would help identify the system elements (e.g., detection, water supply, maintenance routines) and map out their interrelations, such as how delayed maintenance reduces system effectiveness over time. Building on this, a SD model could simulate how sprinkler effectiveness quantitatively evolves based on factors such as maintenance frequency, detection accuracy, and fire growth rate. This simulation would help engineers test the long-term impact of different maintenance schedules on fire suppression performance, allowing them to optimize intervention strategies and allocate resources more effectively.



ST is a structured approach to address complexity. The Complexity paradigm recognizes that many real-world systems, including those related to fire safety, exhibit hardly predictable behaviors due to their intricate structures and interactions (Dueñas Santana et al., 2024). More explicitly, complexity is understood as a property of systems in which numerous interdependent elements interact in dynamic and/or non-linear ways, leading to emergent patterns that are not directly traceable to individual components (Checkland, 1981; D. H. Meadows, 2008). In the FSE context, such complexity may manifest in scenarios where technical systems, human actors, and regulatory frameworks interact—such as during an emergency evacuation—producing outcomes that are difficult to predict using reductionist approaches. ST allows decision-makers to account for these complexities by modeling the system as a whole, from a holistic perspective, rather than analyzing components in isolation (Dueñas Santana et al., 2025).

As touched upon earlier with regard to ST, in this thesis, Systems Thinking (ST), Complexity, and Sustainability are considered across three levels of understanding (Table 2.2). At the philosophical level, ST represents a worldview emphasizing interconnections, feedback, and emergence; Complexity reflects a scientific perspective on adaptive, non-linear systems; and Sustainability provides a normative vision for long-term viability. At the methodological level, ST is expressed through approaches such as System Dynamics, qualitative system mapping, or hybrid socio-technical modeling; Complexity is treated as a conceptual orientation for analyzing interdependent system behavior; and Sustainability is framed as a principle guiding assessment methods and design strategies. Finally, at the tool level, ST is operationalized through techniques such as Causal Loop Diagrams (CLDs), System Archetypes (SAs), and simulation models; Complexity is represented through indicators or metrics of interdependence and adaptivity; and Sustainability is applied through tools like life cycle assessment, resilience metrics, or multi-criteria evaluation frameworks.

This multi-level framing highlights how these perspectives interact in Fire Safety Engineering: philosophical principles shape methodological choices, which are then implemented through practical tools. This distinction is particularly relevant for fire safety challenges that require balancing immediate performance with long-term resilience (Dueñas Santana et al., 2024) and aligns closely with recent work on dynamic systems modeling of social–ecological systems (Radosavljevic et al., 2023). For example, choosing suppression agents for fire suppression systems requires a deep understanding of how these agents impact ecological health and resource use (Mawhinney & Back, 2016). Similarly, evacuation strategies must consider the

diverse needs of different populations by ensuring equitable protection for all building occupants (Maluk et al., 2017; Meacham, 2023). ST thus fosters a proactive approach to sustainability by modeling how interventions affect both immediate outcomes and lifecycle performance (Kodur et al., 2020).

**Table 2.2: Definition of terms and representation of concepts covered in this thesis considering three levels of understanding**

| Term                          | Philosophical level                                                                                                                                                            | Methodological level                                                                                       | Tool level                                                               |
|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Paradigm                      | Overarching worldview or conceptual lens for interpreting systems and problems.                                                                                                | N/A                                                                                                        | N/A                                                                      |
| System                        | Conceptual model of interacting elements forming a whole.                                                                                                                      | Frameworks for analyzing system boundaries, interactions, and functions.                                   | System maps, stock-and-flow diagrams, network representations.           |
| Systems Thinking (ST)         | A worldview emphasizing interconnections, feedback, emergence, and holistic framing (Checkland, 1981; Forrester, 1961; D. H. Meadows, 2008; Salmon et al., 2022; Senge, 1990). | Approaches such as System Dynamics, qualitative system mapping, hybrid socio-technical modeling.           | Causal Loop Diagrams (CLDs), System Archetypes (SAs), simulation models. |
| Complexity                    | Perspective on adaptive, non-linear, emergent system behaviors.                                                                                                                | Conceptual orientation to study interdependence and dynamics in the field.                                 | Complexity indicators, resilience measures, sensitivity analyses.        |
| Sustainability                | Normative paradigm guiding design toward long-term viability.                                                                                                                  | Assessment methodologies such as life cycle analysis, resilience frameworks, or multi-criteria evaluation. | Tools like LCA software, sustainability metrics, cost-benefit models.    |
| Socio-technical systems (STS) | Perspective integrating social and technical subsystems.                                                                                                                       | Analytical frameworks to study human-technology-institution interactions in the field.                     | Socio-technical models, agent-based simulations, stakeholder mapping.    |

Overall, the integration of these three paradigms ST, Complexity, and Sustainability, may foster the development of fire safety solutions that are efficient, resilient, adaptable, and aligned with long-term sustainability goals. The integration of these three paradigms at the philosophical, methodological, and tool levels provides the conceptual foundation upon which the FRISE framework is constructed.

## 2.4- Integration of the FRISE Framework

The integration of the three paradigms—Sustainability, Complexity, and Systems Thinking—is operationalized in this research through the FRISE framework (Fire Safety, Risk, Integration, Sustainability, and Engineering). The FRISE framework acts as a conceptual and

methodological bridge linking the theoretical foundations presented in this chapter with the quantitative applications developed in the following ones. Within FRISE:

- **Fire Safety (F)** and **Risk (R)** represent the technical and probabilistic core of the framework, where hazards, barriers, and vulnerabilities are dynamically modeled.
- **Integration (I)** refers to the systemic coupling of disciplinary domains—economic, environmental, and social—into a single dynamic architecture.
- **Sustainability (S)** introduces long-term perspectives, ensuring that short-term risk mitigation strategies align with broader developmental objectives.
- **Engineering (E)** provides the applied and computational layer in which the conceptual models are implemented through *Causal Loop Diagrams* (CLDs), *System Dynamics* (SD) modeling, and *Graph Theory* analytics.

Through FRISE, the 3P model transcends its abstract definition to become an actionable framework for decision-making in **Risk Assessment (RA)** and **Safety Management (SM)**. It allows analyzing how safety, environmental, and economic policies interact over time, capturing reinforcing and balancing feedbacks that determine the system's resilience or fragility. Consequently, the FRISE framework provides the backbone for the subsequent modeling chapters, where its conceptual elements are translated into quantifiable simulations and cross-modular feedback analyses. In this way, the FRISE framework operationalizes the 3P model, providing a systemic lens for addressing complexity in Risk Assessment and Fire Safety Engineering.

## 2.5- Causal Loop Diagrams, a visualization tool for complex interactions

CLDs are powerful tools used in ST for visualizing and understanding the complex interactions within a system. CLDs provide a graphical representation of how different variables within a system influence one another through feedback loops, helping to identify the dynamic behavior of the system over time. CLDs are ideal for dealing with complex systems because they allow to consider simultaneously interconnected factors, assess risks, predict outcomes, and therefore, inform effective interventions (Martín García, 2006).

At the core of a CLD are variables, which represent anything from a physical quantity (such as temperature, and smoke concentration) to more abstract concepts (such as perceived safety or response time). These variables are connected by arrows that indicate the polarity of the causality. A positive causality between two variables (“A” and “B”) means that (all else

remaining equal) an increase in the variable “A” will lead to an increase in the value of the variable “B” above what it would otherwise have been. On the contrary, a negative causality means that an increase in the variable “A” will lead to a decrease of the value of the variable “B” below what it would otherwise have been. The connections between variables form feedback loops, which can be reinforcing (positive feedback) or balancing (negative feedback) (Andres & Poler, 2016).

In FSE, CLDs can thus help model complex interactions that are difficult to capture using traditional linear approaches. A good example is considering a scenario involving fire spread in a building. A CLD can visually represent how factors such as fuel availability, ventilation, and suppression systems interact with one another to influence fire growth (Nayak et al., 2024; Van Hees, 2013). Feedback loops can illustrate how an increase in fire intensity leads to higher temperatures, which, in turn, accelerates combustion (reinforcing loop). At the same time, a balancing loop captures how the activation of sprinklers can reduce the fire’s intensity, thus controlling its spread. These CLDs make it easier to identify which variables are key drivers of the system’s behaviour and how interventions may ripple through the system (Wen et al., 2024).

One of the primary advantages of CLDs is their ability to simplify complex systems into a more digestible format, making it more feasible for engineers, policymakers, and other stakeholders to communicate and collaborate effectively. By visualizing the relationships and feedback loops within a fire safety system, CLDs allow stakeholders to better understand how different interventions (such as changes in building materials, fire suppression methods, or evacuation strategies) will impact the overall system. This clarity helps in decision-making processes, ensuring that actions taken to improve fire safety are informed by a comprehensive understanding of the SD at play (Bendor & Kaza, 2012).

CLDs also serve as a foundation for developing simulation models, such as those used in SD-based models. By first mapping out the qualitative relationships between variables in a CLD, engineers can then move on to developing quantitative models that simulate the behaviour of the system under different scenarios. For example, a CLD of an evacuation process can highlight how crowd density, exit availability, and evacuation routes interact, which can then be translated into a more complex quantitative simulation to optimize evacuation strategies under various fire conditions (Kumar et al., 2022; Ronchi, 2021).

## 2.6- System Dynamics overview: flows, stocks, and delays

SD is a powerful quantitative modeling approach used to simulate the behavior of complex systems over time. Originally developed by Jay W. Forrester in the 1960s (Lane & Sterman, 2011), it has since been applied across several fields, including economics, environmental studies, and engineering. In FSE, SD offers a framework to model the dynamic interactions within fire safety systems, allowing engineers to predict how different variables change over time, evaluate the impacts of policies, and optimize the overall system performance (Ding et al., 2018; Ghamarimajd et al., 2024).

Figure 2.1 shows the basic structure of a generic SD model. There are three main components in an SD-based model: stocks, flows, and delays. Also, there are auxiliary variables which simplify the definition of relationships for the simulation. Stocks represent the accumulation of resources, materials, or other quantifiable entities in a system at any given time. Stocks are essentially the “state” of the system and can be thought of as containers that hold quantities of something. In FSE, examples of stocks can include the amount of combustible material present in a building, the number of operational fire extinguishers, or the current temperature of a room during a fire event. Stocks change over time as they are filled or drained by flows (see below). Stocks represent the system’s memory, storing information about past actions and conditions. They also provide inertia, meaning that changes in the system often occur gradually rather than instantaneously (Lane & Sterman, 2011).

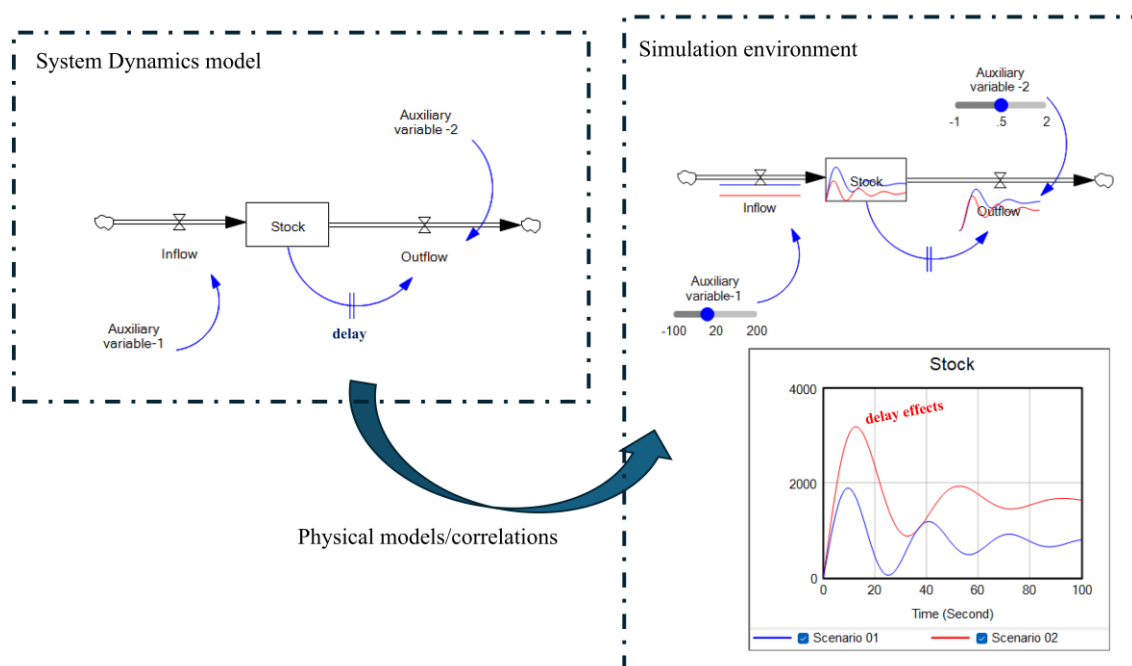


Fig. 2.1: System Dynamics modeling process

Flows represent the rates at which stocks increase or decrease. In other words, flows are the processes that fill or drain the stocks in a system. Flows can be seen as the movement of resources into or out of a stock over a certain time. Flows are driven by decisions, policies, physical processes, and external influences. Understanding the factors that influence flows is crucial for predicting the behavior of a fire safety system. For instance, the rate at which fire spreads (a flow) can be influenced by factors such as ventilation, fuel type, and fire suppression activities. Engineers can manipulate flows to achieve desired outcomes, such as slowing the spread of fire by increasing fire suppression efforts (Martín García, 2006).

Delays represent the time lag between an action or decision and its effect on the system. Delays are inherent in many real-world systems and can significantly influence system behavior, often contributing to unexpected outcomes. Delays can create instability and oscillation within a system, especially when feedback loops are involved. For example, in a fire evacuation scenario, a delay in the decision to evacuate can result in increased danger as conditions deteriorate. Identifying and accounting for delays is essential when designing fire safety interventions, as they can influence the timing and effectiveness of responses (Ronchi, 2021; Ronchi et al., 2024).

The interactions between stocks, flows, and delays form the basis of dynamic behavior in systems. By mapping these interactions, SD models can capture the complex, non-linear behaviors often observed in real-world fire safety systems. This holistic view allows for the identification of critical points in the system where interventions can have the most significant effect, ultimately improving fire safety outcomes.

While SD modeling can most readily be applied in FSE to represent fire phenomena and safety system performance, it also has the potential to capture dynamics at the level of entire STS. By explicitly modeling the interactions between social, organizational, and technical components, SD could support analyses of how regulatory frameworks, occupant behavior, and emergency response interact with physical fire dynamics. Such applications have been explored in related fields, including social-ecological systems and infrastructure resilience (Radosavljevic et al., 2023), and could be adapted to FSE. However, modeling large STSs requires careful boundary definition, extensive data, and robust validation, which present both methodological challenges and opportunities for future research.

These modeling principles will later be applied to the MATLAB modules developed for risk, social, environmental, and cross-modular analyses (Chapters 5–6).

## 2.7- The Three-Paradigm (3P) model

### 2.7.1- Theoretical background

This section focuses on presenting a new three-paradigm (3P) model considering a holistic perspective for achieving sustainability. Table 2.3 shows the advantages of using each paradigm as well as the challenges linked with the use of each one.

**Table 2.3: Advantages and challenges of integrating each paradigm in the same model**

| Paradigms        | Advantages                                                                                                                          | Challenges                                                                                                                                                                            |
|------------------|-------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sustainability   | Analyzing effective long-term policies for sustainable development considering the economic, environmental, and societal impacts.   | Handling emerged complexity linked to the economic (Dueñas Santana et al., 2022), environmental, and societal impacts (Dueñas Santana et al., 2021) as well as their synergic effect. |
| Complexity       | Considering the common phenomena of complex systems, and the complex relations among the environment, the economy, and the society. | Dealing with multi-agent networks and multiple interdependencies and causalities.                                                                                                     |
| Systems Thinking | Providing a decision-making approach for analyzing the dynamic behavior of a given system.                                          | Collaborative thinking in the framework of emerged complexity due to multiple interrelations.                                                                                         |

Traditional approaches often treat systems as static entities, failing to capture their dynamic nature and the interplay of feedback loops over time. By integrating Systems Thinking, Sustainability, and Complexity paradigms, it is much better understood how complex systems evolve, adapt, and respond to changes in their environment. Therefore, considering the dynamic nature of the systems is crucial to studying the interconnections among the economy, the environment, and the society linked to energy sustainability.

The integration of these paradigms has itself many challenges, some of which will be addressed in this research (such as the role of collaborative thinking, and the way for dealing with multiple interdependencies), the others have been outlined as future research lines.

At the same time, these paradigms are intrinsically related. Figure 2.2 shows the general picture of this 3P (Sustainability-Complexity-Systems Thinking) model. The development of a Systems Thinking approach is needed for addressing the complex phenomena related to all the possible interactions in order to achieve sustainability. The complexity of the sustainability paradigm relies on the emergent behavior of the interdependencies among economic development, environmental respect, and societal implications. At the same time, a Systems

Thinking algorithm provides an effective decision-making framework which leads to effective policies for sustainable production.

The most effective way for capturing these interrelations and causalities is through the Systems Thinking paradigm (CLDs plus Forrester diagrams). Additionally, common properties related to the complexity paradigm challenge applying a Systems Thinking approach (such as the non-linear dynamics, multidirectional relations, feedback loops, multiscale properties, and inherent uncertainty). However, these properties are inherent in most complex systems, which are necessary to consider for implementing effective decisions (using a Systems Thinking approach) for achieving sustainable development.

Moreover, the Systems Thinking approach provides many advantages such as the identification of leverage points, the design of effective interventions, and the prediction of the system behavior which leads to long-term viability (necessary for sustainable development) and promotes adaptive management. Using this adaptive management will minimize undesirable outcomes or consequences, assuring sustainability.

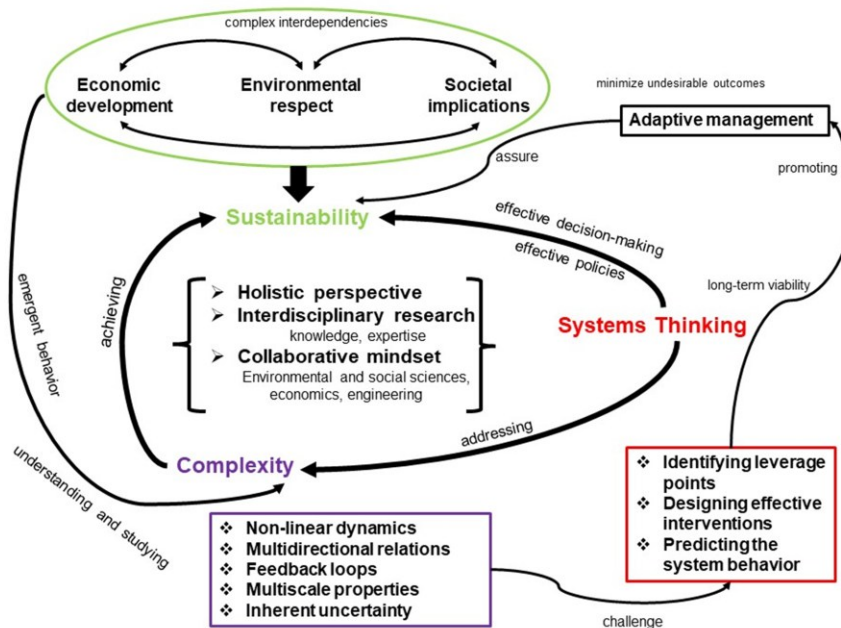


**Fig. 2.2- General picture of the new proposed three-paradigm model (Sustainability-Complexity-Systems Thinking)**

Hence, for integrating these three paradigms into a new model, it is necessary to develop interdisciplinary research and a collaborative mindset among environmental and social



sciences, economics, and engineering. As part of this stage, a CLD and an SD-based model will be proposed for understanding the advantages and limitations of the proposed 3P approach.

### **2.7.2- CLDs and SD-based model for the proposed 3P approach**

In this section, a new CLD and an SD-based model for the proposed 3P approach are discussed. This section addresses the challenge of using collaborative thinking in the framework of emerged complexity due to multiple interrelations in the 3P model. Figure 2.3 shows a developed CLD for analyzing the factors linked to the integration of paradigms. In this CLD, there are two feedback loops: a reinforcing loop (R1), and a balancing loop (B2). The R1 contains the idea that the efforts for interdisciplinary research will increase the integration of paradigms in this context, and that, at the same time, this integration (due to the positive results and effective sustainable decisions) will lead to more efforts for interdisciplinary research. In this sense, collaborative thinking plays an essential role, setting a starting point for discussion and analysis which leads to more interdisciplinary applications. However, the integration of paradigms has limitations. The System Archetype (SA) “Limit to Success” gives the opportunity to explore these constraints in the 3P framework. As the integration of paradigms increases, there is high consumption of resources such as time, funding, and expertise, and this can lead to putting less effort into this integration (represented by B2).

This CLD can be transformed into an SD-based model considering the integration of paradigms as a stock (accumulation). Figure 2.4 shows the SD-based model for describing this integration in the context of the 3P model. The integration of paradigms will lead to more sustainable solutions, and the success of these, after a given time (for checking such success and for resource distribution) will increase the resources’ availability (in the model it decreases the resources’ limitations rate). At the same time, the integration increases the efforts for interdisciplinary research, the collaborative thinking, and this directly pushes up the integration rate; and therefore the integration of paradigms. However, this integration will lead to more complexity, and this could lead to periods of frustration or misunderstanding among the experts, affecting the collaborative thinking effect after a given time. Hence, this SD-based model allows to understand the risks associated with the application of the 3P model proposed in this research and its limitations as well.

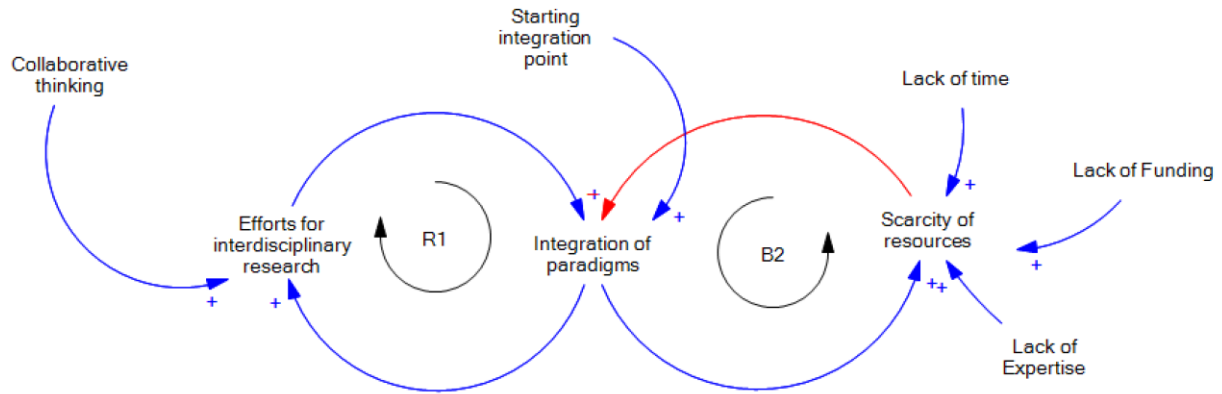


Fig. 2.3- CLD for analyzing the integration of paradigms in the 3P context

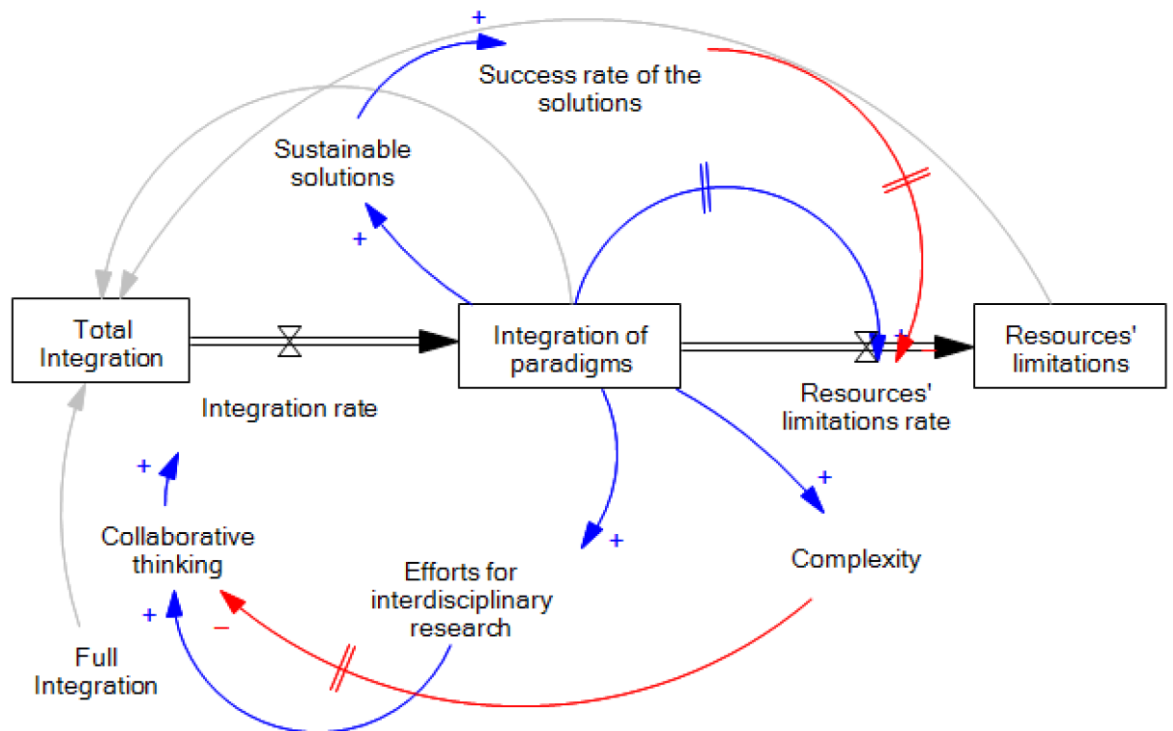


Fig. 2.4- SD-based model for analyzing the integration of paradigms in the 3P context

Setting the Integration of Paradigms in a range from  $[-100-100]$  and running a simulation using the model, Figure 2.5 is obtained. The minimum value ( $-100$ ) represents no integration at all, while the maximum value ( $100$ ) represents the full or complete integration of paradigms. Also, ( $0$ ) represents the common or usual integration of paradigms in a normal collaborative thinking framework. In this sense, the efforts for the integration can be measured as the values above  $0$ .

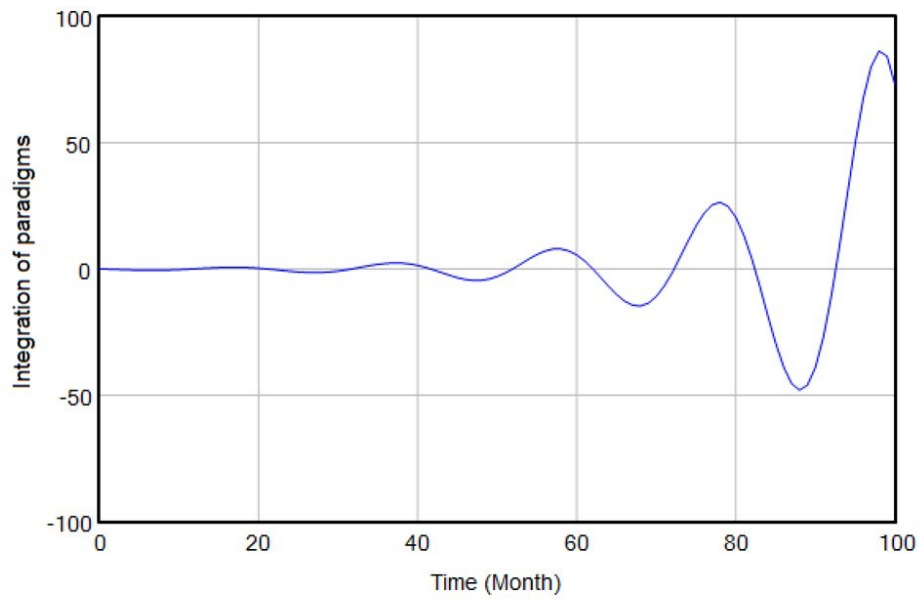


**Fig. 2.5- Dynamic behavior of the Integration of Paradigms**

In the dynamic evolution of the Integration of Paradigms, it can be noted that there are periods of poor integration followed by periods of good integration in general. Also, the periods of good integration are each time of better integration considering the proposed scale. The oscillations are due to the delays that are part of the system, between the studied parameters. The main interpretation of this behavior is that a minimum starting effort for integrating paradigms will lead in a given time to higher values of integration even knowing the limitations of resources. These concerns will be addressed through the effectiveness and success of sustainable and effective measures in the long-term period. These solutions will bring more funding, more experts, and more time for the integration of paradigms.

There are practical implications that emerged from the proposed integration of paradigms. Firstly, by simulating various policy scenarios, policymakers can identify strategies that maximize positive outcomes while minimizing negative trade-offs. Industry stakeholders can use their simulation results to make informed investment decisions that align with sustainability goals. For example, by simulating the long-term impacts of investing in renewable energy infrastructure versus traditional fossil fuel projects, stakeholders can assess the financial and environmental risks associated with each option.

Moreover, the proposed paradigm integration can help stakeholders anticipate and mitigate risks associated with sustainability initiatives. By simulating worst-case scenarios and conducting sensitivity analyses, stakeholders can identify vulnerabilities and develop

contingency plans to address potential challenges. The simulation results can serve as a basis for stakeholder engagement and collaboration. By providing stakeholders with a visual representation of complex systems and their interactions, the simulation model can facilitate dialogue, consensus-building, and collective action toward shared sustainability goals.

The limitations of the proposed paradigm integration, due to high resource consumption, raise important considerations for policy and practice in addressing sustainability challenges. One way to mitigate the limitations of high resource consumption is to prioritize resource efficiency strategies. Policies can encourage industries to adopt cleaner production. Additionally, investing in technological innovation can enable the development of cleaner and more efficient technologies that reduce resource consumption and environmental impact.

Finally, policymakers can adopt integrated policy frameworks that consider the interconnectedness of environmental, social, and economic factors in decision-making processes. Addressing the limitations of high resource consumption requires collaboration across sectors, disciplines, and stakeholders. Policymakers can facilitate multi-stakeholder partnerships that bring together government, industry, academia, and civil society to co-create solutions and implement coordinated action plans for sustainability.

Methodologically, the interaction among the three paradigms in the 3P Model is operationalized throughout the modeling workflow of the FRISE framework. *Sustainability* provides the evaluative criteria that inform the selection of system-level objectives and performance indicators; *Complexity* guides the identification of dynamic structures, nonlinear interactions, and multi-scale dependencies that must be represented; and *Systems Thinking* offers the modeling tools, such as CLDs and SD formulations, that translate these structural insights into coherent system representations. Together, these paradigms shape both the conceptual framing and the methodological execution of the modeling process, ensuring that the resulting analyses remain consistent with contemporary socio-technical system theory.

## **2.8- Graph-Theory perspective in Systems Thinking**

While the 3P–FRISE integration relies primarily on causal and dynamic modeling, it is equally important to understand the structural topology of these interconnections. To this end, Graph Theory provides a complementary analytical tool. Systems Thinking and System Dynamics enable the analysis of feedback structures and temporal evolution, Graph Theory complements them by offering a structural representation of system interconnections. In this research, each variable identified in a CLD is represented as a node, and each causal link as a directed edge.

This translation permits the use of network-science metrics—such as in-degree and out-degree centrality (influence and dependency), betweenness centrality (bridge roles), eigenvector centrality (systemic prominence), and PageRank (overall importance)—to quantify the influence of individual elements within the system.

Graph-theoretic analysis provides three main benefits within the FRISE framework:

1. Structural diagnostics: it reveals critical nodes and pathways that concentrate system influence, identifying potential leverage points for intervention.
2. Cross-modular comparison: it allows comparing the structural complexity and resilience of the Environmental, Economic, Social, Safety-Management, and Risk-Assessment modules.
3. Quantification of systemic robustness: it enables assessing how network connectivity and feedback density contribute to stability or vulnerability.

Therefore, Graph Theory acts as a complementary analytical lens that enhances the interpretability of Systems Thinking models. Its inclusion transforms qualitative CLDs into semi-quantitative network representations, strengthening the scientific rigor and reproducibility of the complex-systems analysis conducted in later chapters.

## **2.9- Limitations and future implications of the 3P–FRISE integration**

Although the integration of Sustainability, Complexity, and Systems Thinking into the FRISE framework provides a robust conceptual foundation, limitations should be acknowledged. First, the 3P model relies on conceptual abstraction and assumes that key interdependencies can be adequately represented through aggregated variables. Second, the availability and consistency of interdisciplinary data (economic, environmental, and societal) may constrain the full calibration of dynamic models. Third, the interpretation of reinforcing and balancing feedbacks remains partly dependent on expert judgment and scenario definition.

While the combined use of Systems Thinking, System Dynamics, and Graph Theory offers complementary perspectives on the structure and evolution of complex socio-technical systems, this integration also presents methodological limitations. Graph-theoretic indicators capture only static structural properties and therefore cannot be interpreted as predictors of dynamic behavior, which is instead governed by the nonlinear feedback mechanisms represented in the SD models. Similarly, the qualitative nature of Systems Thinking requires careful translation into quantitative formulations to avoid oversimplification of interactions. The combined approach adopted in FRISE thus relies on using each paradigm within its

appropriate epistemological boundary: GT as a structural lens, ST for conceptual framing, and SD for dynamic quantification.

Despite these constraints, the framework offers significant future opportunities. Firstly, the integration of graph-theoretical metrics with dynamic modeling opens new research directions in quantitative systems analysis and policy testing. Furthermore, the FRISE framework can be extended beyond energy systems to other complex socio-technical domains—such as fire safety in buildings, chemical process safety, and sustainable infrastructure design.

Future work may also include coupling with machine-learning algorithms for automated identification of leverage points or multi-objective optimization to balance safety, cost, and sustainability targets. Therefore, these limitations highlight both the challenges and the potential of the FRISE framework as a dynamic tool for interdisciplinary research.

## **2.10- Concluding remarks**

This chapter has established the conceptual and theoretical foundation of the thesis by developing a unified Three-Paradigm (3P) model integrating Sustainability, Complexity, and Systems Thinking within the FRISE framework (Fire safety, Risk, Integration, Sustainability, Engineering). The chapter demonstrated how Systems Thinking, through Causal Loop Diagrams (CLDs) and System Dynamics (SD) modeling, provides a holistic structure for analyzing complex interactions among economic, environmental, and societal factors relevant to Risk Assessment and Safety Management (RA–SM).

By embedding these paradigms into the FRISE framework, the chapter offers a methodological bridge between conceptual reasoning and quantitative modeling. This integration allows decision-makers to assess dynamic feedback processes and leverage points that determine the long-term effectiveness of sustainability and safety policies.

The inclusion of Graph Theory further enriches this framework, enabling the quantitative assessment of causal interconnections and identifying the nodes and links with the highest systemic influence. Together, these paradigms constitute a unified basis for analyzing and managing complexity in Risk Assessment and Safety Management. Ultimately, this chapter provides the theoretical scaffolding for the subsequent literature analysis (Chapters 3-4).

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## **Chapter 3 – Systematic Literature Review of Fire Safety Engineering: Systems Thinking and Sustainability Trade-offs**

This chapter conducts a systematic literature review of Fire Safety Engineering (FSE) through the lens of the Three-Paradigm (3P) model—Sustainability, Complexity, and Systems Thinking. It examines 35 studies to identify how systems-based methodologies such as Causal Loop Diagrams (CLDs), System Dynamics (SD), System Archetypes (SAs), and Socio-Technical Systems (STS) theory have been applied or adapted within FSE. The review reveals limited but growing integration of feedback-oriented and sustainability-driven approaches in the field, highlighting research gaps in dynamic modeling, interdisciplinary coupling, and quantitative validation. By mapping these gaps, the chapter provides empirical justification for the development of the FRISE Framework as a unifying structure capable of embedding feedback, sustainability, and cross-sectoral insights. It thus establishes the conceptual and methodological bridge from the theoretical foundations in Chapter 2 to the cross-domain synthesis presented in Chapter 4.

### **3.1- Introduction to Fire Safety Engineering domain**

Fire Safety Engineering (FSE) is a multidisciplinary field that integrates thermodynamics, fluid mechanics, material science, human behavior, risk assessment, and structural engineering to protect life, property, and the environment from fire hazards through the design of protection systems and emergency strategies (Gernay, 2024; Hofmeister, 2016; Hurley et al., 2016). Fire safety relies on active measures—such as detectors, alarms, sprinklers, and extinguishers—that automatically detect and suppress fires (Cleef et al., 2024), and passive measures—such as fire-resistant walls, doors, and compartmentation—that limit fire spread, preserve structural stability, and provide safe evacuation routes (Hofmeister, 2016). The interaction between these systems is essential for effective fire control (Ronchi, 2021), while consideration of human behavior ensures evacuation strategies supported by signage, lighting, and communication guide occupants to safety (Johansson & Svensson, 2019; Kumar et al., 2022; Li et al., 2022; Ronchi et al., 2024).

Fire risk assessment identifies hazards, evaluates consequences, and determines measures to reduce risks by analyzing fire likelihood, vulnerabilities, and potential impacts on people and property; it is carried out during design and updated as use, occupancy, or regulations change, guiding decisions and prioritizing safety interventions (Unobe et al., 2024). FSE is also shaped by national and international standards, such as NFPA codes in the USA and European

Standards (EN), which prescribe requirements for protection systems and their design, installation, and maintenance (Kuligowski, 2016b; Ronchi, 2021).

Traditionally, FSE has relied on well-established principles, empirical data, and regulatory frameworks to propose fire safety solutions (Spinardi et al., 2017; Van Coile et al., 2019). However, the complexity of modern buildings, urban environments, and the interdependencies within fire safety systems demand a framework which considers the feedback effects present in FSE (Ghamarimajd et al., 2024; Malagnino et al., 2022). As the field has been evolving, several authors have recognized the need for more holistic, systems-based approaches within FSE. Early contributions by Beard (Beard, 1997) and Santos-Reyes & Beard (Santos-Reyes & Beard, 2001, 2002) highlighted the importance of considering the interplay between technical, human, and organizational factors. Subsequent works, such as Bjelland, (Bjelland, 2013) and Gehandler, (Gehandler, 2017), further emphasized risk governance, systemic perspectives, and the integration of multidisciplinary insights into fire safety practice. More recently, calls have been made for integrating Systems Thinking (ST) into FSE frameworks (Malagnino et al., 2022; B. J. Meacham, 2022a).

The ST paradigm has been widely used in different fields worldwide from business management to medicine, and engineering (Sterman, 2002). One of the main advantages of its application is that it provides a holistic view of the analyzed system (Dueñas Santana, Di Benedetto, & Salzano, 2024; Dueñas Santana, Di Benedetto, González Gómez, et al., 2024; Dueñas Santana et al., 2025). Using a ST approach provides insight for decision-making and developing long-term solutions to complex problems (Martín García, 2006). The integration of the *Complexity* and *Sustainability* paradigms, and their interactions, with the ST approach furthermore provide several benefits (Dueñas Santana, Di Benedetto, González Gómez, et al., 2024; Martín García, 2006). ST also provides the tools for exploring the complex interactions of a given system, i.e., SAs, CLD, and SD models (Martín García, 2006; Sterman, 2002). Moreover, SD can be integrated with other tools by modeling the dynamic behavior of variables (Andres & Poler, 2016; Lane & Sterman, 2011; Martín García, 2006).

ST is currently not yet a common conceptual framework within FSE, but there have been applications of specific methodologies and tools in selected contexts. For example, Meacham et al., (B. J. Meacham, 2022a) proposed a framework for advancing performance-based design (PBD) for fire safety and move towards a Socio-technical systems (STS) approach. STS theory originated in the work of Emery & Trist (Emery & Trist, 1960), who explored the complex

interdependencies between social actors and technological systems in organizational settings. These early studies recognized that real-world systems are inherently complex, adaptive, and shaped by both human and technical elements, thus challenging the adequacy of purely technical or reductionist approaches (Checkland, 1981; von Bertalanffy, 1968). STS perspectives were developed to address this complexity, emphasizing joint optimization of social and technical subsystems and acknowledging that changes in one inevitably affect the other. This foundational understanding underpins more recent applications of STS to FSE, where buildings and infrastructures can be viewed as socio-technical entities whose fire safety performance emerges from the interaction of people, technology, and regulatory frameworks (Mumford, 2006). STS development focused on optimizing the interaction between employees, organizations, and new technologies (McNamee & Meacham, 2023). Variations of STS theory have been influenced by disciplines such as psychology, sociology, engineering, political science, and economics. STS theories have been applied, additionally, to areas such as accident analysis, risk management, interactions between building-hazards and regulation, and critical infrastructure interdependencies (Frantzich et al., 2024; B. Meacham et al., 2023).

ST also offers a powerful methodology for understanding and managing the complex interactions within (fire safety) systems through the implementation of SD (Martín García, 2006; Sterman, 2002). Unlike traditional linear approaches, SD thus enables fire safety engineers to model the interconnected components of a fire safety system as a whole, considering feedback loops, delays, and non-linear behaviors (Andres & Poler, 2016; Lane & Sterman, 2011). This holistic perspective is essential for capturing the emergent behavior and properties of fire safety systems, such as, the spread of fire, the effectiveness of suppression methods, and human evacuation behaviors, which are often difficult to forecast using conventional techniques (Cleef et al., 2024; Khan et al., 2021). The application of SD in FSE offers several advantages as it facilitates the development of more robust models for simulating real-world scenarios, helping engineers and decision-makers to anticipate potential issues before they arise (Park & Park, 2024; Ronchi, 2021).

This section aims to review and synthesize existing literature studies on the application of ST and SD in FSE for buildings and infrastructures, by identifying key trends, methodologies, challenges, and research directions. Special emphasis is placed on providing a review on the application of STS theory to FSE and on discussing developed SD models. In addition to ST, SD, and STS approaches, other systems-oriented perspectives are highly relevant to fire safety. These include safety systems approaches, such as Leveson's STAMP, CAST, and STPA

(Leveson, 2011), and resilience thinking (Hollnagel et al., 2006; Woods, 2006) which emphasizes the adaptive capacity of systems to anticipate, respond, and learn from disruptions. Although not the focus of this review, these approaches provide complementary insights and underscore the breadth of systems-oriented work in safety science.

### **3.1.1- Socio-technical systems (STS) an emerging approach for FSE**

Buildings and infrastructures can be viewed as Socio-Technical Systems (STS), where performance emerges from interactions among actors, components, and regulatory processes, making fire safety design a sociotechnical challenge rather than a purely technical one (McNamee & Meacham, 2023; B. J. Meacham, 2022a, 2022b, 2023a). This perspective represents a paradigm shift in performance-based design (PBD), emphasizing the safe operation of the building or infrastructure throughout its lifecycle rather than merely achieving regulatory approval (B. J. Meacham, 2022b). Originating from studies of organizational dynamics, STS theory highlights interdependencies between social and technological elements across three levels: primary work systems (e.g., a sprinkler system installation), organizational systems (e.g., the processes governing the operation of the building), and macrosocial systems involving wider institutions and communities (e.g., fire and rescue service) (B. J. Meacham, 2022b; Trist & Murray, 1993). The theory recognizes that multiple stakeholders with diverse goals continuously reshape systems, which—unlike centrally designed technologies such as smartphone operating systems—cannot be fully controlled or fixed but evolve through these interactions (McNamee & Meacham, 2023; B. J. Meacham, 2022b).

The emerging complexity in FSE can according to STS theory be addressed by the study of the interrelations among societal, regulatory, and technological aspects. This STS vision is aligned with the main focus of this research aim, because it offers a new framework for applying a ST paradigm to FSE, and provides a pathway for exploring the interdependencies among the Complexity, Sustainability, and ST paradigms, which were discussed in the previous subsection. The quantitative study of system interrelations as well as their complex dynamics is within the scope of SD modeling.

It is relevant to highlight as part of this review that related systems-based approaches have been influential in safety science. Leveson's Systems-Theoretic Accident Model and Processes (STAMP), along with CAST and STPA, provide structured methods for analyzing accidents and hazards within a systems-theoretic framework (Leveson, 2011). Similarly, the field of resilience engineering highlights system adaptability, learning, and robustness under

uncertainty, with foundational contributions from Woods (Woods, 2006) and Hollnagel et al. (Hollnagel et al., 2006). These approaches align with many principles of ST and could enrich fire safety research through integration with FSE practices (see also Salmon et al., 2022). In the context of FSE, early frameworks such as the NFPA 550 Fire Safety Concepts Tree (Association, 2021; Solomon, 2008) provided structured approaches for conceptualizing fire safety design. While not fully aligned with the ST perspective adopted in this paper, they can be seen as important precursors that shaped the evolution of system-based thinking in FSE.

In conclusion, the STS perspective offers a compelling lens for understanding fire safety as an emergent property of the interplay between social and technical components. This may appear at odds with current building codes which often (nominally) enforce simple requirements — such as requiring full evacuation without assistance or disregarding fire service intervention for structural fire protection. This does not constitute a limitation of the STS approach, however. On the contrary, STS approaches allow to evaluate the “real” system performance given the nominally enforced requirements. Thus, while the STS framework is not intended to replace current regulations, it can (i) complement performance-based design by encouraging a broader view of fire safety that includes interdependencies often overlooked by traditional methods, and (ii) provide input towards improving the effectiveness of regulatory requirements.

### **3.1.2- Conceptual link with the Three-Paradigm Model (Sustainability–Complexity–Systems Thinking)**

The analysis conducted in this chapter builds directly upon the conceptual foundations established in Chapter 2, where the Three-Paradigm Model—Sustainability, Complexity, and Systems Thinking (3P)—was introduced as the theoretical lens of the FRISE Framework. These paradigms collectively provide the epistemological grounding for interpreting Fire Safety Engineering (FSE) as a complex socio-technical system characterized by interdependencies, feedback loops, and trade-offs among safety, performance, and sustainability.

From a Sustainability perspective, this review examines how fire safety measures contribute to or constrain long-term environmental and social goals, particularly regarding material selection, energy efficiency, and lifecycle performance. From a Complexity viewpoint, the literature reveals that modern FSE systems exhibit nonlinear interactions, emergent behaviors, and feedback-driven dynamics that cannot be captured through traditional linear risk models. Finally, Systems Thinking (ST) offers the methodological framework through which these

complex relationships are mapped, modeled, and understood—using tools such as Causal Loop Diagrams (CLDs), System Archetypes (SAs), and System Dynamics (SD) models.

Accordingly, the systematic literature review that follows operationalizes the 3P model within the FSE domain. Each identified study is interpreted not merely as an isolated contribution but as part of a broader movement toward feedback-based, integrative methodologies that align with the Feedback-based Risk Integration for Safety and Sustainability in Engineering (FRISE) framework.

### **3.2- Methodology of the systematic literature review**

This section explains the general framework employed in this literature review chapter which is divided into six main stages: starting (stages 1-2), core (stages 3-4), and applications (stages 5-6). Stage 1 focuses on identifying the key terms essential for investigating the application of ST and SD in the FSE field. Stage 2 outlines the literature review methodology, including the filtering and selection of articles for analysis. Stage 3 outlines the main applications of the ST framework to FSE as derived from the identified studies and SAs. Stage 4 examines the identified studies for current applications of SD. Stage 5 proposes hypothetical applications of ST tools to FSE based on the existing state of the art. Finally, Stage 6 highlights future research directions by addressing the challenges and limitations of the approaches discussed, based on the current research needs for the FSE profession reported by SFPE (SFPE, 2025). Figure 3.1 illustrates the general framework proposed in this review chapter.

#### **3.2.1- Stage 1: Identification of keywords**

The first stage involves identifying the primary keywords necessary for exploring the application of ST tools in the FSE field. In this literature review, the focus is on studying the use of SD in FSE. Therefore, a combination of ST-related keywords with FSE-specific keywords is considered (as shown in Table 3.1). The identification process is divided into two main steps. The first step focuses on studies that directly applied SD to FSE, while the second step includes studies that utilized an ST approach in related fields connected to FSE. In some cases, broader keywords (e.g., ‘sustainability’) were paired with ‘Systems Thinking’ or ‘System Dynamics’ to identify relevant studies in related domains, due to the limited number of direct applications in FSE. To maintain relevance, a two-step filtering process was implemented: (1) initial screening of titles and abstracts to confirm the use of a predefined ST tool and a safety-related context relevant to FSE, and (2) application of the inclusion criteria in

Table 3.1, ensuring that the study either directly addressed FSE or could be reasonably adapted to it.

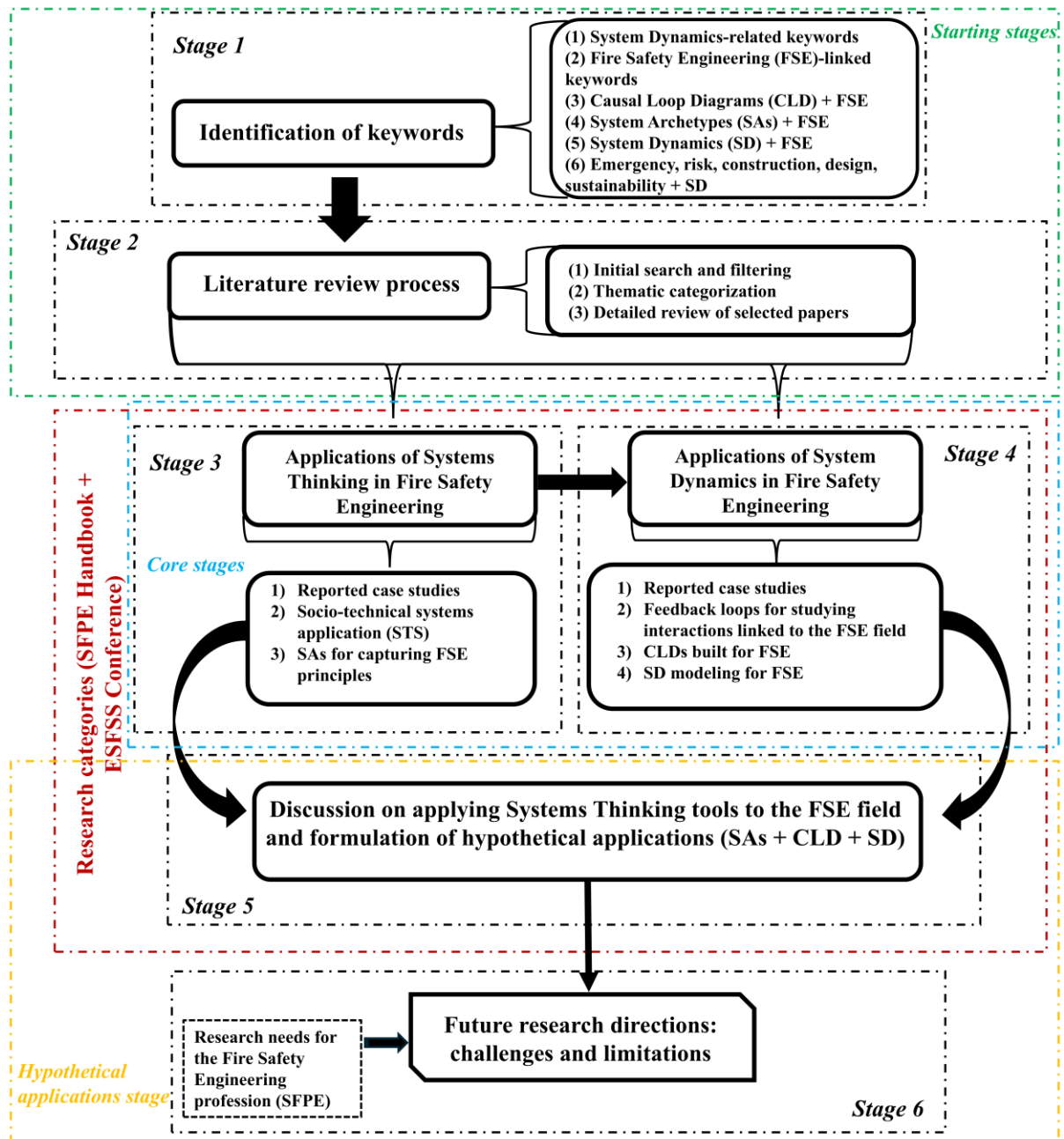


Fig. 3.1: Applied framework for the literature review



**Table 3.1: Combination of keywords in this literature review chapter**

| Combination of keywords ↗                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Systems Thinking                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | System Dynamics | System Archetypes | Causal Loop Diagram |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|-------------------|---------------------|
| Fire Safety Engineering                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Primary focus<br>Aim: To explore the main studies which directly applied a Systems Thinking approach to the FSE field.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                 |                   |                     |
| Risk                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Secondary focus<br>Aim: To explore studies which have applied a Systems Thinking approach that can contribute to the FSE field.<br><br>Inclusion criteria: The article has to include at least one application of an ST tool that can be expanded to the FSE field. The study needs to contain a structured application of an ST tool related to fire safety, construction safety, risk management, emergency response, or sustainability in safety systems. The inclusion of papers in this category was stopped when it was observed that the inclusion of further papers in this category no longer influenced the (preliminary) conclusions drawn from the analyses. |                 |                   |                     |
| Emergency                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                 |                   |                     |
| Construction                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                 |                   |                     |
| Design                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                 |                   |                     |
| Sustainability                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                 |                   |                     |
| Note: In this review, ‘ST tool’ refers specifically to System Archetypes, Causal Loop Diagrams, System Dynamics, or the Socio-Technical Systems framework, as defined in established Systems Thinking literature and selected a priori by the authors. Broader search terms (e.g., “sustainability”) were paired with ‘Systems Thinking’ or ‘System Dynamics’ to identify potential cross-domain studies. All results were screened and filtered to retain only those relevant to FSE or closely related safety contexts. |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                 |                   |                     |

The keywords were used to search academic databases, including Scopus, Web of Science, Google Scholar, and IEEE Xplore, resulting in the identification of relevant peer-reviewed journal articles, conference papers, technical reports, and books. The literature search was conducted until February 2025. Two main search codes were applied. The first code — ("Systems Thinking" OR "System Dynamics" OR "System Archetypes" OR "Causal Loop Diagram") AND ("Fire Safety Engineering") — yielded 191 results and targeted studies directly linking ST tools to the FSE domain. The second code — ("Systems Thinking" OR "System Dynamics" OR "System Archetypes" OR "Causal Loop Diagram") AND ("Specific field" AND "Fire Safety") — was run separately for each ‘Specific field’: Risk (1770 results), Emergency (1190 results), Construction (1560 results), Design (2190 results), and Sustainability (1160 results). After removing duplicates from the combined results, titles and abstracts were screened to confirm the use of at least one predefined ST tool in a safety-related context relevant to FSE. The full texts of the remaining papers were then reviewed according to the inclusion criteria in Table 3.1. This process resulted in 35 studies being retained for detailed analysis in this review.

### 3.2.2- Stage 2: Literature review process

This stage focuses on developing the literature review process. Initially, a first search and filtering of the identified studies is conducted, taking into account the aim and inclusion criteria outlined in Table 3.1. Specifically, for an article to be included, it must either directly apply an ST-related tool to the FSE field or present a developed model in a related field that adds value

to FSE. For the purposes of this review, ‘ST tool’ refers to a predefined set of methodologies widely recognized in the ST literature: SAs, CLDs, SD, and the STS framework. These tools were selected a priori based on established definitions (Kim, 1992; Sterman, 2000). Following the filtering, a thematic categorization is performed for clustering the identified studies depending on which ST tool has been used and if this is directly connected to FSE or considers a related field. Finally, a detailed analysis of the selected papers is conducted, which is further expanded upon in subsequent stages.

### **3.2.3- Stage 3: Applications of Systems Thinking in Fire Safety Engineering**

This stage identifies the main applications of ST theory to FSE as identified through the literature search. For this purpose, the main studies which have conducted a theoretical or a practical application of ST are evaluated in depth based on their potential to be further expanded to an SD approach. Specifically, the following aspects are investigated: (1) reported case studies. (2) STS application, and (3) SAs for capturing FSE principles.

### **3.2.4- Stage 4: Application of System Dynamics in Fire Safety Engineering**

In stage 4, a detailed analysis of key case studies is conducted considering their application of SD to the FSE field. The investigation focuses on the main feedback loops, CLDs, and SD models, as well as the availability of equations and performed simulations. Specifically, the following aspects are examined: (1) reported case studies; (2) feedback loops for analyzing interactions within the FSE field; (3) CLDs developed for FSE; and (4) SD modeling techniques for FSE. To group the results, research categories are adopted which cluster chapters from the *SFPE Handbook of Fire Protection Engineering* and key topics from the *European Symposium on Fire Safety Science* (ESFSS 2024) conference.

### **3.2.5- Stage 5: Discussion on applying Systems Thinking tools to the FSE field and formulation of hypothetical applications**

This stage focuses on formulating possible applications of ST tools in the FSE field, based on the current state of the art identified in the previous stages. These potential applications are aligned with the previously defined research categories and with the research needs for the FSE profession proposed by SFPE (SFPE, 2025).

### **3.2.6- Stage 6: Future research directions: challenges and limitations**

The final stage aims to identify gaps in the current literature and outline potential future research directions, taking into account the challenges and limitations associated with the SD

approach. Additionally, guidelines are provided to facilitate the exploration of each proposed research line.

### 3.3- State-of-the-art of applications of Systems Thinking and System Dynamics in Fire Safety Engineering

This section outlines the results of the literature review, considering the methodology outlined in Section 3.

#### 3.3.1- Studies included in this literature review chapter (Stages 1-2)

This section presents the main results from Stages 1-2 of the applied literature review framework (see Figure 3.2). The initial keyword searches yielded a large set of publications. Following the two-step filtering process described in Stage 1, this pool was narrowed to 35 retained studies that either directly addressed FSE or could be meaningfully adapted to it. Tables 3.2 and 3.3 show the retained studies. Fig. 3.2 shows the categorization for each study depending on which ST-related approach was developed or adopted, the research field, and the interactions among tools, concepts, and keywords.

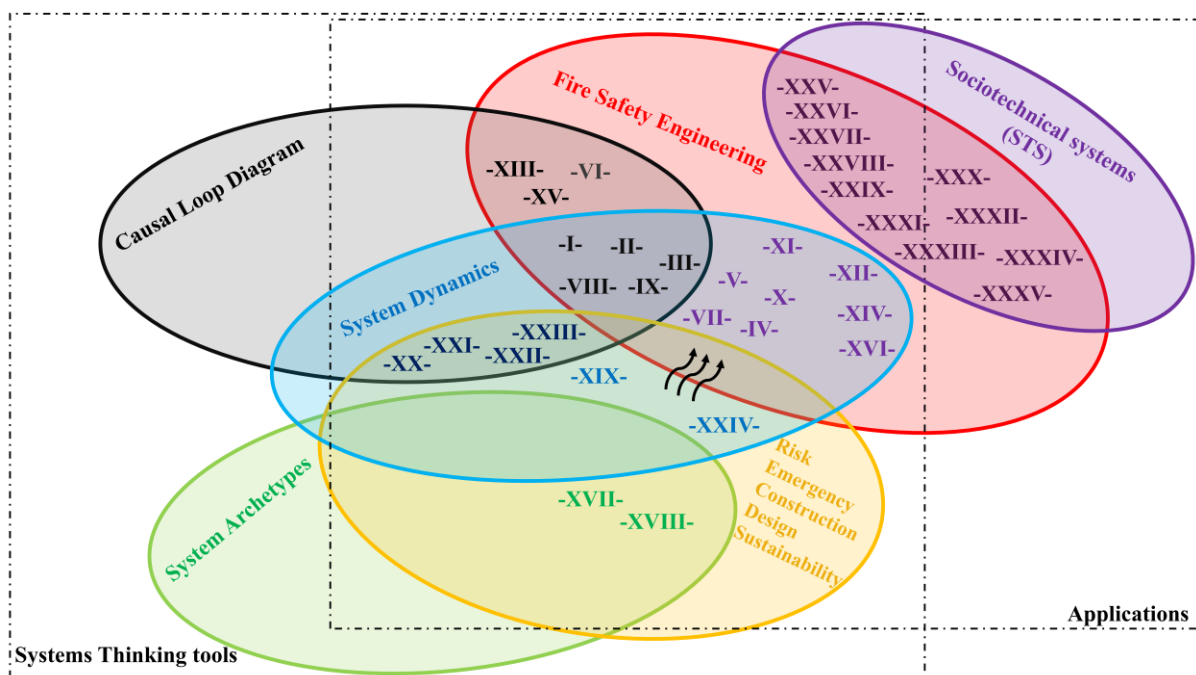


Fig. 3.2: Clustering the retained research studies according to the applied Systems Thinking approach

**Table 3.2: Retained studies considering the SD application included in this literature review**

| Code/Title                                                                                                                                                                                                   | Source                                               | Type of source   | Year | Reference                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|------------------|------|-------------------------------------------|
| <b>-I-</b> System Dynamics analysis for petrochemical enterprise fire safety system.                                                                                                                         | Procedia Engineering                                 | Conference paper | 2018 | (Zhang et al., 2018)                      |
| <b>-II-</b> Probability prediction and cost-benefit analysis based on SD.                                                                                                                                    | Process Safety and Environmental Protection          | Journal paper    | 2018 | (Y. F. Wang et al., 2018)                 |
| <b>-III-</b> Study on evacuation behavior of urban underground complex in Fire Emergency based on SD.                                                                                                        | Sustainability                                       | Journal paper    | 2022 | (Li et al., 2022)                         |
| <b>-IV-</b> Dynamic simulation of the group behavior under fire accidents based on SD.                                                                                                                       | Procedia Engineering                                 | Conference paper | 2018 | (Song et al., 2018)                       |
| <b>-V-</b> Subway fire cause analysis model based on SD: a preliminary model framework.                                                                                                                      | Procedia Engineering                                 | Journal paper    | 2016 | (Yan et al., 2016)                        |
| <b>-VI-</b> A system thinking approach for evacuation during fire incidents considering SD.                                                                                                                  | IEEE                                                 | Conference paper | 2022 | (Kumar et al., 2022)                      |
| <b>-VII-</b> The research of high-rise building fire safety simulation model based on SD.                                                                                                                    | Applied Mechanics and Materials                      | Journal paper    | 2014 | (J. F. Wang et al., 2014)                 |
| <b>-VIII-</b> A simulation model for studying the implementation of performance-based fire safety design in buildings.                                                                                       | Automation in Construction                           | Journal paper    | 2008 | (Lo, Zhao, Liu, et al., 2008)             |
| <b>-IX-</b> A study of the use of a performance-based approach to fire safety design in buildings.                                                                                                           | Structural Survey                                    | Journal paper    | 2008 | (Lo, Zhao, & Yuen, 2008)                  |
| <b>-X-</b> Using System Dynamics for Cost-Benefit Analysis of fire safety engineering features.                                                                                                              | ESFSS 2024 Conference                                | Poster           | 2024 | (Dueñas Santana, Van Coile, et al., 2024) |
| <b>-XI-</b> Impact of Technical, Human, and Organizational Risks on Reliability of Fire Safety Systems in High-Rise Residential Buildings—Applications of an Integrated Probabilistic Risk Assessment Model. | Applied Sciences                                     | Journal paper    | 2020 | (Tan et al., 2020)                        |
| <b>-XII-</b> Sensitivity and Uncertainty Analyses of Human and Organizational Risks in Fire Safety Systems for High-Rise Residential Buildings with Probabilistic T-H-O-Risk Methodology.                    | Applied Sciences                                     | Journal paper    | 2021 | (Tan et al., 2021a)                       |
| <b>-XIII-</b> Applying systems thinking concepts in the analysis of major incidents and safety culture.                                                                                                      | Safety Science                                       | Journal paper    | 2010 | (Goh et al., 2010)                        |
| <b>-XIV-</b> Incorporation of technical, human, and organizational risks in a dynamic probabilistic fire risk model for high-rise residential buildings.                                                     | Fire and Materials                                   | Journal paper    | 2021 | (Tan et al., 2021b)                       |
| <b>-XV-</b> Lessons learned from critical accidental fires in tunnels.                                                                                                                                       | Tunnelling and Underground Space Technology          | Journal paper    | 2021 | (Lin & Chien, 2021)                       |
| <b>-XVI-</b> Blowout fire probability prediction of offshore drilling platform based on system dynamics.                                                                                                     | Journal of Loss Prevention in the Process Industries | Journal paper    | 2019 | (Y. fu Wang et al., 2019)                 |
| <b>-XVII-</b> Developing safety archetypes of the construction industry at the project level using SD.                                                                                                       | Journal of Safety Research                           | Journal paper    | 2018 | (Mohammadi et al., 2018)                  |
| <b>-XVIII-</b> Identifying safety archetypes of construction workers using SD and content analysis.                                                                                                          | Safety Science                                       | Journal paper    | 2020 | (Mohammadi & Tavakolan, 2020)             |

| Code/Title                                                                                                                                               | Source                                               | Type of source | Year | Reference               |
|----------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|----------------|------|-------------------------|
| -XIX- System dynamics research of non-adaptive evacuation psychology in toxic gas leakage emergencies of chemical park.                                  | Journal of Loss Prevention in the Process Industries | Journal paper  | 2021 | (Xu et al., 2021)       |
| -XX- Sustainable building materials assessment and selection using system dynamics.                                                                      | Journal of Building Engineering                      | Journal paper  | 2021 | (Sahlol et al., 2021)   |
| -XXI- Modelling of safety performance in building construction projects using system dynamics approach in Tanzania.                                      | Safety                                               | Journal paper  | 2024 | (Kajumulo et al., 2024) |
| -XXII- Risk analysis and simulation of large bridge construction based on system dynamics.                                                               | Buildings                                            | Journal paper  | 2024 | (Fu et al., 2024)       |
| -XXIII- A system dynamics-based environmental benefit assessment model of construction waste reduction management at the design and construction stages. | Journal of Cleaner Production                        | Journal paper  | 2018 | (Ding et al., 2018)     |
| -XXIV- Use of system dynamics as a decision-making tool in building design and operation.                                                                | Building and Environment                             | Journal paper  | 2010 | (Thompson & Bank, 2010) |

As can be noticed from Fig. 3.2, a limited number of studies have so far proposed an integration between ST tools such as CLD + SD and FSE . The most complete research studies included the development of a CLD and a further translation to a Forrester diagram (an SD model), such as in I, II, III, VIII, and IX (Li et al., 2022; Lo, Zhao, & Yuen, 2008; Lo, Zhao, Liu, et al., 2008; Y. F. Wang et al., 2018; Zhang et al., 2018). Additionally, some studies developed SD models in the FSE field such as IV, V, VII, X, XI, XII, XIV, and XVI (Dueñas Santana, Van Coile, et al., 2024; Song et al., 2018; Tan et al., 2020, 2021a, 2021b; J. F. Wang et al., 2014; Y. fu Wang et al., 2019; Yan et al., 2016); while others only developed a CLD d such as VI, XIII, and XV (Goh et al., 2010; Kumar et al., 2022; Lin & Chien, 2021). These first 16 studies are directly connected to FSE. Moreover, there are eight other studies which meet the inclusion criteria proposed in this framework. These focused on fields related to the FSE, adopting at least one ST-related tool that can be used in the FSE field. The most used tool among the 35 identified articles was the SD-modeling (19 studies), followed by the CLD (12 studies), the STS (11 studies), and finally SAs (2 studies). Fourteen of the studies explicitly presented the used equations for the development of their models, and 20 of the studies performed simulations.

**Table 3.3: Relevant studies related to the STS application included in this literature review**

| Code/Title                                                                                                                  | Source                                          | Type of source | Year | Reference                            |
|-----------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|----------------|------|--------------------------------------|
| -XXV- Decision Support Framework for Sustainable and Fire Resilient Buildings (SAFR-B).                                     | Fire Technology                                 | Journal paper  | 2024 | (Frantzich et al., 2024)             |
| -XXVI- Tunnel fire safety management and systems thinking: Adapting engineering practice through regulations and education. | Fire Safety Journal                             | Journal paper  | 2024 | (Bjelland et al., 2024)              |
| -XXVII- Conceptual Basis for a Sustainable and Fire Resilient Built Environment.                                            | Fire Technology                                 | Journal paper  | 2023 | (McNamee & Meacham, 2023)            |
| -XXVIII- Risk and Performance Assessment Framework for a Sustainable and Fire Resilient Building Environment (SAFR-BE).     | Society of Fire Protection Engineers Foundation | Report         | 2023 | (B. Meacham et al., 2023)            |
| -XXIX- Fire safety of existing residential buildings: Building regulatory system gaps and needs.                            | Fire Safety Journal                             | Journal paper  | 2023 | (B. J. Meacham, 2023a)               |
| -XXX- Sustainable and Fire Resilient Built Environment (SAFR-BE).                                                           | Springer International Publishing               | Chapter        | 2023 | (B. J. Meacham & McNamee, 2023)      |
| -XXXI- Toward a Sociotechnical Systems Framing for Performance-Based Design for Fire Safety.                                | Springer International Publishing               | Chapter        | 2022 | (B. J. Meacham, 2022b)               |
| -XXXII- A Sociotechnical Systems Framework for Performance-Based Design for Fire Safety.                                    | Fire Technology                                 | Journal paper  | 2022 | (B. J. Meacham, 2022a)               |
| -XXXIII- A holistic framework for development and assessment of risk-informed performance-based building regulation.        | Fire and Materials                              | Journal paper  | 2021 | (B. J. Meacham et al., 2021)         |
| -XXXIV- A socio-technical system framework for risk-informed performance-based building regulation.                         | Building Research & Information                 | Journal paper  | 2018 | (B. J. Meacham & van Straalen, 2018) |
| -XXXV- Risk-informed performance-based approach to building regulation.                                                     | Journal of Risk Research                        | Journal paper  | 2010 | (B. J. Meacham, 2010)                |

### 3.3.2- Application and discussion of the ST theory to the FSE field (Stage 3)

Stage 3 of the literature review examines the identified papers for their application of ST. Three aspects are considered: (1) reported case studies; (2) STS application, and (3) SAs for capturing FSE principles.

#### 3.3.2.1- Case studies applying ST theory to the FSE field

The case studies consider the application of STS and SAs in fire safety and building regulation. Meacham et al. (B. J. Meacham, 2010) and Meacham & van Straalen (B. J. Meacham & van Straalen, 2018) proposed a risk-informed, performance-based approach integrating acceptable risk levels and performance expectations within regulatory systems, recognizing complex

stakeholder interactions. Meacham (B. J. Meacham, 2022a) emphasized treating fire safety as an emergent property of infrastructure. Frantzich et al. (Frantzich et al., 2024) introduced the SAFR-B framework using risk indexing and decision-support tools to balance sustainability and fire resilience. STS and ST principles were also applied to tunnel fire safety management (TFSM), integrating risk management, feedback loops, and adaptive decision-making. Furthermore, two studies explored the use of SAs in safety engineering, proposing eight SAs that could be adapted for FSE (Mohammadi et al., 2018; Mohammadi & Tavakolan, 2020). Overall, these studies demonstrate the potential of the ST approach in advancing fire safety regulation through interdisciplinary, systems-based thinking.

### ***3.3.2.2- Socio-technical systems applications***

Performance-based building codes encourage innovation but face skepticism due to goals and requirements that are deemed unclear, and insufficient data, tools, and methods to meet safety expectations (B. J. Meacham, 2010). To address these challenges, Meacham et al. (B. J. Meacham, 2010) and Meacham & van Straalen (B. J. Meacham & van Straalen, 2018) proposed a risk-informed, performance-based approach integrating acceptable risk levels, performance expectations, and design criteria within the regulatory system, viewing it as an STS that considers legal, regulatory, and market interactions. Meacham (B. J. Meacham, 2022a) further emphasized treating fire safety as an emergent property of infrastructure, identifying key system attributes that can be controlled during design to reduce long-term uncertainties. This aligns with SAs in ST, such as “Fixes That Fail,” where short-term compliance can create long-term vulnerabilities, and “Shifting the Burden,” where prescriptive rules hinder adaptive, risk-informed decision-making. Frantzich et al. (Frantzich et al., 2024) contributed by introducing the Sustainable and Fire Resilient Buildings (SAFR-B) framework, which applies risk indexing and analytical hierarchy processes to balance sustainability and fire resilience, leveraging ST tools like CLDs to map feedback mechanisms. The broader application of STS and ST principles in fire safety has been explored by Meacham & McNamee (B. J. Meacham & McNamee, 2023), as well as studies on Sustainable and Fire Resilient Built Environments (SAFR-BE) (McNamee & Meacham, 2023; B. Meacham et al., 2023). By incorporating whole-of-life, multi-agency, and holistic regulatory considerations, as explored by Meacham (B. J. Meacham, 2023b), these frameworks advance the understanding of regulatory evolution and the necessary conditions for widespread acceptance of PBD in fire safety.

More recently, STS and ST concepts have been applied to TFSM. This approach integrates risk management and FSE with prescriptive and experience-based solutions while incorporating ST to evaluate the system as a whole. By viewing TFSM as an interconnected system, the study highlights the role of feedback loops, stakeholder interactions, and adaptive decision-making in enhancing safety and efficiency. Furthermore, regulatory adaptation, interdisciplinary collaboration, and improved education programs have been identified as essential enablers of this systems-based approach (Bjelland et al., 2024).

Hence, integrating STS and ST approaches—including CLDs, SD modeling, and SAs—can provide a structured methodology for addressing the complexities of performance-based building regulation and fire safety. Recognizing the interdependencies among stakeholders, regulatory frameworks, and technological advancements enables a more resilient and adaptive approach to building safety. The progression of these frameworks, from Meacham’s early work on PBD for fire safety to recent studies on SAFR-BE and TFSM, illustrates the growing attention to interdisciplinary, systems-based thinking in managing fire risk and sustainability challenges within the built environment.

### ***3.3.2.3- Using System Archetypes for capturing Fire Safety Engineering principles***

In this section, SAs as part of the ST theory, are discussed and compared. Two studies have been identified in this literature review that explore the use of SAs for purposes within the scope of this review: (1) interactions among safety, accident causation, and human factors (Mohammadi et al., 2018), and (2) interdependencies among accident investigation, workers, and productivity (Mohammadi & Tavakolan, 2020).

In total eight SAs were proposed between these two studies (Mohammadi et al., 2018; Mohammadi & Tavakolan, 2020), in each article the SAs were comprehensively discussed considering dynamic complexity, behavior over time, and leverage points in order to provide guidance on how to deal with the archetype. These archetypes were applied to the construction industry, but they can be adapted to the FSE field. The direct application of SAs to FSE has not been explored yet. Therefore, potential applications based on the architecture of the SAs, and on how they have been applied previously, are shown in Table 3.4.



**Table 3.4: Potential uses for the FSE field**

| <b>System Archetype</b> | <b>Potential uses for the Fire Safety Engineering field</b>                                                                             |
|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| Limits to Success       | Identify and address constraints (e.g., resources, budgets, system capacity) that limit improvements in fire safety.                    |
| Shifting the Burden     | Avoid over-reliance on quick fixes and prioritize fundamental solutions (e.g., long-term investments in infrastructure or training).    |
| Eroding Goals           | Maintain high safety standards and resist pressures to lower goals, especially in the face of cost or time constraints.                 |
| Tragedy of the Commons  | Promote collective responsibility for fire safety in shared systems and environments to prevent resource depletion or underperformance. |

For instance, the "Limits to Success" archetype can be applied to fire safety regulations where resource constraints, such as budgets or system capacity, hinder continuous improvement. Addressing these constraints requires a systems-level approach that aligns with the STS framework proposed by Meacham (B. J. Meacham, 2022a; B. J. Meacham & van Straalen, 2018), ensuring that regulatory and market environments do not impose barriers to progress. The "Shifting the Burden" archetype is evident in the reliance on prescriptive fire safety measures rather than investing in long-term adaptive solutions, an issue also highlighted in SAFR-B frameworks (Frantzich et al., 2024; McNamee & Meacham, 2023). Similarly, the "Eroding Goals" archetype reflects the tendency to lower safety standards under cost or time pressures, reinforcing the need for robust performance-based approaches that integrate risk-informed decision-making. Moreover, the "Tragedy of the Commons" archetype underscores the importance of collective responsibility in shared fire safety environments, such as multi-use buildings or community-level infrastructure. This aligns with Meacham's (B. J. Meacham, 2023b) work on whole-of-life regulatory approaches and multi-agency collaboration, demonstrating how systemic interdependencies influence fire safety resilience.

### **3.3.3- Application and discussion of SD modeling to the FSE field (Stages 4-5)**

In stages 4-5 of the adopted research framework current SD applications are investigated and possible ST applications in FSE are presented. Different subsections are introduced, increasing the level of complexity linked to each SD-related tool: from the adoption and development of feedback loops to their integration in CLDs and SD-based models. First, Section 4.3.1 explains the relevance of each of the identified 24 studies. Then, in Section 4.3.2, the main feedback loops are described. In Section 4.3.3 a CLD from the literature is explained in detail. Finally, Section 4.3.4 presents the observed implications of SD-modeling for the FSE field.

Additionally, possible new applications are proposed taking into account the following research categories identified from the SFPE Handbook and the ESFSS 2024 Conference: (1) Fluid mechanics and fire dynamics (Merci, 2016; Miles, 2016; Quintiere & Wade, 2016; Walton et

al., 2016; Wood, 2016); (2) Structural fire engineering (Bisby, 2016; Kodur & Harmathy, 2016); (3) Fire scenarios and performance-based design (PBD) (Hurley & Rosenbaum, 2016; Mehaffey, 2016); (4) Fire detection and suppression systems (Bahadori, 2016; Di Nenno & Forssell, 2016; Fleming, 2016; Grant, 2016; Hofmeister, 2016; Isman, 2016; Mawhinney & Back, 2016; B. J. Meacham, 2016; Scheffey, 2016; Senecal, 2016); (5) Human behavior and egress design (Akizuki, 2016; Fahy, 2016; Kuligowski, 2016a, 2016b; Rosenbaum, 2016; J. S. Tubbs, 2016); (6) Risk Analysis and decision-making (Donegan, 2016; Hall, 2016; Joglar, 2016b, 2016a; B. J. Meacham et al., 2016; Notarianni & Parry, 2016); and (7) Sustainability (J. Tubbs & Woodward, 2016).

### 3.3.3.1- Case studies that applied an SD-related tool to the FSE field

Table 3.5 shows the aim of each research article included in *Stage 4*, as well as a short description of the study.

**Table 3.5: Relevant information for each selected research article (Stage 4)**

| <i>Code</i> | <i>Aim</i>                                                         | <i>General description</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <i>Methods/ Tools</i> | <i>Database/source of info. /Software</i>                                                                        | <i>Relevance for FSE (Research category)</i>                      |
|-------------|--------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| <b>-I-</b>  | Study the fire safety dynamics linked to an oil tank storage area. | Fire safety level considers the following four main parameters: (1) personnel awareness level, (2) fire safety management level, (3) level of fire fighting facilities, (4) technological level.                                                                                                                                                                                                                                                                                                        | CLD, SD               | Case study: Chemical plant in Nanjing Liuhe Chemical Industrial Park in Nanjing, Jiangsu province.<br><br>Vensim | Risk Analysis and decision making.                                |
| <b>-II-</b> | Dynamic probability prediction, and cost-benefit analysis.         | A new method for evaluating blowout fire prevention and control measures is introduced considering a cost-benefit analysis. Firstly, a dynamic probability prediction model for blowout fire is introduced using SD. Secondly, a cost-benefit analysis of the corresponding safety measures is carried out using SD simulation. Thirdly, case studies of blowout fire probability prediction and the cost-benefit analysis of safety investments are demonstrated for some offshore drilling platforms. | CLD, SD, CBA          | Probability database (fire safety handbook)<br><br>Vensim                                                        | Fire scenarios and PBD.<br><br>Risk Analysis and decision making. |

| <i>Code</i>   | <i>Aim</i>                                                                                                                                                       | <i>General description</i>                                                                                                                                                                                                           | <i>Methods/<br/>Tools</i>                                                 | <i>Database/source of<br/>info. /Software</i>                                                                          | <i>Relevance for<br/>FSE (Research<br/>category)</i>                                                                  |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| <b>-III-</b>  | Study large-scale evacuation behavior of urban underground complexes with limited evacuation routes and egress during a fire.                                    | The model captures the typical phenomenon of group evacuation behaviors under seven operating situations with different total initial occupant numbers.                                                                              | Fishbone diagram, CLD, SD, Evacuation simulation software, Case analysis. | Previously developed research.<br><br>Vensim                                                                           | Human behavior and egress design.<br><br>Fire detection and suppression systems.                                      |
| <b>-IV-</b>   | Study the group behavior under severe fire accidents in chemical industrial parks.                                                                               | A model of the group behavior was developed based on the epidemic model and an SD theory and method.                                                                                                                                 | Epidemic model (the SIR model), SD.                                       | Vensim                                                                                                                 | Human behavior and egress design.                                                                                     |
| <b>-V-</b>    | Study the main influencing factors on the occurrence, spread, and controlling of subway fires.                                                                   | This research collects major subway fire cases in nearly 20 years. The causes of the fire accidents are assessed. The influencing factors are extracted including equipment, human, environmental, and emergency management factors. | Statistics, and SD.                                                       | Reports on the proportion of different inducing factors related to subway accidents in China and abroad.<br><br>Vensim | Fluid mechanics and fire dynamics.<br><br>Risk Analysis and decision making.                                          |
| <b>-VI-</b>   | Analyze the evacuation of buildings during a fire.                                                                                                               | This research develops a Systems Thinking framework for the evacuation of buildings during a fire. The methodology includes the fire evacuation process as a whole considering different factors affecting the evacuation process.   | Feedback loops, CLD.                                                      | Feedback loops.                                                                                                        | Human behavior and egress design.<br><br>Risk Analysis and decision making.                                           |
| <b>-VII-</b>  | Study the factors affecting high-rise building fire safety considering staff awareness, fire design, fire-fighting facilities, daily management, and technology. | The model was applied to a high-rise building.                                                                                                                                                                                       | SD                                                                        | Vensim                                                                                                                 | Structural fire engineering.<br><br>Fire detection and suppression systems.<br><br>Risk analysis and decision-making. |
| <b>-VIII-</b> | Examine the effect of                                                                                                                                            | The model is conceptualized around                                                                                                                                                                                                   | CLD + SD                                                                  | Hong Kong specifics.                                                                                                   | Fire scenarios and PBD.                                                                                               |

| <i>Code</i> | <i>Aim</i>                                                                                                                                                                                                         | <i>General description</i>                                                                                                                                                                                                                                                                                                                                                    | <i>Methods/<br/>Tools</i> | <i>Database/source of<br/>info. /Software</i>                     | <i>Relevance for<br/>FSE (Research<br/>category)</i>                                                             |
|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|-------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
|             | introducing a performance-based approach in the regulatory system by using a conceptual system dynamic model.                                                                                                      | the technical and mental factors that impact the decisions of building control officials and various challenges regarding the Hong Kong building control system.                                                                                                                                                                                                              |                           | Vensim                                                            |                                                                                                                  |
| <b>-IX-</b> | Compare the use of performance-based fire safety design in different locations by using SD modeling.                                                                                                               | This paper shows a brief comparison of the use of performance-based fire safety design in three locations and presents the use of an SD model to examine how technological investment influences the use of performance-based fire safety design.                                                                                                                             | CLD + SD                  | Hong Kong specifics.<br><br>Vensim                                | Fire scenarios and PBD.                                                                                          |
| <b>-X-</b>  | Show how SD models can be used for the CBA of fire safety features for buildings. The CBA corresponds with an ALARP evaluation whereby the Life Quality Index (LQI) is adopted for the evaluation of risk to life. | Three case studies are adapted from existing literature: (1) sprinklers in Australian single-family residences, (2) sprinkler requirements considering different sprinkler classes, and (3) door width requirements for retail spaces.                                                                                                                                        | SD                        | Data reported from the fire-specialized literature.<br><br>Vensim | Risk analysis and decision-making.<br><br>Sustainability.                                                        |
| <b>-XI-</b> | Application of an alternative probabilistic risk assessment methodology known as T-H-O-Risk, which integrates technical, human, and organizational risks using Bayesian network (BN) and SD modeling.              | The approach is demonstrated through seven case studies involving the design of high-rise residential buildings. By adopting an incremental risk assessment framework, the study quantifies the effects of human and organizational errors (HOEs) on various fire safety systems, including sprinklers, occupant warning systems, smoke detectors, and smoke control systems. | BN + SD                   | Data collection. Fire statistics. HOEs data.<br><br>Vensim        | Risk analysis and decision-making.<br><br>Fire scenarios and PBD.<br><br>Fire detection and suppression systems. |

| <i>Code</i>   | <i>Aim</i>                                                                                                                                                                                   | <i>General description</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | <i>Methods/<br/>Tools</i> | <i>Database/source of<br/>info. /Software</i>                                         | <i>Relevance for<br/>FSE (Research<br/>category)</i>                                                              |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|---------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| <b>-XII-</b>  | This study adopts the technical-human-organizational risk (T-H-O-Risk) methodology to fill critical knowledge gaps in probabilistic risk analysis (PRA) for high-rise residential buildings. | <p>Develop an Enhanced PRA Methodology: Address limitations in deterministic fire engineering methods, which tend to significantly underestimate safety levels, leading to inaccurate fire risk assessments.</p> <p>Improve Fire Safety Verification: Integrate probabilistic risk analysis and HOEs to provide a more comprehensive risk perspective and overcome the deterministic nature of current verification practices.</p> <p>Conduct Sensitivity and Uncertainty Analyses: Address uncertainties in numerical estimates used in fault trees, event trees, Bayesian networks, and system dynamics, and assess their propagation within probabilistic models.</p> <p>Quantify Human and Organizational Risks: Provide insights that support a policy shift toward a sustainable, risk-based regulatory framework for high-rise residential buildings.</p> | BN + SD<br>Event Tree.    | <p>Data obtained from the literature for high-rise building fires.</p> <p>Vensim.</p> | <p>Risk analysis and decision-making.</p> <p>Fire scenarios and PBD.</p> <p>Human behavior and egress design.</p> |
| <b>-XIII-</b> | Enhancing traditional causal analysis tools by integrating systems thinking methodologies                                                                                                    | The paper illustrates an ST approach through a case study of the Bellevue hazardous waste fire in Western Australia. The analysis reveals how various actors, responding to individual pressures, collectively fostered a poor safety culture that significantly contributed to the 2001 fire.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | CLD                       | Feedback loops.                                                                       | Risk analysis and decision-making.                                                                                |

| <i>Code</i>  | <i>Aim</i>                                                                                                                                                       | <i>General description</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | <i>Methods/<br/>Tools</i> | <i>Database/source of<br/>info. /Software</i>                                                   | <i>Relevance for<br/>FSE (Research<br/>category)</i>                                                            |
|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
| <b>-XIV-</b> | This paper introduces a comprehensive technical-human-organizational risk (T-H-O-Risk) methodology to enhance PRA by integrating human and organizational risks. | Three case studies involving structures ranging from 18 to 24 storeys demonstrate the approach. Societal risks are visualized through F-N curves. Findings reveal that fire safety designs neglecting HOEs typically underestimate risks by around 20% and, in extreme cases, up to 42%. Additionally, HOE-related risks can fluctuate by up to 30% over a 10-year period. Sensitivity analyses highlight the significant impact of factors such as inadequate training, poor safety culture, and ineffective emergency plans on overall risk.                                                                                    | BN + SD<br>Event tree.    | Data collection.<br>Fire statistics.<br>HOEs data.                                              | Risk analysis and decision-making.<br><br>Human behavior and egress design.<br><br>Structural fire engineering. |
| <b>-XV-</b>  | To review literature on historical tunnel accidents and map the common timeline of tunnel fire events.                                                           | Key findings: (1) Complex Causes and Greater Damage: Tunnel fires are far more complex and destructive than other types of fires; (2) Dynamic and Interconnected Systems: These incidents involve numerous continuous and dynamic causal relationships, including interactions among vehicle systems, tunnel control mechanisms, and safety responses; (3) Critical Mental Models: Two mental models emerged as vital for enhancing safety: (a) "The experience of tunnel control center operators is as crucial as the safety response itself" and (b) "Safety should take precedence over traffic volume in tunnel operations." | CLD                       | Data on critical accidental fires in tunnels that occurred between 1949 and 2016.<br><br>Vensim | Risk analysis and decision-making.<br><br>Structural fire engineering.                                          |
| <b>-XVI-</b> | A dynamic probability prediction model is introduced by integrating the                                                                                          | The model is applied to predict the dynamic probability of blowout fires in offshore drilling operations. Additionally, sensitivity analyses using                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Fault Tree + SD           | Probability database (fire safety handbook).<br><br>Vensim                                      | Risk analysis and decision-making.<br><br>Fire scenarios and PBD.                                               |

| <i>Code</i>    | <i>Aim</i>                                                                                                                                            | <i>General description</i>                                                                                                                                                                                                                                                                                                                           | <i>Methods/<br/>Tools</i>                                                 | <i>Database/source of<br/>info. /Software</i>                                                                                                                                                                       | <i>Relevance for<br/>FSE (Research<br/>category)</i> |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|
|                | fault tree with a system dynamics model.                                                                                                              | mutual information are conducted to identify key contributory factors to blowout fires.<br>The research provides safety managers with reliable and practical risk control strategies to help prevent future accidents.                                                                                                                               |                                                                           |                                                                                                                                                                                                                     |                                                      |
| <b>-XVII-</b>  | This research aims to detect and categorize behavior patterns in recurring in construction safety management.                                         | Four archetypes were identified. These archetypes take into account the following variables (i) delay in design, (ii) number of subcontractors, (iii) cost of the project, and (iv) safety. Each archetype is discussed at different steps of dynamic complexity, behavior over time, and the leverage point to show how to deal with the archetype. | System Archetypes, Content analysis, and Ground Theory Method (GTM).      | Systems Archetypes structure.<br><br>Vensim                                                                                                                                                                         | Risk analysis and decision-making.                   |
| <b>-XVIII-</b> | To better understand the dynamic complexity of construction safety by identifying behavioral patterns of workers that recur in construction projects. | Construction project management implies a complex effort due to the unique, dynamic, and temporary nature of construction projects. Moreover, there is a gap in exploring the systematic patterns responsible for the occurrence of accidents. 100 papers were reviewed and 20 interviews were conducted.                                            | Content analysis and ground theory method (GTM), System Archetypes (SAs). | The databases included the Scopus database, Taylor & Francis Online, and American Society of Civil Engineers (ASCE) library. They were searched using keywords such as “accident” and “construction.”<br><br>Vensim | Risk analysis and decision-making.                   |
| <b>-XIX-</b>   | An SD model for people's behavior is developed considering the disaster environment and the evolution of crowd motion.                                | Simulation experiments were carried out for different disaster severity, visibility, and occupant groups.                                                                                                                                                                                                                                            | SD                                                                        | A major toxic gas leakage accident in a chemical plant is used as an example.<br><br>Anylogic                                                                                                                       | Human behavior and egress design.                    |
| <b>-XX-</b>    | This paper proposes an SD-based model for simulating parameter interactions for                                                                       | The parameters that affect the selection of sustainable building materials are derived from rating systems, previous studies, and expert criteria. A case                                                                                                                                                                                            | Questionnaire survey, CLD, SD, Analytical Hierarchy Process (AHP)         | A case study to consider the performance of common building materials like wood, concrete,                                                                                                                          | Sustainability.<br><br>Structural fire engineering.  |

| <i>Code</i>    | <i>Aim</i>                                                                                                                                                                    | <i>General description</i>                                                                                                                                                       | <i>Methods/<br/>Tools</i> | <i>Database/source of<br/>info. /Software</i>                                                           | <i>Relevance for<br/>FSE (Research<br/>category)</i>                   |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|---------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
|                | selecting sustainable building materials.                                                                                                                                     | study to appreciate the performance of common building materials is presented to prove the main characteristics of the suggested model.                                          |                           | and steel is presented.<br><br>Vensim                                                                   |                                                                        |
| <b>-XXI-</b>   | Develop an SD model to study the influencing factors on safety performance in building construction projects.                                                                 | Identification of key variables using factor reduction; 19 factors out of 143 variables from a questionnaire were found to be key factors.                                       | CLD + SD                  | 255 building construction projects in five zones of Tanzania.<br><br>Stella                             | Structural fire engineering.<br><br>Risk analysis and decision-making. |
| <b>-XXII-</b>  | Study the interaction mechanisms and dynamic changes during the construction of large bridges.                                                                                | A CLD and an SD model are proposed. As a case study, a large bridge construction project is considered.                                                                          | CLD + SD                  | Case study large bridge construction.<br><br>Vensim                                                     | Structural fire engineering.<br><br>Risk analysis and decision-making. |
| <b>-XXIII-</b> | Build a two-stage environmental benefit assessment based on SD modeling which includes construction waste reduction management, waste generation, and environmental benefits. | The simulation results demonstrate that the dynamic model assessed the environmental benefit of construction waste reduction effectively at the design and construction stage.   | CLD + SD                  | Case study construction waste reduction management at the design and construction stages.<br><br>Vensim | Sustainability.                                                        |
| <b>-XXIV-</b>  | Develop a decision-making tool based on SD for building design and operation.                                                                                                 | A method is discussed to link a building information model (BIM) of the building with an SD model to enable the automated capture of relevant building features in the SD model. | SD.                       | Historic uses within civil and environmental engineering.<br><br>Stella                                 | Risk analysis and decision-making.                                     |

The main software used is *Vensim*, while the database adopted strongly depends on the aim of each research. Some other methods have been combined with an ST approach to support a holistic evaluation, such as the Analytical Hierarchy Process (AHP), ground theory method (GTM), Fishbone diagram, and Cost-benefit analysis (CBA). A recent trend considers combining Bayesian Networks (BN) with SD modeling (Tan et al., 2020, 2021a, 2021b). This



approach has several advantages for FSE (Tan et al., 2020, 2021a, 2021b). Table 3.6 shows examples from the literature of combining ST tools with non-ST methods. The most common research category is *Risk analysis and decision-making*, which is aligned with one of the major advantages of using an ST-tool.

**Table 3.6: Examples of combining Systems Thinking (ST) tools with non-ST methods in the reviewed literature**

| ST Tool(s)                     | Non-ST Tool(s) Combined             | Capability of ST Tool(s) explored in the reference                  | Typical Role of the Non-ST Tool(s)                                        | Reference(s)                                                     |
|--------------------------------|-------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------|
| System Dynamics (SD)           | Cost-Benefit Analysis (CBA)         | Simulates system dynamics over time; evaluates intervention impacts | Quantifies costs and benefits; assesses economic feasibility              | Wang et al. (Y. F. Wang et al., 2018)                            |
| Causal Loop Diagram (CLD) + SD | Probabilistic Risk Assessment (PRA) | Maps feedback loops and interactions influencing risk               | Quantifies probabilities and consequences of failure scenarios            | Tan et al. (Tan et al., 2020),<br>Tan et al. (Tan et al., 2021a) |
| CLD                            | Bayesian Networks (BN)              | Identifies system structure and causal pathways                     | Calculates conditional probabilities and supports probabilistic reasoning | Tan et al. (Tan et al., 2021b)                                   |
| SD                             | Event Tree Analysis                 | Models time-dependent changes in safety system performance          | Structures possible event sequences from initiating events                | Tan et al. (Tan et al., 2021a)                                   |
| SD                             | Fault Tree Analysis                 | Simulates dynamic effects of component failures                     | Models logical combinations of failures leading to system-level events    | Wang et al. (Y. fu Wang et al., 2019)                            |
| SD                             | Analytical Hierarchy Process (AHP)  | Tests dynamic impacts of parameter choices over time                | Weighs decision criteria and ranks alternatives                           | Sahlol et al. (Sahlol et al., 2021)                              |

### 3.3.3.2- Main feedback loops for studying the interactions linked to the FSE field

Table 3.7 presents the feedback loops (FLs) identified through the literature review most relevant for the FSE field. These loops highlight interdependencies in FSE, particularly in high-risk environments like petrochemical enterprises and tunnel systems. The FLs can be categorized into reinforcing loops (RLs), which amplify certain behaviors, and balancing loops (BLs), which stabilize systems.

For example, FL01-04 highlights that investment in fire safety within petrochemical enterprises plays a crucial role in enhancing staff training, fire safety management, and technological advancements. These improvements create a reinforcing cycle, increasing overall fire safety

and efficiency. Similarly, performance-based approaches in FSE influence administrative processes, shaping regulatory frameworks and professional awareness (FL05-06).

A key example in tunnel fire safety is the balance between safety responses and infrastructure investments. FLs 7-10 illustrate the dynamic interactions between fire risk, safety measures, and traffic regulations in tunnels. The balancing loops (B1, B2, B3) work to control fire hazards: restrictions on vehicle types and cargo (B1) reduce traffic volume and vehicle-related problems, lowering fire incidents and eventually easing restrictions; heightened fire risks (B2) increase fire severity, prompting stronger engagement from self-defense fire brigades, which mitigates risk; and severe fires (B3) drive local fire squads to act, containing fire spread and enhancing tunnel safety. In contrast, the reinforcing loop (R1) presents a challenge—more vehicle ignitions lead to increased investments in tunnel protection, which relaxes vehicle restrictions, raises traffic volume, and ultimately results in more ignitions.

This feedback loop-based analysis underscores the critical role of coordinated safety efforts, technological improvements, and infrastructure investment in minimizing fire risks. Efficient management of balancing loops ensures system stability, while reinforcing loops, when harnessed effectively, promote continuous improvement in fire safety.

**Table 3.7: Some feedback loops (FLs) developed for the FSE field**

| <b>No.</b> | <b>Feedback loop</b>                                                                                                                                                                                                                                                             | <b>Meaning</b>                                                                                                                                                                                                           | <b>Code<br/>(Table 3.5)</b> |
|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| 01         | RL (A)- petrochemical enterprises fire safety investment → + staff training → + personnel fire training level → + safety level of petrochemical enterprises → + firefighting efficiency → + fire safety improvement → + petrochemical enterprises fire safety investment.        | According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on staff training, firefighting efficiency, and fire safety improvement.    | -I-                         |
| 02         | RL (B): petrochemical enterprises fire safety investment → + fire facilities purchase → + fire service level → + safety level of petrochemical enterprises → + firefighting efficiency → + fire safety improvement → + petrochemical enterprises fire safety investment.         | According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on the available fire fighting facilities.                                  | -I-                         |
| 03         | RL (C): petrochemical enterprises fire safety investment → + fire safety management → + fire safety management level → + safety level of petrochemical enterprises → + firefighting efficiency → + fire safety improvement → + petrochemical enterprises fire safety investment. | According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on safety management, firefighting efficiency, and fire safety improvement. | -I-                         |
| 04         | RL (D): petrochemical enterprises fire safety investment → + technical improvement → + the technical level → + safety level of petrochemical enterprises → + firefighting efficiency → + fire                                                                                    | According to this feedback loop, investments in fire safety for petrochemical plants induce a positive feedback effect through their effects on the technical improvement,                                               | -I-                         |

| <i>No.</i> | <i>Feedback loop</i>                                                                                                                                                                                                                                                                                      | <i>Meaning</i>                                                                                                                                                                                                                                                                       | <i>Code (Table 3.5)</i> |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|
|            | safety improvement → + petrochemical enterprises fire safety investment.                                                                                                                                                                                                                                  | firefighting efficiency, and fire safety improvement.                                                                                                                                                                                                                                |                         |
| 05         | RL2- No. of projects using FSE approach → + No. of FSE applications submitted to Fire Safety Committee (FSC) → + No. of approved FSE applications → + Awareness of building professionals → + Rate of using performance-based approach in buildings design → + No. of projects using FSE approach.        | Self-strengthening effect of the number of projects using an FSE approach because of its impact on the number of applications submitted and approved, the awareness of building professionals, and the rate of using a performance-based approach in building design.                | -VIII-                  |
| 06         | BL3- No. of FSE applications submitted to FSC → + Workload pressure of building authorities → - Passing rate of FSE applications → + No. of approved FSE applications → + Technological level → + Rate of using performance-base approach in buildings design → + No. of using FSE building applications. | According to this feedback loop, the number of FSE applications submitted to FSC induces a negative feedback effect (balancing) through their effects on the workload pressure of building authorities, the technological level, and the rate of using PBD in buildings.             | -IX-                    |
| 07         | B1 (Limited Vehicle Use Loop): Limit to Vehicle Types and Carried Goods → - Traffic volume → + Vehicle Problem Rates → + Limit to Vehicle Types and Carried Goods.                                                                                                                                        | When severe vehicle-related issues arise, authorities impose restrictions on vehicle types and cargo. This decreases tunnel traffic volume, which in turn reduces the frequency of vehicle problems, leading to fewer fires. This eventually results in less stringent restrictions. | -XV-                    |
| 08         | B2 (Self-Defense Fire Brigade Commitment to Safety Response): High Risks → + Fire Severity → + Self-defense Fire Brigade Commitment to Safety Response → - High Risks                                                                                                                                     | High risks increase the severity of fires. This leads to greater engagement from self-defense fire brigades, ultimately reducing risks.                                                                                                                                              | -XV-                    |
| 09         | B3 (Tunnel Damage Containment Loop): Fire Severity → + Local fire squad commitment to safety response → - Unsafe Conditions → + Fire Severity                                                                                                                                                             | The possibility of severe fires leads to more local fire squads' efforts in fire suppression, which help contain fires and prevent them from spreading, improving overall tunnel safety.                                                                                             | -XV-                    |
| 10         | R1 (Tunnel Protection Investment Loop): Vehicle Ignition → + Tunnel Protective Investment → - Limits on vehicles → - Traffic volume → + Vehicle Problem Rates → + Vehicle Unsafe Conditions → + Vehicle Ignition.                                                                                         | An increase in vehicle ignitions leads to greater investment in tunnel protection, which relaxes vehicle restrictions, resulting in higher traffic volume and, consequently, more ignitions.                                                                                         | -XV-                    |

### **3.3.3.3- Causal Loop Diagrams built for Fire Safety Engineering**

CLDs aim to capture and visualize the complex interdependencies among different influencing factors. A CLD is built considering the integration of different FLs, so the ultimate dynamic behavior is controlled by the force and number of BLs and RLs that compose the system. CLDs capture the complexity of a given system by visualizing their intrinsic interdependencies. This has a huge advantage in the FSE field because FSE needs to move beyond static risk assessment approaches by adopting dynamic models that account for the interrelations among different safety features.

To demonstrate the concept, a CLD is chosen from the literature (Zhang et al., 2018) which models the interrelations linked to the safety level and fire safety investment in a petrochemical enterprise (Fig. 3.3). This CLD contains four RLs (previously explained in Table 3.7- FLs 01-

04). The expected behavior of this system is exponential growth or decline. Also, the presence of multiple RLs can increase the nonlinearity and instability. At the core of the diagram is the role of financial investment in fire safety, which cascades into various subsystems.

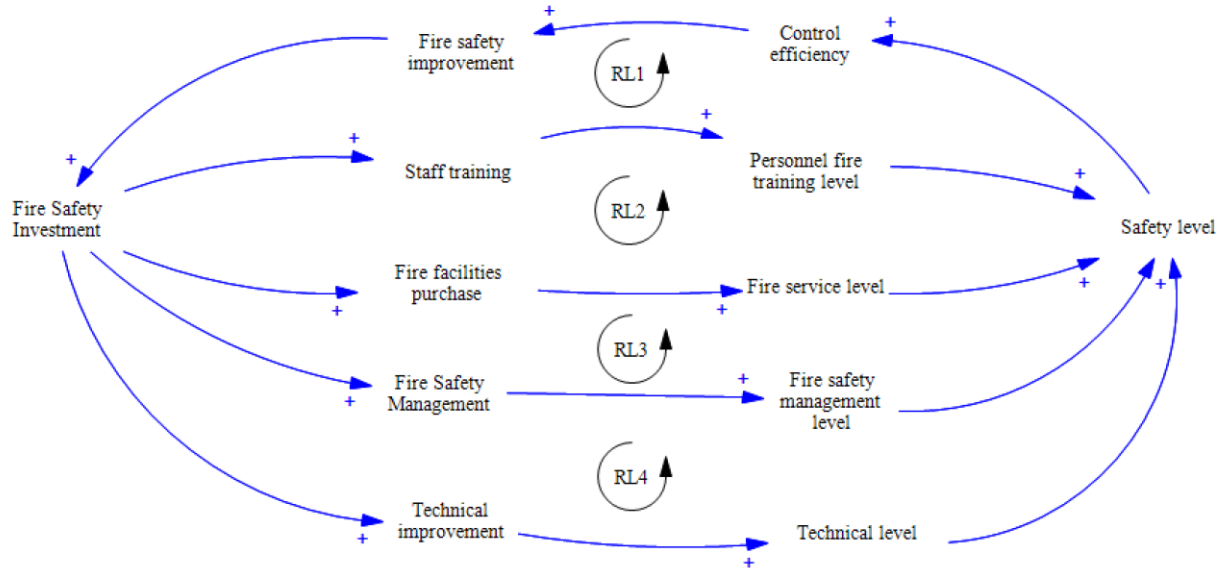


**Fig. 3.3: CLD for modeling the interrelations linked to the safety level and fire safety investment.**

*Adapted from* (Zhang et al., 2018)

The CLD suggests four critical pathways through which investments enhance fire safety: staff training, facility purchases, safety management, and technical improvements. These factors collectively contribute to an increased safety level. According to (Zhang et al., 2018), a higher safety level fosters a greater commitment to ongoing fire safety improvements, which, in turn, encourages further investment in fire safety measures. Thus, four reinforcing loops are formed. The reinforcing nature of all four loops creates a virtuous cycle, where increased investment leads to enhanced safety measures, better-trained personnel, more advanced equipment, and higher managerial efficiency, culminating in a safer chemical industry park and even higher fire safety investments. Positive feedback loops are critical in ensuring that small gains in safety performance drive further investments, creating sustained improvement over time. This CLD can serve as a basis for developing more realistic models in the FSE field, specifically aligned with the research categories of *Risk analysis and decision-making*, and *Sustainability*.

More complex CLD models have been developed in previous studies. For instance, a CLD for modeling the complex interdependencies linked to the occurrence and prevention of a blowout fire is introduced in (Y. F. Wang et al., 2018), considering event probabilities, safety measures, and dynamic relationships. Aligned with the research category *Human behavior and egress*

*design*, a CLD for representing mass crowd evacuation behavior during an emergency is proposed in (Li et al., 2022). A CLD was built for the building approval system in Hong Kong (Lo, Zhao, & Yuen, 2008; Lo, Zhao, Liu, et al., 2008), to represent the interrelations between the proposal, approval, and application of performance-based fire designs. Other identified CLDs that can be helpful for FSE are related to sustainable building materials assessment and selection (Sahlol et al., 2021), safety performance in building construction projects (Kajumulo et al., 2024), environmental benefits assessment (Ding et al., 2018), and risk evolution of large bridge construction (Fu et al., 2024).

Overall, by applying the CLD principles fire safety engineers can better anticipate risks, implement more effective safety measures, and ultimately enhance the system safety. Although CLDs can offer a clear representation of complex system safety, they do not provide quantitative input for decision-making. To address this issue, CLDs can be further translated into SD models, and by performing simulations for different scenarios, the decision-making process can be improved.

#### ***3.3.3.4- System Dynamics Models for Fire Safety Engineering***

Despite the several advantages offered by the development of CLDs, these are often adopted as a qualitative tool; so it is necessary sometimes to transform the CLD into a Forrester-diagram (or SD-based) model for quantifying key variables and support efficient decision-making. This section focuses on explaining the main advantages of SD-based models developed and applied in the FSE field, or that can be used for specific purposes linked to FSE.

In this section, an SD model is chosen from the literature (Y. F. Wang et al., 2018) to illustrate the concept. The SD model has been created to perform a cost-benefit analysis for an offshore platform considering investments in safety management and safety education, the probability of a blowout fire, the total accident loss, the safety management costs, the total demand for safety management, and the number of employees (Fig. 3.4).

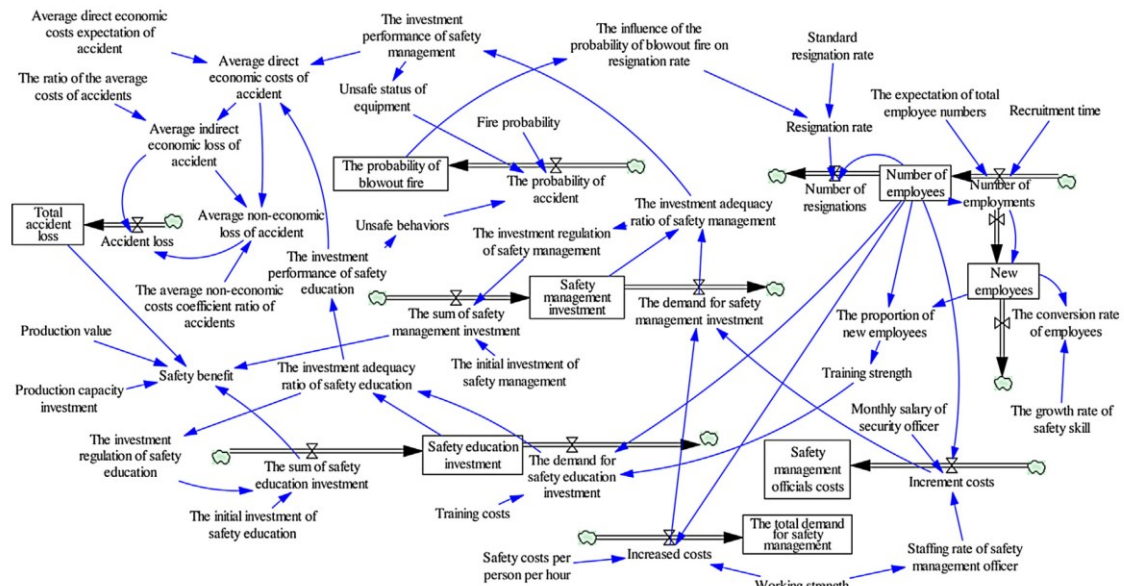


**Fig. 3.4: SD for performing a Cost-benefit analysis (Y. F. Wang et al., 2018)**

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This SD model illustrates a complex interplay between various factors influencing safety management, accident risks, and costs associated with fire safety. Investments in safety management directly impact the probability of accidents and fires by addressing unsafe behaviors and equipment conditions. Safety education investment improves employee training and the proportion of skilled employees, reducing the likelihood of unsafe actions. Additionally, the diagram outlines the economic consequences of accidents, including direct costs (e.g., damages and compensation) and indirect costs (e.g., production downtime and reputation loss). These are aggregated into total accident loss, which feeds back into the benefit of enhanced safety measures.

The model also considers human resource dynamics. Employee turnover, training, and skill growth are central to maintaining a safe working environment. Resignation rates (linked to stress, unsafe conditions, or fire incidents) affect the number of new employees and their proportional representation in the workforce. New employees often require more intensive training, adding to safety education costs. Training strength, influenced by safety education investment, increases the safety skill level of employees, thus reducing accidents.

The model highlights feedback loops where improved safety management and education investments enhance overall safety performance. This leads to fewer accidents, reducing both economic losses and the need for reactive investments, thus strengthening the investment in improved safety management and education.

Safety costs per person per hour, total safety management investment, and associated increased costs—such as salaries of safety officers and training expenses—create a balancing feedback loop between investment adequacy and organizational budget constraints. Increased safety investments must be justified by measurable improvements in safety performance and corresponding reductions in accident-related losses. As safety management effectiveness reduces accident risks and associated costs, it reinforces the rationale for continued investment. However, rising costs place financial pressure on budgets, limiting the extent of future investments. This balancing mechanism, as shown in the SD model (Y. F. Wang et al., 2018), results in a cap on the practically achievable level of safety.

Other SD models have been applied in the FSE. For example, an SD model was developed for studying evacuation planning considering exit evacuation capacity and guidelines (Li et al., 2022). Complementing a previous CLD, an SD model for the building approval system in Hong Kong considering the proposal, submission, and approval of building design projects has been established (Lo, Zhao, & Yuen, 2008; Lo, Zhao, Liu, et al., 2008). Additionally, an SD model for the safety performance in building construction projects considering accident frequency, and associated costs was developed (Kajumulo et al., 2024). To compute the fire safety level of high-rise buildings considering the fire fighting efficiency and fire protection benefits, an SD model has been built (J. F. Wang et al., 2014). Recent studies have coupled SD modeling with Bayesian modeling and Event trees for probabilistic risk assessments (Tan et al., 2020, 2021a, 2021b). This new Technical-Human-Organizational-Risk (T-H-O-Risk) methodology offers an interesting approach to addressing FSE challenges. Despite SD modeling being only a stage in this methodology, it offers dynamic risk profiles (Tan et al., 2021b). This approach has been applied to high-rise residential buildings (Tan et al., 2020, 2021b).

Although these studies highlight the potential of SD in FSE, additional case studies and real-world applications are necessary to validate these models and enhance their accuracy and effectiveness. Practical implementations would help identify potential gaps, refine assumptions, and improve the reliability of SD-based approaches in predicting fire risks and optimizing safety measures. Integrating empirical data from real fire incidents and safety interventions would strengthen model calibration, ensuring that SD applications in FSE reflect the complexities of fire dynamics, human behavior, and regulatory constraints. Expanding case studies and practical applications will ultimately bridge the gap between theoretical advancements and their real-world utility, fostering a more robust and data-driven approach to fire safety management.

### 3.3.4- Discussion on the added value of ST theory and SD modeling approaches (Stage 5)

Figure 3.5 shows the interrelationship among the previously analyzed methods. This analysis explores how STS, SAs, CLD, and SD modeling are interconnected within the ST framework, progressively linking high-level system interactions to detailed, quantitative models.

At the macro level, STS defines the broader fire safety context, emphasizing the interplay between regulations, human behavior, organizational structures, and fire safety technologies. Buildings and infrastructures are not merely physical entities; they are dynamic STS where fire safety depends on the effective interaction of stakeholders, policies, and emergency response mechanisms. STS theory highlights that fire safety cannot be managed in isolation—it must be analyzed in terms of its dependencies on regulatory processes, societal expectations, and technological advancements (B. J. Meacham, 2022a; B. J. Meacham & van Straalen, 2018).

Within this broader STS framework, SAs help identify recurring patterns of system behavior that influence fire safety decision-making. Recognizing these archetypal behaviors enables fire safety engineers and policymakers to anticipate unintended consequences and adopt more resilient, long-term solutions. To translate these system patterns into a structured visual format, CLDs provide a graphical representation of the cause-and-effect relationships in fire safety systems. By mapping these relationships, CLDs help identify leverage points where interventions can have the most significant impact on improving fire safety strategies.

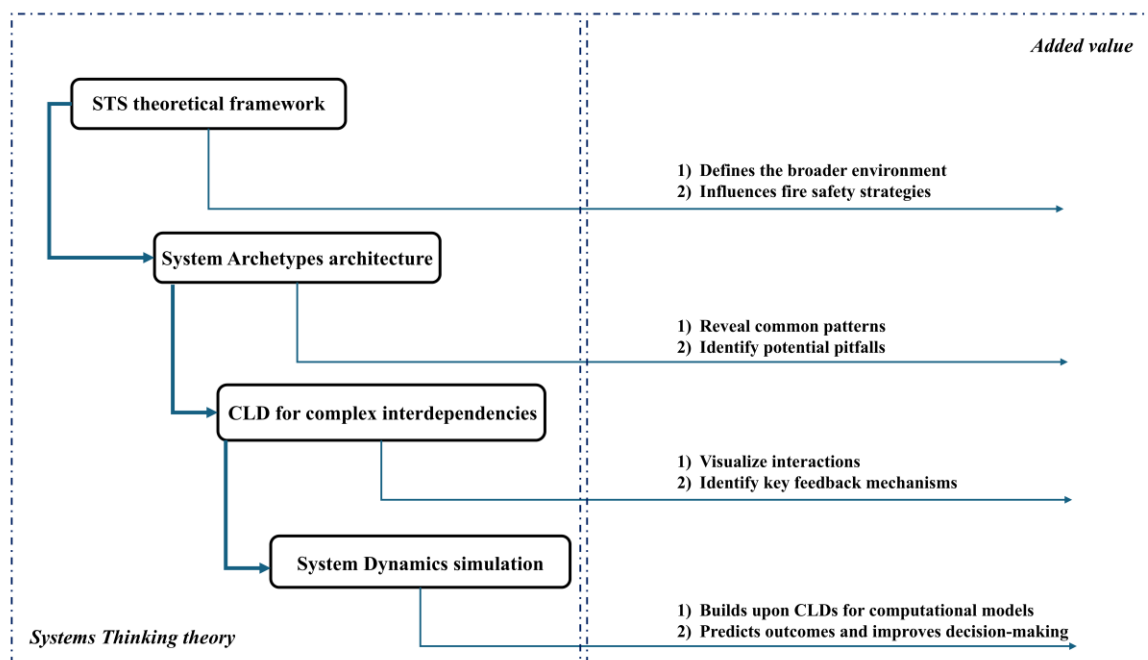


Fig. 3.5: Added value for FSE for each analyzed method within the Systems Thinking theory



Finally, to move from qualitative system mapping to quantitative decision-making, SD modeling builds on CLDs by simulating the real-time behavior of fire safety systems. For example, an SD model can evaluate the long-term effects of increasing fire safety budgets on incident reduction and regulatory compliance. By integrating SD modeling, fire safety professionals can test different policy scenarios, optimize resource allocation, and enhance emergency preparedness strategies.

The ST perspective can also extend beyond the immediate scope of fire safety. When viewed from a systems perspective, fire safety is inherently interconnected with other disciplines. For example, structural design choices—such as using cross-laminated timber (CLT) instead of reinforced concrete—not only influence fire performance but also affect acoustic performance, environmental impact, and structural behavior under load. Such interactions can present synergies—such as aligning fire safety improvements with sustainability goals—but can also create conflicts that require trade-off analysis. Adopting a Systems Thinking approach at the earliest design stages enables stakeholders to evaluate these interdependencies holistically and integrate fire safety into broader performance objectives.

In conclusion, STS provides the overarching framework, SAs reveal systemic weaknesses and opportunities, CLDs visualize the interactions within the system, and SD enables simulation-based decision-making. By combining these methodologies, fire safety strategies can transition from static, rule-based approaches to adaptive, data-driven solutions that evolve with changing risks and technological advancements.

### **3.4- Future research directions: Challenges and limitations (Stage 6)**

This section outlines the future research lines identified from this literature review by proposing how ST tools can be applied to FSE. Considering the seven clustered research categories adopted in section 4, the research needs for FSE specified by the SFPE (SFPE, 2025), and the discussion on the current state of the art in the sections above, possible ST applications are shown in Table 3.8.

An ST approach can connect the different areas of a comprehensive fire safety strategy, emphasizing the interplay of materials, fire dynamics, structures, and human behavior in fire safety. By adopting SAs, CLDs, and SD modeling, such an integrated framework can enable fire safety engineers to predict, analyze, and mitigate fire risks holistically. An integrated and holistic approach could address some of the research needs identified by the SFPE, especially in the topics of decision-making, resilience, sustainability, and human behavior. Embracing

emerging technologies, utilizing real-time data, establishing standardized validation procedures, exploring cross-disciplinary approaches, and focusing on policy and implementation studies will be crucial for advancing the field and addressing current gaps.

**Table 3.8: Potential ST applications to the FSE field**

| Research topic                         | Potential application                                                                                                                                                            | Hypotheses for ST developments                                                                                      |                                                                                   |                                                                                                                                                |
|----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
|                                        |                                                                                                                                                                                  | SAs                                                                                                                 | CLD                                                                               | SD                                                                                                                                             |
| Fluid mechanics and fire dynamics      | Fire plumes, compartment fires, tunnel fires, facades.<br><br>Designing ventilation systems to control smoke spread.                                                             | "Limits to Growth" – Suppression slows fire spread within certain boundaries.                                       | Map feedback effects between airflow, fire growth, and suppression effectiveness. | Simulation of airflow and its effects on fire plume behavior.<br><br>Test interventions (e.g., ventilation systems) for varied fire scenarios. |
| Fire modeling and heat transfer        | Developing compartment fire models for scenario evaluations.<br><br>Simulate fire spread in large enclosures.                                                                    | "Escalation" — How uncontrolled heat transfer accelerates fire spread.                                              | Interaction between heat transfer, material ignition, and smoke production.       | Multi-variable simulations to test fire suppression strategies.                                                                                |
| Fire detection and suppression systems | Designing and optimizing automatic sprinklers, water mist systems, and gas extinguishers.                                                                                        | "Shifting the Burden" — Overreliance on one suppression method reducing overall system redundancy.                  | Relationships between system activation, water usage, and fire containment.       | Optimizing suppression systems' response times and efficiency.                                                                                 |
| Human behavior and egress design       | Planning evacuation strategies based on human behavior in fire emergencies.<br><br>Designing egress strategies with consideration for visibility and movement efficiency.        | "Success to the Successful" — Prioritizing resources toward paths with high importance for successful evacuation.   | Interaction between visibility, smoke, and occupant movement.                     | Simulate evacuation scenarios to test and improve egress designs.                                                                              |
| Risk Analysis and decision-making      | Conducting quantitative fire risk assessments for buildings and products.<br><br>Implementing decision analysis tools for fire safety strategies.                                | "Growth and Underinvestment" — Rapid technology adoption increases risks without adequate safeguards.               | Connect innovation, safety investments, and environmental outcomes.               | Evaluate long-term risks and mitigation strategies for sustainable fire safety.                                                                |
| STS-level integration                  | Modeling entire socio-technical systems (STS) that integrate regulatory oversight, organizational practices, occupant behavior, emergency response, and physical fire phenomena. | "Eroding Goals" or "Tragedy of the Commons" may emerge when standards are relaxed or shared resources overstressed. | Map feedback loops across technical, social, and institutional dimensions.        | Extend SD beyond fire phenomena to simulate large STSs; assess systemic interactions, resilience, and policy impacts.                          |

A key area for future research involves critically examining how regulatory systems interact with socio-technical systems (STS) perspectives. As highlighted in Section 2.2, STS frameworks allow for a richer representation of fire safety dynamics by accounting for social behaviors, informal interactions (e.g., neighbor support), and institutional actions (e.g., fire service response). However, current regulatory models often enforce simplified assumptions—such as complete occupant self-evacuation or disregarding active intervention by others. Bridging this gap requires careful inquiry into how regulations can evolve to taking into account STS-based insights, and how STS can be adopted within existing regulatory frameworks.

Finally, another promising research direction lies in applying ST to integrate fire safety with other disciplines during early-stage design and planning. Many decisions in areas such as structural design, façade system selection, and urban or spatial planning inherently influence both fire safety performance and other performance objectives such as sustainability, occupant comfort, or accessibility. Systems-based approaches can be used to model these interdependencies, identify potential synergies, and anticipate conflicts before design commitments are made. Future work should focus on developing multi-domain frameworks and simulation models capable of quantifying trade-offs, such as between energy efficiency and façade fire performance, or between compact urban layouts and evacuation capacity.

### **3.5- Concluding remarks**

The application of Systems Thinking (ST) tools and System Dynamics (SD) to the Fire Safety Engineering (FSE) field has so far been limited. Only 35 studies were found which include a direct application of an ST method to FSE, even when selected applications in nearby fields such as construction and design were included. However, multiple potential applications of SD to the FSE field were identified by considering research categorization clustering, architecture of ST tools (such as System Archetypes and Causal Loop Diagrams), and relevant previously developed models available in the literature.

A very relevant framework relies on seeing buildings and infrastructures as STS. This offers a powerful framework for addressing fire safety challenges. Another significant approach is related to the combination of SD modeling and Bayesian Networks, as has been applied for assessing the reliability of high-rise residential buildings. More generally, by analyzing factors such as fire growth rate, accident probability, and dynamic losses and benefits, SD models can provide valuable insights for developing more effective fire safety strategies and safety

investment plans. Similarly, in construction and urban environments, SD has been instrumental in simulating evacuation processes, assessing the impact of safety culture, and promoting the adoption of sustainable building materials.

Considering the above, the application of ST tools in FSE is found to be a powerful method for understanding and managing the complex dynamics of fire safety in buildings and infrastructure. At the same time, SD models offer a quantitative framework for modeling such dynamics. The literature review highlights the potential versatility of SD models in addressing a wide range of fire safety challenges, such as nonlinearity, complexity, time dependence, and human behavior, across a range of industries and contexts. Despite these advancements, many challenges remain. While many studies have demonstrated the potential of SD in FSE, more case studies and practical applications are needed to validate these models and refine their accuracy and effectiveness.

The findings of this chapter can be structured within a three-level hierarchy of ST applications: (1) *philosophical level* – ST as a worldview that emphasizes interconnections, feedback, emergence, and holistic problem framing; (2) *methodological level* – the set of analytical approaches consistent with ST principles, including SD, qualitative system mapping, and hybrid socio-technical modeling frameworks; and, (3) *tool level* – specific techniques, such as CLDs, SAs, and simulation models, which operationalize ST methodologies. Tools and techniques from outside the traditional ST domain—such as probabilistic risk analysis—can be integrated if applied consistently with ST principles. This may require adaptations, such as embedding feedback mechanisms in risk models.

Future research could apply ST tools such as CLDs to analyze major fire events, for example the Grenfell Tower Fire. Such analyses could reveal the interplay of STS interactions and recurring SAs, such as the Tragedy of the Commons and Eroding Goals. These applications would illustrate the value of ST for understanding systemic failures and guiding improvements in fire safety governance and practice.

Additionally, future research should focus on improving the accessibility and usability of SD models for practitioners in the FSE field. Developing user-friendly tools and interfaces that allow engineers, architects, and safety managers to easily create, modify, and run SD simulations will be crucial for the widespread adoption of this methodology in practice. Collaborations between researchers, industry professionals, and software developers can

facilitate the creation of more intuitive and versatile SD platforms tailored to the specific needs of fire safety stakeholders.

In conclusion, SD represents a valuable and versatile tool for advancing the field of FSE. As researchers and practitioners work to refine and expand SD methodologies, this approach can play an important role in safeguarding buildings and infrastructures from fire hazards, ultimately contributing to a safer and more resilient built environment.

Within the FRISE Framework, the integration of Systems Thinking and System Dynamics in Fire Safety Engineering provides an example of how feedback structures (Stage 1 of FRISE) can be identified, quantified, and optimized to balance safety and sustainability performance. The literature reviewed in this chapter provides the empirical and methodological foundation for defining the feedback architecture that are later operationalized in the FRISE applications.

This review confirms that System Dynamics modeling, coupled with Systems Thinking principles, represents a practical instantiation of the FRISE philosophy within Fire Safety Engineering. It demonstrates how feedback-informed methodologies can reconcile safety imperatives with sustainability goals, forming a vital bridge between theory and application in complex engineering systems.

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## **Chapter 4 – Comparative Literature Review: Risk and Safety Modeling in Complex Engineering Systems**

This chapter presents a comparative literature review of risk and safety modeling approaches in complex engineering systems, with particular focus on the chemical, energy, and hydrogen sectors. It traces the evolution from static probabilistic methods toward feedback-based and dynamic risk assessment frameworks. By analyzing interdependencies among technical, environmental, economic, and social dimensions, the chapter identifies key research gaps that motivate the development of the FRISE Framework. These findings establish the conceptual and methodological bridge between the theoretical paradigms discussed in Chapter 2 and the framework implementation in Chapter 5.

### **4.1- Risk and safety modeling in the chemical and energy sectors**

Industrial risk and safety management have long been fundamental to the operation of chemical, petrochemical, and energy systems. Over the past five decades, multiple frameworks have evolved to identify, quantify, and mitigate hazards associated with technological and process systems. These approaches—ranging from fault tree analysis to quantitative risk assessment (QRA)—have played a vital role in improving industrial safety and guiding regulatory decisions.

However, the progressive integration of sustainability objectives, renewable energy technologies, and decarbonization strategies has introduced new layers of complexity into risk modeling. The chemical and energy sectors are no longer isolated technical systems; they now constitute interconnected socio-technical ecosystems influenced by technological, economic, environmental, and societal feedbacks (Reniers & Cozzani, 2013; Aven, 2016).

The methodological evolution described in this section anticipates the modular logic of the FRISE Framework (*Feedback-based Risk Integration for Safety and Sustainability in Engineering*). Each modeling approach—from static QRA to dynamic System Dynamics—represents a step toward the feedback-oriented philosophy central to FRISE, where Risk Assessment (RA) and Safety Management (SM) are dynamically coupled through feedback loops linking technical, organizational, and sustainability dimensions.

#### **4.1.1- Evolution of risk assessment and safety management in the process industries**

The foundation of modern process safety lies in the development of deterministic and probabilistic methods for hazard identification and consequence analysis. Techniques such as Hazard and Operability Studies (HAZOP), Event Tree Analysis (ETA), and Fault Tree Analysis

(FTA) were standardized throughout the 1970s and 1980s following major industrial accidents (e.g., Flixborough, Seveso, Bhopal). These methodologies focused primarily on technical reliability and failure probability quantification, offering a systematic means of identifying potential accident sequences (Lees, 2012).

During the 1990s and 2000s, probabilistic risk assessment evolved into Quantitative Risk Assessment (QRA), which incorporated consequence modeling, frequency estimation, and risk visualization (Khan & Abbasi, 1998; CCPS, 2008).

Yet, these models largely remained static representations—providing a snapshot of risk rather than its dynamic evolution. They typically assumed constant failure rates and neglected temporal degradation, maintenance effects, and adaptive responses (Salzano et al., 2014; Bouloiz et al., 2013).

To address these limitations, research began to introduce dynamic risk assessment (DRA) frameworks. DRA approaches consider the time dependency of system variables and explicitly model feedbacks among system components. Examples include Bayesian updating of failure probabilities, dynamic barrier modeling, and hybrid probabilistic–deterministic methods (Paté-Cornell, 2012; Aven, 2016). Despite this progress, most DRA approaches remain limited to technical variables, with minimal integration of managerial or societal factors.

#### **4.1.2- Domino effects, interdependencies, and emerging complexity**

One of the most studied manifestations of complexity in the chemical and energy sectors is the domino effect, where an initial accident triggers secondary events, magnifying the overall impact (Khan & Abbasi, 1998; Reniers & Cozzani, 2013).

Domino modeling has advanced from deterministic threshold methods to probabilistic and Monte Carlo simulations that assess escalation likelihoods across storage units and process areas. Nonetheless, these models still treat systems as mechanistic, neglecting human, organizational, and systemic feedbacks that contribute to escalation.

Recent works (Dueñas Santana et al., 2024; 2025) demonstrate that domino and escalation behaviors can be better understood using Systems Thinking and System Dynamics (SD) modeling. By representing hazard propagation, safety culture, and response mechanisms as interdependent variables, it becomes possible to analyze both direct physical interactions (e.g., thermal radiation leading to vessel failure) and indirect systemic effects (e.g., delayed maintenance, policy inertia, or budget erosion) within a unified framework.

Moreover, modern energy infrastructures exhibit strong interdependencies between sectors. The integration of renewable energy, hydrogen production, and chemical storage creates feedback-rich networks where risk propagates not only through physical proximity but also through economic and regulatory channels (Laimon et al., 2022). For example, the shutdown of a hydrogen storage facility due to safety concerns can affect regional energy supply, economic performance, and public perception—demonstrating how risk interconnectivity transcends traditional plant boundaries.

#### **4.1.3- From conventional risk models to systemic safety management**

Traditional safety management models, such as the Swiss Cheese Model (Reason, 1997) or bow-tie analysis, conceptualize accidents as linear failures of successive barriers. While intuitive and widely adopted, these models fail to represent the feedback-driven erosion of barriers and the adaptive behavior of organizations.

Recent work has emphasized the need for resilience-oriented safety management, where safety is viewed not merely as the absence of failure but as the ability to anticipate, adapt, and recover (Hollnagel et al., 2006; Le Coze, 2019). Systemic approaches to safety management employ Systems Thinking principles to represent interactions among technical, human, and organizational elements. For example, Bouloiz et al. (2013) developed a system dynamics model linking safety investment, culture, and accident rates, revealing how budget reductions lead to delayed and amplified increases in risk. Similarly, Dueñas Santana et al. (2024) demonstrated that feedback between safety culture and risk perception is critical for sustaining proactive safety performance in hydrogen and energy systems.

These studies highlight a growing recognition that safety is an emergent property of complex socio-technical systems rather than a static outcome of isolated interventions. The transition toward sustainability and clean energy intensifies this complexity, requiring integrative frameworks that incorporate risk, management, and sustainability within a single dynamic architecture.

#### **4.1.4- Sustainability in the energy sector from a Systems Thinking perspective**

In this section, a brief literature review of the most relevant studies which proposed a solution from a Systems Thinking perspective to sustainable energy production is exposed. This subsection aims (1) to understand that a Systems Thinking has been effectively used for decision-making in sustainable development, and (2) to demonstrate that despite this use, there



are still complex concerns that have not been addressed, highlighting the importance of our proposed integration of paradigms.

A new conceptual model was developed by Laimon et al., (2022) for studying the energy sector in Australia by analyzing the potential consequences of current energy development policies. One important conclusion was that while the classical linear thinking approach focuses solely on symptom treatment with quick-fix solutions, disregarding the intricacies and challenges of sustainability in the energy sector, the Systems Thinking approach takes a different path.

This idea was additionally supported by the review article of Rebs et al. (2019) and the research study by Guzzo et al., (2023). The authors concur that system dynamics modeling is a potent method for representing the intricate interplay and dynamic connections among various causal factors in sustainability and that the dynamic complexity arises from the interdependent relationships among system elements and how these interactions evolve.

Moreover, there are some previous studies which explored the sustainability of the energy sector linked to cleaner production. Silva et al., (2020) proposed a new index for computing energy sustainability considering five main dimensions: environmental, economic, social-cultural, political-territorial, and technological. The utilization of green hydrogen synergy has the potential to foster the clean and sustainable growth of offshore and coastal industries by creating new opportunities for clean energy expansion (Kumar et al., 2023). Furthermore, Saleh and Brem, (2023) addressed the question: “How can creativity foster sustainability?” through an exhaustive literature review of the sustainability literature. Their research revealed four distinct levels of creativity for sustainability, namely, at the individual, community, organizational, and institutional levels.

Overall the Systems Thinking paradigm has been applied to the sustainability of the energy sector, using Causal Loop Diagrams and System Dynamics-based models (depending on the research aim as described above). However, previous studies focused more on individual concerns linked to energy sustainability rather than on providing a holistic view of the problem. That is why the complexity paradigm is needed as there is an emergent behavior (from the interactions among the economy, society, and the environment) directly linked to the sustainability paradigm that needs to be addressed.

Even when a Systems Thinking approach has been applied to achieving Sustainability in these aforementioned studies, there are still many complex constraints and interdependencies that were not considered before. For this reason, a new framework like FRISE is needed.

#### 4.1.5- Gaps and research directions

Despite substantial advances, several research gaps remain evident in the literature:

1. Fragmented integration – Most risk and safety models remain domain-specific (technical, organizational, or environmental) and lack the cross-modular integration necessary for holistic sustainability assessment.
2. Static probabilistic assumptions – Many approaches treat failure probabilities as constant, failing to represent degradation, maintenance cycles, or adaptive policy effects.
3. Limited socio-technical scope – Human and cultural factors are typically treated qualitatively rather than integrated dynamically into quantitative models.
4. Weak sustainability coupling – Economic, environmental, and social consequences are often analyzed independently, without dynamic feedbacks among them.
5. Lack of interdisciplinary frameworks – Few studies combine Systems Thinking, Complexity, and Sustainability paradigms to form a unified methodological structure.

These gaps justify the development of the FRISE framework that integrates the technical, managerial, and sustainability dimensions of risk management. By embedding ALARP, CBA, EI, and LQI into a System Dynamics–based modeling architecture, the present thesis seeks to address these deficiencies and provide a dynamic, interdisciplinary, and policy-relevant tool for decision-making in the chemical and energy sectors.

The literature in the chemical and energy sectors demonstrates a progressive evolution from static risk quantification toward dynamic and systemic modeling. Nevertheless, the transition to cleaner and more sustainable energy systems exposes the limitations of current practices, which often fail to capture feedbacks, time dependencies, and interdependencies among safety, sustainability, and societal dynamics.

By adopting a Systems Thinking approach under the Three-Paradigm (3P) model, this research builds upon the existing body of knowledge while extending it to encompass sustainability-oriented decision-making. The next section (3.2) examines in greater depth the hydrogen economy and safety literature, highlighting the systemic challenges associated with hydrogen production, storage, and adoption, and illustrating how the proposed framework can address these emerging complexities.

## **4.2- Hydrogen economy and safety: production, storage, and adoption challenges**

In this section, a comprehensive literature review about current hydrogen production and storage technologies, hydrogen safety, hydrogen sustainable challenges, and some facts related to the economic and environmental impacts of hydrogen production.

One of the most crucial challenges nowadays in the energy sector is the hydrogen economy. In this regard, hydrogen enrichment represents one of the most efficient practices for sustainable hydrogen energy. In other words, adding hydrogen to a mixture of other fuels is a ready alternative that can be a pathway toward a hydrogen economy in the near term.

Hydrogen energy content at the higher heating value is 141.8 MJ/kg (298 K) and at lower heating value is 120 MJ/kg (298 K), which are 3.2 and 2.7 times higher than the heating value of gasoline (44 MJ/kg at 298 K) respectively. However, liquid hydrogen possess four time less energy density by volume than gasoline (8 MJ/l-hydrogen vs 32 MJ/l-gasoline). Thus, hydrogen gas has a good energy density by weight, but poor energy density by volume; so it requires a larger tank to store than hydrocarbons. The relative low ignition temperature provokes that the major risk is related to its usage. Finally, it has the ability to escape from materials due to the small molecule size and destructive capability, which is well-known as hydrogen embrittlement (mechanical degradation and failure in the point of leakage of some materials) (Dawood et al., 2020; Jafari et al., 2012; T. Khan et al., 2022; Rivkin et al., 2015; Wei et al., 2022).

The hydrogen value chain includes the following stages: production, storage, transport, and distribution to the final user. Brown/grey hydrogen production pathways coupled with CCS systems has emerged as the technology with the lowest total cost including externalities. CO<sub>2</sub> can be separated via gas absorption, gas adsorption, membrane technology, and cryogenic separation; and this can be used or stored. On the one hand, CO<sub>2</sub> emissions can be considered as a resource for some new industrial processes instead of an unwanted by-product and this can act as a spur to capture CO<sub>2</sub>. On the other hand, developing a market for CO<sub>2</sub> could be controversial because it might discourage investments in renewable hydrogen production. With respect to CO<sub>2</sub> storage systems, there are many issues due to technical barriers and social acceptability. Underground CO<sub>2</sub> sequestration in geological formations is the most mature technique with a capacity range between 5000 and 25 000 Gt of CO<sub>2</sub>. However, even if the storage capacity is large, it is finite, therefore, it is not a sustainable process over time, and there is a leakage risk as well from the caprock. Additionally, other concerns such as the

induced seismicity is associated with underground storage of CO<sub>2</sub>, despite this is unclear because of the lack of sufficient CCS projects, it could contribute to the negative impact on the perception of some stakeholders and could lead to potential protests in society. Another pilot-scale technology for carbon sequestration is carbon mineralization of mafic and ultramafic rocks, which has the potential to store around 60 million of Gt of CO<sub>2</sub> in solid form, and this choice is promising in terms of safety (Lagioia et al., 2023; Mohammadfam & Zarei, 2015; Moradi & Groth, 2019; Okolie et al., 2021; Ren et al., 2013).

Nowadays, 120 Mt of hydrogen is produced per year. From them, 75 Mt correspond to the pure hydrogen (39 Mt in refining, 33 Mt for ammonia production, and less than 0.01 Mt for fuel cell electric vehicles); and 45 Mt is being mixed with other gases (CO and synthetic gas-syngas) for methanol production (14 Mt) and for the direct reduction iron making and other industrial processes (source of high-heat). Around 98% of total current hydrogen is obtained from the reformation of methane or the gasification of coal or similar materials of fossil-fuel origin (such as pet coke or asphaltene). Only about 1% of this hydrogen produced from fossil fuels, is coupled with carbon capture and storage technology (CCS). Around 1.9% of hydrogen is produced as a bi-product of chlorine and caustic soda production. And only 0.4% of hydrogen is obtained via electrolysis of water powered by renewable electricity. Hence, the 98% of global hydrogen production is emissions intense, generating around 830 Mtpa of CO<sub>2</sub> (Amin et al., 2022; Annaswamy et al., 2023; Chai et al., 2021; Cozzi & Gould, 2019; Global CCS Institute, 2020).

#### **4.2.1- Hydrogen production and storage pathways**

Grey hydrogen (Grey-H<sub>2</sub>) is mainly produced using the reforming of fossil fuels; therefore, it generates a huge amount of industrial waste gases and causes serious environmental pollution. Blue hydrogen (Blue-H<sub>2</sub>) is an improvement of the Grey-H<sub>2</sub> production adding a carbon capture and storage technology, despite this, it still emits certain carbon emissions. Green hydrogen (GH) is a form of clean energy with low-carbon emissions production method and it is mainly produced by electrolysis of water using renewable energy. Additionally, GH does not generate any environmental pollution in the whole process of production. That is why, transition from Gray-H<sub>2</sub> and Blue-H<sub>2</sub> to GH is the current idea for hydrogen production development. Moreover, GH is identified as an energy source that can help to the decarbonization of the energy sector because it can be transformed to heat and electricity without carbon emissions in the process; and it can be used as an alternative energy carrier with a wide range of applications. Furthermore, GH solves in an indirect way the randomness of

renewable energy power output. Despite these facts, GH production has a high cost compared to other hydrogen production pathways and to fossil fuels. This high production cost is mainly due to the cost of electrolyzers and the high electricity price. In order to reduce the GH production cost, governments have implemented different subsidy policies for encouraging this production pathway (Aditiya & Aziz, 2021; Castelvechi, 2022; H. Li et al., 2022; Nemmour et al., 2023; Yue et al., 2021).

Lagioia et al., (2023), after an exhaustive literature review, proposed a three-level classification for the main hydrogen production technologies in terms of maturity and competitiveness. The only one technology which has high maturity and high competitiveness nowadays is the fossil-based production coupled with carbon capture. Electrolysis has a high level of maturity but a medium level of competitiveness. Biomass gasification and biogas reforming have both a medium level of maturity and a low level of competitiveness. Other technologies such as photolysis, photoelectrolysis, the thermochemical water splitting cycles, dark fermentation and photo fermentation are in a low level of maturity and competitiveness.

The main production methods for hydrogen using natural gas are SMR, POX, and ATR. SMR is a well-established technology that represents the 50% of the world's total hydrogen production and 95% of the USA hydrogen production (Chau et al., 2022). The advantages of this production pathway is related to its large-scale capabilities and relatively inexpensive production costs. On the other hand, it is an energy-intensive method with high carbon emissions. Partial oxidation reaction (POX) is an attractive exothermic process which reacts hydrocarbons (such as methane) with oxygen to produce hydrogen. In this technology it is necessary a close monitoring of the temperature for preventing safety concerns (such as thermal runaway). Autothermal reforming (ATR) combines the principles of both SMR and POX into one same unit where the unreacted methane goes through a SMR product process by reacting with oxygen and water in a bed reactor using a catalyst. The main advantages of the ATR are that this method has an inexpensive catalyst usage, absence of energy input, and the combination of the 3 components in only one stage reducing the number of steps (Kaur & Pal, 2019; Moradi & Groth, 2019; Ren et al., 2017; Sazali, 2020).

For hydrogen production from electrolytic sources, the main technologies are the alkaline electrolysis (AE), proton electrolyte membrane (PEM), and solid oxide electrolyzer cell (SOEc). AE involves an alkaline electrolyte such as KOH or NaOH, where the water reduction occurs on the cathode surface (nickel) and produces hydrogen gas and two hydroxyl ions. Then,

these hydroxyl ions diffuse through a diaphragm to the anode and are oxidized. Industrial alkaline electrolyzers use nickel-based catalysts because of their availability and cost effectiveness. However, AE has cost and safety concerns, because of the use of highly corrosive chemicals (SMR production cost is significantly lower than AE). PEM electrolysis eliminates the necessity for highly corrosive electrolytes such as KOH, using polysulfonated membranes. Also, the operation occurs at higher pressures which reduces the energy required for it and it has competitive capabilities in the design and a faster response time than AE. SOEc is a relatively new technology that is yet to be commercially available. SOEc uses conductive ceramics as catalysts despite the traditional metal (such as nickel). SOEc can operate even at higher pressure and temperature, which improves the thermodynamic efficiency of the water-splitting reaction. This leads to energy savings which directly reduces the production costs. On the other hand, SOEc requires specialized and expensive materials with short life-span for normal operations (Ding et al., 2023; Kopp et al., 2017; B. Li et al., 2021; Vidas & Castro, 2021).

Finally, hydrogen can be obtained from alternative sources such as steam iron process, sulfur-iodine (S-I) cycle, copper-chlorine (Cu-Cl) cycle, and via nuclear technologies. The production using steam iron process has as main concern the lack of efficiency and the usage of coal and oil. The S-I cycle is attributed to coupling with nuclear reactors to reduce operating costs, and the issues are related to the use of corrosive chemicals, and high temperature conditions. The attractiveness of the Cu-Cl cycle is that operation occurs with low voltage and lower grade heat, also the recycling of all the materials which is environmentally friendly. However, it uses corrosive chemicals and there are concerns related to the optimization and integration of the electrolytic design. Moreover, nuclear fission is proposed as a thermochemical process for hydrogen production which is highly efficient and lowers the electricity cost, but it has the classical safety concerns of the nuclear industry when failure occurs (Abdelkareem et al., 2022; Chau et al., 2022).

Hydrogen can be compressed, liquified, or even accumulated in liquid-state carriers and solid-state storing means. Nowadays, liquid-state hydrogen carriers are the most promising pathway, together with compressed hydrogen storage in salt caverns. Regarding the deployment of the hydrogen produced, pipelines are the best option for distances up to 1500-3000 km, while LOHC and ammonia transport by ship are preferred for longer distances. Moreover, if it were possible, the use of ammonia directly without converting it back to hydrogen, would be the

most cost-effective choice (Lagioia et al., 2023; Tarkowski et al., 2021; Usman, 2022; Yue et al., 2021).

According to the research of Lagioia et al., (2023) liquid carriers are the only technology which has high maturity and competitiveness. Compression in tanks and liquefaction exhibit a high maturity level and medium competitiveness, whereas compression in pipelines and geological formations exhibit high competitiveness but only medium maturity. Other technologies such as porous materials and metal hydrides have both low levels of maturity and competitiveness.

Efficiency losses occur at every single stage of the hydrogen supply stage. With respect to the production step, it is pretty difficult for GH to compete with brown/grey hydrogen and even blue pathways, in terms of energy efficiency. Electrolyzer efficiency is only 50-70%, while other technologies allow an efficiency of up to 85%. Most of hydrogen is produced via SMR, which coupled with CCS triggers a reduction rate of up to 95% in GHG emissions, but provoking a reduction in the process efficiency of 5-14% (Global CCS Institute, 2021; Lagioia et al., 2023; Newborough & Cooley, 2020).

Hydrogen needs to be stored in traditional compressed or liquid deposits and tanks (because of its low volumetric energy density), or by means of chemisorption and physisorption on surfaces, in solid materials and in liquid carriers. Liquid hydrogen possess a high volumetric density, but it requires an energy-intensive process, consuming about 36-64% of the hydrogen energy content. Transport via pipelines is better for medium distances, but the losses related to the use of current existing natural gas networks could reach up to 20%. Solid-state storage leads to greater efficiency, but most of these technologies are still immature. Finally, hydrogen can be also stored by conversion in carriers such as methanol, methane, and ammonia, and thus their use requires an additional stage for reconvertng them into hydrogen which leads to more energy losses. Depending on its application, hydrogen can be used as feedstock, burned, or transformed into electricity via fuel cells. In general, the alkaline fuel cell is the most efficient with 50-60% efficiency, followed by PEM (40-60% efficiency) which is actually the most used because of its suitability for transportation applications (Abohamzeh et al., 2021; Hafsi et al., 2022; Hassan et al., 2021; Lagioia et al., 2023; Lamb et al., 2019; Megía et al., 2021; Yue et al., 2021).

#### **4.2.2- Hydrogen safety**

For the safe operation of hydrogen energy-based systems, especially high-pressure operation, the design must consider the hydrogen embrittlement. In terms of strength design, the

characteristics of hydrogen gas should be included, considering the high diffusivity, the fast leakage, and a wide range of hydrogen concentrations within the explosion limit. Moreover, issues related to human errors should be eliminated (Kotchourko et al., 2014; Sasaki et al., 2016; Xu et al., 2019).

Hydrogen is characterized by a low molar mass (which indicates low gas density), lack of odor and color (which increases difficulty of detection), and the possibility of flaming (when air is mixed with a hydrogen volume fraction of only 4%). The minimum ignition energy, ignition limit range and energy density of hydrogen indicate that it can be easily ignited and could release a huge amount of thermal energy. Due to its small molecular volume, hydrogen can easily diffuse into steel and other metals in large quantities which triggers a reduction in the material strength and embrittlement (Kubler et al., 2016; Najjar, 2013; Saffers & Molkov, 2014; F. Yang et al., 2021).

In general, safety is of paramount importance in the alkaline and PEM electrolyzers. There are three main stages which should be considered in both technologies: water purification, electrolysis, and separation; which require a careful attention for avoiding serious accidents. The water treatment unit deionizes and purifies the tap water, and then, removes excess heat using a heat exchanger. The purification unit in general is coupled with a heat exchanger for regulating the operating temperature; and after water treatment, electrolysis occurs. Alkaline electrolyte possess safety concerns due to the usage of corrosive chemicals at a 20-30% concentration. PEM issues are related to cross-permeation across the membranes which could trigger disastrous results due to the formation of flammable mixtures (at the time that hydrogen tries to recombine with oxygen). This effect is amplified at higher pressure conditions and there are also risks of material defects or deterioration and sensor failures. Thus, it is extremely important continuous monitoring of process conditions and water distribution for performing electrolysis (Acar et al., 2018; Chau et al., 2022; F. I. Khan et al., 2004; Thengane et al., 2014).

The hazards associated with hydrogen can be categorized into: physiological (asphyxiation, thermal burns, frostbite, hypothermia, and overpressure injury), physical (component failures due to low temperature deterioration of mechanical properties, thermal contraction, and hydrogen embrittlement), and chemical (burning or explosion). Among all of them, the primary hazard is producing a flammable or explosive mixture with air (Fotis Rigas & Paul R. Amyotte, 2013; Paul R. Amyotte & Fotis Rigas, 2013).



US Department of Energy reported 120 hydrogen incidents between 1999 and 2019. In general, laboratories are the most accident locations (38.3% of total incidents), followed by hydrogen fueling stations and hydrogen-related commercial facilities, accounting for 10.6% and 9.0% respectively. Human error are most related to incorrect disassembly, assembly, movement, and replacement due to unconscious or unintentional mistakes. Also, damages are generally property loss (41.83%), and in a minor proportion cause human injury (10.27%), and fatalities (5.32%). The fatality rate of hydrogen incidents was twice that of the natural gas incidents (Najjar, 2013; Rigas & Amyotte, 2012; F. Yang et al., 2021).

Dueñas Santana et al., (2022) developed a new index (Fire and Explosion Economic Losses *FEEL*- Index) for quantifying the economic impact of accidents in hydrocarbon facilities. This model can be applied also to hydrogen systems and can be expanded using a systems thinking approach.

In general, among hydrogen, methane and gasoline, gasoline seems to be the easiest and therefore the safest fuel due to its higher boiling point, lower volatility, and narrower flammability and detonability limits. However, hydrogen and methane can also be stored in a safe way using current technology (Fotis Rigas & Paul R. Amyotte, 2013; Paul R. Amyotte & Fotis Rigas, 2013).

#### **4.2.3- Hydrogen sustainable production goals. Current status and challenges**

The Climate Change Performance Index (CCPI) compares 60 countries plus the European Union (EU) which are together responsible for more than 90% of the Global Greenhouse Gas (GHG) emissions. The climate change performance is assessed according to standardized criteria and the final results are ranked. Every country has its own mitigation targets according to the Paris Agreement in 2015. The global community highlights the fact that there is a necessity to limit the global temperature rise in a value below to 2 °C or even 1.5 °C (Burck et al., 2022b).

The CCPI evaluated how far countries have come in achieving this goal. Therefore, it helps to judge the climate policy for each country, their recent development, current levels and well-below-2 °C compatibility of GHG emissions, renewable energy use and their targets for 2030 (Burck et al., 2022b, 2022a).

The climate change performance is computed using the following four categories: (1) GHG emissions (40% of overall score), Renewable Energy (20% of overall score), Energy Use (20% of overall score), and Climate Policy (20% of overall score). For the category related to GHG

emissions, the index considers the current and the past trend of GHG per capita, the current level of GHG emissions per capita compared to a well-below-2 °C compatible pathway and the GHG emissions reduction 2030 target. Renewable energy includes the current share of renewables per TPES, the development of energy supply from RE sources, the current share of renewables per TPES compared to a well-below-2 °C compatible pathway, and the RE 2030 target. The Energy Use category considers the current level and the past trend of energy use (TPES per capita), the current level compared to a well-below-2 °C compatible pathway and the TPES/capita 2030 target. Finally, the climate policy incorporates the use of national and international climate policies (Burck et al., 2022a; IRENA, 2022d).

The results are shown in a world-map, where no country performs well enough in all index categories to achieve an overall very high rating in terms of the CCPI. This means, that the top three places in the overall ranking remain empty in 2022. The highest ranked country is Denmark (76.67), but it does not perform well enough to achieve an overall very high rating. Four G20 countries are among the high-performing ones: United Kingdom (7<sup>th</sup>), India (10<sup>th</sup>), Germany (13<sup>th</sup>), and France (17<sup>th</sup>). Eleven countries receive a low or very low overall rating means that G20 are responsible for about 75% of the world's greenhouse gas emissions. Saudi Arabia is the worst-performing country among the G20, ranked 63<sup>rd</sup> (Burck et al., 2022b).

The European Union (59.21) drops six places to 22<sup>nd</sup> in 2022, and no longer is among the high performers because the EU and its 27 member states are responsible for the EU's outcome. Denmark and Sweden are the best-performing EU-countries (ranked 4<sup>th</sup> and 5<sup>th</sup> respectively); and other five countries are high performers. The Netherlands is one of the most improved countries (up 10 ranks) but still performing at a medium level. Among the worst-performing countries are Slovenia, Czech Republic, Poland, and Hungary, each one receiving a very low rate (Burck et al., 2022b).

In general, the EU increased its Nationally Determined Contribution to a domestic net emissions reduction target of at least 55% up from at least 40%. Even though this is not yet completely compatible with a Paris Agreement, it reflects a substantial effort to deal with its emissions gap. Additionally, proposed reforms under the “Fit for 55” policy package, which plans to ensure a 55% emissions reduction by 2030, will be important for addressing the misalignment and for achieving the 2050 climate neutrality target.

GH is the most suitable hydrogen production pathway for achieving a fully sustainable energy transition worldwide. The most established technology choice for producing GH is water

electrolysis using renewable electricity, water electrolysis represents about 4% of the H<sub>2</sub> production, but at the state of the art, one of the main obstacles to the penetration of this technology is the low efficiency of the process. GH production is consistent with the net-zero route, allows the exploitation of synthetic gas from sector coupling, decreasing the technology costs and providing flexibility to the power system. Additionally, low variable renewable energy (VRE) cost and technological improvement are decreasing the production cost of GH. That is why, GH from water electrolysis has gained an increased interest in the last years (Asif, 2022; Capurso et al., 2022; De Risi et al., 2023; Ourya et al., 2023; Ratnakar et al., 2021).

In general, hydrogen contributes to energy security because it provides another energy carrier with different supply chains, producers and markets; it can diversify the energy mix and improve the resilience of the system; it can also reduce air pollution when used in fuel cells, with zero emissions other than water; and finally, it can promote economic growth and employment creation due to the huge investment needed for infrastructure.

The utilization of GH pathways have the following drivers according to IRENA, (2022b, 2022c). First of all, with a clear tendency to decrease, the cost of solar photovoltaic and wind electricity, the production of GH is increasingly attractive, therefore the major cost driver for GH is the cost of electricity. Additionally, the cost of electrolysis has fallen by 60% since 2010, which implies a direct decrease of the GH production cost from a range of USD 10-15 /kg to USD 4-6 /kg. Also, the scalation of GH pathways will make them more attractive as production costs decrease. Moreover, there are benefits for the power system, such as more flexibility. Hydrogen is suitable for long-term, seasonal energy storage, and complementing hydropower plants. Therefore, GH supports the integration of higher shares of VRE into the grid, which increases the cost-effectiveness and the system efficiency. Another driver is the GH helps to government objectives for net-zero energy systems (more than 120 countries have announced net-zero emissions goals). The broader use of hydrogen itself in the conversion of it to other energy carriers and products (such as ammonia, methanol and synthetic liquids) takes advantage of synergies to decrease GH costs. Countries with large renewable resources could receive more economic benefits as they might become net exporters of GH in a global hydrogen economy. Finally, GH could receive the interest of multiple stakeholders in both public and private sectors, developing new partnerships for faster collaborations and coordination of efforts.

However, the role of GH production in local or global energy transition scenarios differs greatly due to many different factors. Firstly, not all scenarios address the same GHG reduction target, in general, the more ambitious the GHG target, the larger is the GH expected to be produced in the system. Secondly, not all scenarios rely on the same type of policies, for example the removal of fossil fuels subsidies would increase the space of a carbon-free solutions. Thirdly, the technology options which are available are different among scenarios, in the sense that scenarios that give greater weight to the sustainability challenges require a larger amount of GH. Moreover, the more end uses for GH included in a scenario, the larger will be the use of GH because it provides more flexibility for addressing the decarbonization targets and faster development. Finally, the cost assumptions, additionally, differ among the scenarios (capital and operating costs); in general, those with the highest ambitious for GH development correspond to the most optimistic assumptions for cost reduction (Abraham et al., 2023; Faye et al., 2022; Ghisolfi et al., 2022; Ishaq et al., 2022; Rasul et al., 2022).

Furthermore, the main barriers for adopting GH production pathways are the following: high production costs, lack of dedicated infrastructure, energy losses, lack of value recognition, and the need for ensuring sustainability. GH produced using electricity from an average VRE plant (2019) is around 2-3 times more expensive than Grey-H; and the adoption of GH technologies for end uses is expensive as well (for example vehicles cost is 1.5-2 times more). There are only about 5000 km of hydrogen transmission pipelines around the world, compared with more than 3 million km for natural gas, therefore the infrastructure for GH distribution is really limited. Also, there are 470 hydrogen refueling stations around the world, compared with more than 200 000 of gasoline and diesel refueling stations in the USA and EU. One of the challenges associated with the development of hydrogen fueling stations is ensuring their safe operation. Regarding the energy losses, GH posses a significant energy loss at each stage of the value chain (about 30-35% of the total energy is lost, and additional 40-50% in fuel cells). In general, the total energy loss depends on the final use of the GH, and the larger the energy losses are, the more renewable energy capacity is needed for GH production. Moreover, there is no available a GH market, in the sense that there is no green steel, green shipping fuel and basically no valuation of the lower GHG emissions that GH can trigger; so there are no internationally recognized ways for distinguishing between the GH from the Gray-H. Furthermore, the only way for ensuring that the GH is without any doubt “green” is using electricity from a renewable energy plant; thus the amount of the electricity generated from fossil fuels could be a barrier

(El-Shafie et al., 2019; Ikram et al., 2021; Markert & Kozine, 2012; Olabi, 2021; S. Y. Park et al., 2011; Tashie-Lewis & Nnabuiife, 2021; Y. Wang et al., 2022; West et al., 2022).

GH has the huge task of competing with both fossil fuels and other shades of hydrogen. The GH production cost depends on the investment cost of the electrolyzers, their capacity factor, and the cost of electricity produced from renewable energy. Also, the electricity component in the hydrogen final cost depends on the efficiency of the process itself. Therefore, lower electricity cost is needed (in the order of USD 20/MWh) to produce GH at competitive prices with Grey-H. That is the reason why the main role of many GH producers nowadays is to reduce these costs using different strategies. Overall, once electrolyzers costs have fallen, it will be possible to use higher-cost renewable electricity to produce cost-competitive GH. Regarding the transportation costs, at low volumes (compressed hydrogen) the cost is around USD 3.5/kg (1000 km); while for large volumes, shipping green ammonia is the lowest-cost choice and adds only USD 0.15/kg of hydrogen. Similar low costs are reported for transportation through large pipelines (around 2000 tonnes/day), in general, the cost of transported hydrogen by pipeline is one tenth of the cost of transporting the same energy as electricity (EPO & IRENA, 2022; Ozturk & Dincer, 2021; Shafiei et al., 2017).

The EU strategy is focused on an integrated view of the hydrogen value chain, and determines a supporting governance system and policy framework to promote hydrogen deployment. The ambition of the EU policy-makers is to make the European industry a global leader, both in GH infrastructure and zero-carbon heavy industry. Therefore, this strategy identifies GH as the only shade of hydrogen compatible with a net-zero emission system. The strategy sets a number of actions such as regulatory changes and supporting investments for a kick-start deployment and it is divided into three main stages. The first stage (2020-2024) focuses on decarbonizing applications which already use hydrogen and facilitating the uptake of GH in new end-use applications. Also, it is planned that the electrolyzer capacity scale-up to 6 GW for producing up to 1 Mt/year of renewable hydrogen. The hydrogen supply is generally local in order to avoid the need for extensive infrastructure expansion, and the existing hydrogen production sites are coupled with carbon capture. The second stage (2025-2030) is planned for scaling-up the electrolyzer capacity to 40 GW in EU countries for producing up to 10 Mt/year of renewable energy. Additionally, 40 GW of capacity is planned to be produced in neighboring countries. In this phase, the hydrogen transportation will require a European grid infrastructure which could be based on the existing natural gas. In the third stage (2030-2050) GH reaches maturity at large scales across all the sectors, where other energy choices are more expensive than the

GH production and utilization. The vast majority of hydrogen produced today is the result of methane and natural gas industrial reforming and dehydrogenation at high temperature. Overall, for getting the 2030 target is estimated an investment of EUR 24-42 billion for electrolyzer capacity, plus EUR 220-340 billion for 80-120 GW of additional renewable power generation capacity, EUR 65 billion for infrastructure development, and EUR 11 billion for retrofitting existing natural gas stations (Gudlaugsson et al., 2022; IRENA, 2022f; Sasaki et al., 2016).

Moreover, IRENA, (2022d) proposes a number of evolving policies to support GH divided into three main stages. The first stage is related to the technology readiness where the highest barrier is the cost. Here, hydrogen is produced on-site with really limited infrastructure development. Then, the main role of policy-makers is to accelerate and encourage the development of electrolyzers. Also, there are important short-term policies which help to close the gaps between the investment and operational costs such as research and development funding, risk mitigation policies and co-funding of large prototypes and demonstration projects. One major concern in this first phase is the necessity to ensure sustainable GH production, and for this, supportive government systems and guidelines need to be present. The second stage consists of market penetration policies. At this stage some applications are operational and able to prove what GH can really do and at what cost. Scaling-up, and benefits from synergies between applications will help to reduce costs and cover the profitability gap. Additionally, the first international trading routes for hydrogen are established and a real global hydrogen market is created. For this, it is extremely necessary that sufficient renewable electricity generation is available, therefore, GH production does not displace more efficient direct electrification. In the third stage, GH becomes a well-known and widely used energy-carrier and it is close to achieve its full potential. It is also competitive both on the supply side and in its end uses. Thus, direct incentives are no longer necessary for most applications and private capital has replaced public support in drawing hydrogen growth. Furthermore, there the power system is decarbonized and only GH is being deployed which leads to a full flexibility in the energy sector, where most natural gas infrastructure has been already converted to transport pure hydrogen.

#### **4.2.4- Hydrogen economic and environmental facts and projections**

The Hydrogen Council, and industry group in Brussels estimated that the possible investment of USA would be around USD 240 billion by 2030; and USD 2.5 trillion per year by 2050 (Castelvecchi, 2022).

A crucial factor in determining the speed of the switch to clean hydrogen is the cost of the electrolyzers. Many organizations predicted that this cost will rapidly drop by more than two-thirds by 2030, due to the fact that electrolyzers are made in increasingly automated assembly lines, rather than built by hand. This is the main reason why analysts also forecasted that the cost of GH will drop to USD 1/kg in the future, even without subsidies such as tax breaks. Therefore, it will be competitive with Grey-H and other shades. Moreover, many studies concur that as demand grows, a huge proportion of it will be achieved using BH for the next decades (Castelvecchi, 2022; EPO & IRENA, 2022; Sun et al., 2022)

In the long-term, the biggest contribution of an hydrogen economy will be to slow global warming, but also to be a bridge across disparate activities such as electricity, construction, manufacturing and transportation; which will make cheaper to fully decarbonize all of them together rather than decarbonize separately. The crucial node in this idea is the energy generation (Castelvecchi, 2022; Mella, 2022; Yue et al., 2021)

In the USA, the Inflation Reduction Act has inserted a tax break of USD 3 for every kg of GH, in addition to other policies and funding for the gas. Also, Russia's aggression against Ukraine triggers a new sense of urgency. Without subsidies, clean-H<sub>2</sub> could be more expensive than their other dirty equivalents. Thus, it is necessary a reorganization of the economy for accommodating the hydrogen will lead to social repercussions (Castelvecchi, 2022; Pereira et al., 2022).

The interesting idea of storing renewable energy in hydrogen as an energy carrier would be a way for world decarbonization, decreasing the CO<sub>2</sub> levels in the atmosphere and other greenhouse gases. Therefore, the concept of a Hydrogen-based Energy storage Systems (HydESS) could be a cost-effective solution for large-scale RE storage, transport and export. HydESS are leading the way towards 100% renewable system energy economy which is called the hydrogen economy. With this, carbon-free energy generation and utilization can be achieved a prior. On the other hand, the fact of a full hydrogen dependent economy is really debatable and not realizable nowadays. Hence, there is the necessity of studying which policies really encourage a sustainable transition (Dawood et al., 2020; Gudlaugsson et al., 2022; Pinsky et al., 2020).

The renewable hydrogen possess the link between RE resources and the modernization of energy supply, transport industry and RE energy export. Regarding the safety of hydrogen, more than 70% of hydrogen-related accidents were because of organizational and human

factors. Hydrogen is non-toxic and lighter than air; so, it dissipates quickly after a release. The first safety concern is that if a leak goes to a confined space, it could eventually ignite and cause an explosion (Dawood et al., 2020).

Many authors concur that GH has the potential to decarbonize many industrial applications and it can serve as a clean energy carrier for storing RE and then can be used for a wide range of applications. However, according to Dawood et al., (2020) parallel development in the four corners of the HydESS is vital for achieving techno-economic feasibility. Hence, worldwide, the hydrogen economy is not proposed as a full replacement of the traditional fuels, but as a compliment for achieving a small and low carbon strategy in specific places and applications.

The hydrogen-based energy system is presented as four corners or stages (production, storage, safety and utilization) of a square shaped, integrating the interconnections and interdependencies among these main stages. The hydrogen production method and its associated specific technology are strongly dependent on the kind of energy, the feedstock and the end-use purity required. Moreover, the guarantee of origin is really important to classify hydrogen as a clean energy source. Dawood et al., (2020) proposed a new model called Hydrogen Cleanness Index coding which can be used for future research and development purposes.

The first corner of the square is related to hydrogen production. In general, hydrogen production pathways have been categorized into four main groups such as: electrolysis, photolysis, biolysis, and thermolysis (Abdalla et al., 2018). According to the research of Dawood et al., (2020) the current color coding model which refers to the different hydrogen production methods, fails to precisely determine how clean (low-carbon emission) is that hydrogen. The main reason of this statement is that this code fails to quantify how much GHGs are really emitted during the production process, other sub-systems and/or from the life-cycle of equipment used during these stages. Therefore, it fails to describe how deep is that cleanness assessment.

The selection of the hydrogen production pathway (HPP) must take into consideration the hydrogen fuel purity grade required by the endpoint use and purification technology inability. That is why, Dawood et al., (2020) proposed an innovative hydrogen cleanness index model which considers the least amount of GHG emissions associated with the Life Cycle Assessment (LCA). The cleanness of the HPP is computed by using life cycle cleanness of input energy, materials and equipment. This means that the hydrogen-containing materials (used to extract



the hydrogen) and the catalytic energy or materials which can add GHG emissions are included in the new index referring to the guarantee of origin. The innovative approach proposed used the concept of the color spectrum with cleanness percentage instead of a specific color. The results of this study can be used as a guide for policy makers, manufacturers and stakeholders.

Hydrogen shades are related to different production technologies, but they do not provide information about the safety standpoint for each pathway. Chau et al., (2022) proposed a new structured framework for the assessment of the most desirable hydrogen production technology depending on efficiency, safety, and infrastructure, by using a Multi-Criteria Decision Making (MCDM) integrated with an Analytic Hierarchy Process (AHP) and Life-Cycle Index (LInX) approach.

The modified MCDM framework is applied to the following production technologies: steam methane reforming (SMR), autothermal reforming, partial oxidation, alkaline electrolysis, polymer electrode membrane electrolysis and solid oxide electrolyzer cell processes. The study also proposes the use of Fuzzy set theory for addressing the subjectivity and uncertainty challenges in the data. In general, the research concluded that SMR is the most desirable technology based on the efficiency, safety, and infrastructure criteria. The authors found that despite the environmental advantage of technologies based on electrolysis, these exhibit higher uncertainties than non-renewable technologies such as SMR. Hence, this study addressed the challenge to find the current most desirable and safer technology for hydrogen production (Chau et al., 2022; Muselli et al., 2022).

Hydrogen is a clear potential energy-carrier for achieving a net-zero carbon emission and cleaner energy production which possesses a high energy density (120 MJ/kg) compared to common fossil fuels (gasoline 44 MJ/kg, liquified natural gas 49.4 MJ/kg). Notwithstanding, the average hydrogen production cost is at least 5 times higher than that of fossil fuels (USD 16.26/Gasoline Gallon Equivalent-GGE vs USD 3.09/GGE). Moreover, there are additional concerns in the storage and transportation of liquid hydrogen due to the lack of appropriate logistics and infrastructures. The usage of hydrogen as a fuel for mobile and remote applications will require significant research efforts in the development of chemically inert materials with high diffusion resistance for storing hydrogen in a safe and proper way. These efforts could involve using underground storage reservoirs to store the hydrogen. Developing a dedicated hydrogen infrastructure is necessary to release the full potential of this energy

carrier (Chau et al., 2022; COM, 2021; Markert et al., 2017; Qureshi et al., 2023; Ustolin et al., 2020; F. Yang et al., 2021).

In order to stop Global Warming (GW) it is required that the net GHG emissions fall to zero and remain at zero thereafter. However, many analysts concur that reducing emissions rapidly enough to remain within a 1.5 °C carbon target is basically impossible nowadays. In this sense Circular Carbon Economy (CCE) framework recognizes all the possible reduction choices. Circular Economy consists of three Rs: Reduce, Reuse, Recycle. It is an effective way for describing an approach to sustainable production considering the efficient utilization of resources and wastes. Notwithstanding, this concept is not sufficient to describe a wholistic approach for the complete mitigation of GHG emissions. This is due to the explicit lack of provision for the removal of carbon dioxide from the atmosphere (Carbon Direct Removal or CDR) or even the prevention of CO<sub>2</sub> once produced from releasing into the atmosphere, via carbon capture and storage (CCS). Therefore, the CCE adds a fourth R to Circular Economy: Remove. This report specifically focuses on the potential contribution of Blue Hydrogen (BH), (which has very low life-cycle CO<sub>2</sub> emissions) for climate mitigation. This is based on the fact that BH produced from fossil fuels with CCS can seriously contribute to the Reduce dimension of the CCE by displacing the use of unbated fossil fuels in the energy sector (Castelvecchi, 2022; Guzzo, Pigosso, et al., 2022; Guzzo, Rodrigues, et al., 2022; Kara et al., 2022; Mallick et al., 2023; Trevisan et al., 2023; Zapantis, 2021).

The virtue of hydrogen is that it produces zero carbon emissions at the point of use and it can be burned in turbines or used in fuel cells for electricity generation. Also, it can be used to power electrical vehicles, as a source of domestic and industrial heat, as a feedstock for many wide industrial processes, and to store excess energy generated by intermittent renewable electricity sources when supply exceeds demand (Fan et al., 2021; J. Gao et al., 2023; Keshavarz et al., 2023; Sakamoto et al., 2016; Weidner et al., 2023; Zapantis, 2021).

There is a range of production costs associated with clean hydrogen for both fossil fuels with CCS and renewable powered electrolysis. The key determining factors of cost are the price of coal or natural gas, and the quality of the renewable energy source (which impacts on the electricity price and capacity factor of the electrolyzers). In general, clean hydrogen produced from coal or gas with CCS (BH) has the lowest cost and therefore it is expected to remain so at least until 2030. Currently, technology is being developed to make electrolyzers more

efficient, cheaper and scalable up to market needs (EPO & IRENA, 2022; Lyons et al., 2021; Zapantis, 2021).

The overall cost of BH (produced from SMR with CCS) is around USD 2.40/kg H<sub>2</sub>. Producing hydrogen from coal gasification with CCS is more capital intensive than from SMR with CCS. Increasing the cost of coal from USD 0.43/GJ to USD 1.15/GJ increases slightly the production cost of hydrogen from USD 2.05/kg H<sub>2</sub> to USD 2.20/kgH<sub>2</sub> (IRENA, 2022a; Turner, 2004; Zapantis, 2021).

Overall, the cost of BH and GH is going to drop in the next years. The investment on larger facilities which belong to CCS hubs will benefit a scaling-up in this production and in CO<sub>2</sub> transport and storage, which can reduce the total unit cost of production. Moreover, industrial CCS hubs, where multiple facilities use common CO<sub>2</sub> transport and storage infrastructure, create business ecosystems, which reduces the counterparty risk and the cost of capital. Thus, better integration of hydrogen production with CO<sub>2</sub> capture components of the BH gives significant improvement and opportunities (Lyons et al., 2021; Zapantis, 2021).

Moreover, it is important to highlight that the availability of land, water, electricity, coal, gas, and pore space for CO<sub>2</sub> storage, will determine the best hydrogen production alternative in any specific location. This means that when abundant low-cost land or excellent renewable resources are not available, but coal or gas and pore space for geological storage of CO<sub>2</sub> is, BH will be the best choice for production (Lyons et al., 2021; Zapantis, 2021).

There are available well established policy options for promoting clean hydrogen production which can be grouped into the following recommendations. Firstly, it is important to define the role of BH for addressing national emissions reduction targets based on a rigorous analysis, and then, communicate this to the industrial sector and to the society as well. Then, the creation of a certain, and long-term, high value on the storage of CO<sub>2</sub>. After that, it is crucial the support related to the identification of geological storage reservoirs, to develop and promulgate specific CCS laws. Then, it is necessary to identify opportunities for CCS hubs where BH can be produced. And finally, to provide low cost finance and guarantees to reduce the total investment cost, and to provide materials and capital grants to BH projects (IRENA, 2022g; Oliveira et al., 2021; Zapantis, 2021).

Overall, BH has the additional advantage of allowing renewable and nuclear power to displace unabated fossil fuels electricity operation grids. Additionally, GH must also be deployed where there is a coincidence of excellent renewable energy sources. Finally, really strong and

sustained policies are required to incentivise investment on both BH and GH to support the achievement of climate mitigation targets (Zapantis, 2021).

In the wider context of the European Green Deal, the EU has set the carbon neutrality by 2050 as a target. Thus, it is extremely important to act in the energy sector, which represents more than 75% of EU GHG emissions. In 2019, estimated European brown/grey hydrogen costs were 1.5 €/kg and 2€/kg with CCS. Moreover, in the last 10 years, renewable hydrogen costs (electrolyzer costs) have recorded a reduction of 60%, costing on the range of 4.5 €/kg to more than 10 €/kg depending on the electricity source. In general, hydrogen is more expensive than natural gas or electricity because the production processes, storage, transport, and conversion stages are highly energy-intensive technologies (COM, 2020; Kelemen, 2021; Lagioia et al., 2023; Vautrin et al., 2021).

Meeting the demand for 2030 hydrogen applications for ammonia and methanol via low-carbon production will require 3020 TWh/year of renewable electricity (electricity generation net additions from renewables was about 512 TWh in 2020); or 323 m<sup>3</sup> of natural gas coupled with CCS (which represents around 10% of current global natural gas demand), capturing 450 Mt of CO<sub>2</sub> per year. For this purpose, it would be required additionally, the organization of 450 new CCUS projects by 2030 to manage this huge amount of CO<sub>2</sub>. Nowadays, 40 projects are under development (19 in Europe) with 9 Mt of hydrogen predicted production by 2030. Global capacity can reach 54-91 GW by 2030, with 22 GW in Europe; but only 7% of these projects are under construction. Moreover, if manufacturing capacity expansions are considered, it is expected an increase from 3 GW/year in 2020 to 20 GW/year in 2030. Regarding the transportation, hydrogen pipelines need to increase up to 4 times the current pipeline length (around 5000 km). Underground hydrogen storage in salt caverns is the preferred option, with mainly 4 sites operational and many different projects under current development (Holmes-Gentle et al., 2023; Lagioia et al., 2023; Scheller et al., 2023; Tarkowski et al., 2021).

Some studies forecast that the hydrogen will be the most competitive green solution by 2030 in a wide range of applications, and even that the introduction of a carbon tax will make GH production more competitive than Grey-H and BH. Overall, it is necessary to invest in technological innovation, and avoid paying attention to sectors which could be easily electrified, and for which the use of hydrogen will lead to inefficiency such as light-duty transport (Lagioia et al., 2023; Raman et al., 2022).

In order to achieve the increasing demand of the world for electricity, keeping the Earth clean, at least 10 TW of carbon-free energy need to be generated by 2050. The world's production of fossil fuels is predicted to reach a plateau soon and then decline. Nowadays, the energy infrastructure has many concerns, especially regarding from an environmental point of view due to the CO<sub>2</sub> and GHG emissions, air pollution, and therefore, an increase in GW by the burning of fossil fuels (Kannah et al., 2021; Mukelabai et al., 2022; Qureshi et al., 2023).

The worldwide hydrogen industry has a value of USD 420-500 billion per year, with an annual growth rate of 20%; but it is mainly related to the petrochemical industry, where USD 107 billion is spent on hydrogen generation. In the near future, hydrogen energy will seriously impact on the existence of human race. Hydrogen energy can end millions of fatalities related to CO<sub>2</sub> emissions and air pollution. Therefore, future profits will go to nations who invest in hydrogen technologies, impacting also on the economic autonomy of many countries (Qureshi et al., 2023; Shah, 2020; Tian et al., 2019).

The authors concluded that hydrogen cannot compete with natural gas as an energy carrier on a unit energy bases due to it is needed a process (SMR) for reforming natural gas into hydrogen. Additionally, natural gas supplies are becoming increasingly scarce, and significant financial investment is required to build an hydrogen industry large enough to meet the global demand. Moreover, it will be possible to generate, distribute, store and use hydrogen at prices that are competitive if CCS technology is adopted (Qureshi et al., 2023; Zanolatti et al., 2023).

#### **4.2.5- Hydrogen enrichment of methane and explosion risk**

One of the most feasible short-term strategies for accelerating hydrogen adoption is the hydrogen enrichment of natural gas in existing infrastructures. While this approach enables incremental decarbonization, it also increases explosion potential due to changes in flame speed, ignition energy, and detonation sensitivity. Experimental studies have shown that even small hydrogen fractions (5–20%) can significantly modify combustion properties, leading to increased overpressures and flame acceleration.

Dueñas Santana et al. (2025) applied Systems Thinking and System Dynamics to analyze these phenomena dynamically. Their model quantified the evolution of failure probabilities, domino effects, and risk escalation in pressurized vessels under hydrogen enrichment conditions. The study demonstrated that traditional event-tree analyses, which rely on fixed failure rates, underestimate the dynamic evolution of risk arising from material degradation and operational feedbacks.

By representing hydrogen enrichment as a feedback-driven process—where adoption incentives, safety investments, and failure probabilities interact—the study provided a more realistic picture of the systemic risks involved in transitioning to blended hydrogen–methane systems.

#### **4.2.6- Social acceptance and public perception of hydrogen systems**

Beyond technical risks, hydrogen safety is deeply influenced by social perception and institutional trust. Accidents involving hydrogen—though statistically rare—tend to attract significant media attention, shaping public attitudes toward technology acceptance (Cozzi & Gould, 2022). Public risk perception often diverges from quantitative risk estimates, emphasizing catastrophic potential over statistical probability (Slovic, 2010). Dueñas Santana et al. (2024) incorporated societal feedbacks—such as trust, communication effectiveness, and transparency—into System Dynamics models of hydrogen adoption. Their findings revealed that trust erosion can produce self-reinforcing loops: low trust reduces adoption rates, which in turn reduces investment and slows technological improvement, further diminishing trust. This dynamic underscores the necessity of coupling social and technical modeling, a key feature of the SOC module in the present thesis.

Hydrogen safety and adoption are also constrained by policy frameworks and infrastructural readiness. Current international regulations—such as ISO/TC 197 and the European Commission’s Hydrogen Strategy (EC, 2020)—are evolving but still fragmented across jurisdictions. Dueñas Santana et al. (2024) argue that regulatory uncertainty, combined with high capital intensity, produces policy delays that feedback negatively into innovation and investment cycles.

Infrastructure interdependencies further amplify systemic risks. For instance, hydrogen production from renewable sources depends on intermittent electricity supply, introducing variability in electrolyzer operation and safety-critical maintenance. Likewise, transportation and distribution rely on existing natural gas networks whose materials and designs were not optimized for hydrogen (Rivkin et al., 2015). These interactions call for a systems-level approach that simultaneously evaluates technical performance, policy incentives, and economic feasibility under uncertainty.

#### **4.2.7- Research gaps in hydrogen safety and sustainability**

The literature reveals several critical gaps that motivate the present research:

1. Fragmented modeling approaches – Most studies isolate technical risks from economic, environmental, or social dynamics.
2. Limited dynamic modeling – Few models explicitly represent feedbacks and delays governing hydrogen safety and adoption.
3. Insufficient integration of sustainability – Safety, profitability, emissions, and public acceptance are rarely analyzed in a unified framework.
4. Weak policy coupling – Regulatory effects and policy inertia are seldom included as dynamic variables in safety modeling.
5. Lack of cross-sectoral generalization – Most models are technology-specific and cannot be transferred easily to other sustainability-driven sectors.

Addressing these gaps requires a holistic, modular, and dynamic framework that connects safety management with sustainability metrics and policy levers. This thesis aims to fill this void by developing and applying the FRISE framework that can capture the multi-level interdependencies inherent in hydrogen systems and other energy infrastructures.

The evolution of hydrogen research illustrates the broader transformation of the energy sector—from linear, siloed analysis to systemic, integrated modeling. Hydrogen serves as both a technological and conceptual testbed for developing methods that can handle feedbacks between safety, economics, environment, and society. The reviewed literature demonstrates the potential of Systems Thinking and System Dynamics to model these interdependencies but also highlights the need for a generic, transferable framework that can unify these approaches across sectors.

The preceding analyses set the foundation for FRISE’s integrative philosophy: recognizing that the challenges across domains are systemic rather than sectoral, and that feedback-oriented modeling provides the most coherent means to unify risk, safety, and sustainability.

#### **4.3- Comparative overview of risk and safety across fields**

The preceding sections and Chapter (3) have reviewed the evolution of risk and safety modeling in three major domains—chemical and energy systems, hydrogen safety, and fire safety engineering (FSE). Although these domains differ in application, maturity, and regulatory context, they share a fundamental challenge: the need to reconcile safety performance with sustainability objectives in complex socio-technical environments.

This section compares the key features, modeling paradigms, and emerging challenges across these domains, highlighting their conceptual convergence toward a unified safety–

sustainability perspective following the idea of the FRISE framework. The analysis confirms that the limitations observed are not domain-specific but systemic, thereby justifying the development of a modular RA–SM–ECO–ENV–SOC framework capable of addressing interdependencies across sectors. Table 4.1 summarizes the dominant paradigms, modeling approaches, and integration challenges observed across the three reviewed sectors.

Across these domains, several common trends are identified:

1. A move from linear, probabilistic methods toward non-linear, feedback-oriented representations.
2. Growing emphasis on socio-technical factors—culture, perception, regulation, and trust.
3. Expansion from purely safety-focused frameworks toward integrated sustainability modeling.
4. Convergence of methodological tools—especially Systems Thinking and System Dynamics (SD).

A key observation from the cross-domain comparison is the emergence of Systems Thinking as a unifying paradigm. Across chemical, hydrogen, and fire safety systems, researchers are converging on similar tools and principles:

- Use of CLDs to represent causal structures.
- Adoption of System Dynamics to simulate feedback behavior.
- Application of multi-criteria decision anchors (ALARP, CBA, EI, LQI) to evaluate trade-offs.

This convergence is not coincidental—it reflects a collective recognition that safety, sustainability, and management systems are fundamentally interconnected and co-evolving. Systems Thinking provides the conceptual bridge to integrate these domains within a coherent analytical framework. Our research focuses precisely on developing this new framework named FRISE.

**Table 4.1- Comparative overview of safety and sustainability modeling across domains**

| Dimension       | Chemical / Energy Systems                                             | Hydrogen Safety                                        | Fire Safety Engineering (FSE)                        |
|-----------------|-----------------------------------------------------------------------|--------------------------------------------------------|------------------------------------------------------|
| System maturity | Established industrial sector with codified risk methods (QRA, HAZOP) | Emerging energy vector with evolving safety frameworks | Mature discipline transitioning from prescriptive to |



| Dimension                  | Chemical / Energy Systems                                            | Hydrogen Safety                                                        | Fire Safety Engineering (FSE)                              |
|----------------------------|----------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------|
|                            |                                                                      |                                                                        | performance-based design                                   |
| Dominant paradigm          | Deterministic and probabilistic RA, barrier management               | Systems Thinking and dynamic risk under uncertainty                    | Socio-technical and performance-based risk management      |
| Key modeling tools         | Fault/Event Tree Analysis, Monte Carlo simulation, Bayesian networks | Causal Loop Diagrams (CLDs), System Dynamics (SD), life-cycle modeling | Fire modeling, SD-based evacuation and design optimization |
| Typical hazards / risks    | Chemical releases, domino effects, process escalation                | Hydrogen embrittlement, explosion, storage failure                     | Fire growth, material combustion, evacuation performance   |
| Safety management focus    | Process reliability, barrier integrity, maintenance optimization     | Systemic risk evolution, feedback-driven safety culture                | Human behavior, resilience, sustainable design trade-offs  |
| Sustainability integration | Limited—mostly economic and environmental indices (CBA, EI)          | Multi-dimensional (economic, environmental, social)                    | Growing—fire—sustainability trade-offs, material LCA       |
| Complexity characteristics | High interdependencies and escalation potential                      | Emerging, adaptive, cross-sectoral                                     | Human variability, socio-technical coupling                |
| Main research gaps         | Static methods; weak socio-technical coupling                        | Lack of integrated safety–sustainability modeling                      | Absence of dynamic trade-off analysis                      |
| Transition trend           | From QRA to dynamic RA–SM                                            | From risk-centric to sustainability-oriented safety                    | From PBD to system-based and resilience-based design       |

#### 4.4- Summary of identified research gaps and modeling opportunities

The cross-domain literature reviewed in Chapter (3) and in Sections 4.1–4.3 reveals that despite substantial progress in quantitative risk analysis, sustainability integration, and performance-based design, current safety and sustainability models remain fragmented, static, and disciplinary. They often fail to capture the dynamic feedbacks, interdependencies, and multi-criteria decision structures that characterize modern socio-technical systems such as hydrogen infrastructures, energy networks, and sustainable buildings.

This section consolidates the main research gaps identified across the reviewed domains and maps them to the specific modeling opportunities and contributions developed in this thesis. The objective is to demonstrate how the proposed FRISE framework directly responds to these gaps through its conceptual, methodological, and applied innovations.

Across the literature, five overarching limitations are consistently identified:

1. Fragmentation of modeling approaches
  - Risk assessment, safety management, and sustainability are often treated as separate analytical domains, resulting in compartmentalized models.

- Integration efforts tend to focus on two dimensions (e.g., RA–SM or RA–ENV) without achieving full systemic coupling.
2. Static and linear representations
    - Conventional QRA, PBD, and LCA frameworks employ fixed parameters and steady-state assumptions.
    - They neglect temporal feedbacks, degradation processes, and learning dynamics that govern real system behavior.
  3. Neglect of Socio-technical interactions
    - Human and organizational factors such as culture, trust, and communication are acknowledged qualitatively but rarely integrated quantitatively into risk or sustainability models.
  4. Weak coupling between safety and sustainability
    - Economic, environmental, and social metrics are typically post-hoc assessments rather than embedded within the dynamic structure of safety decision-making.
    - This limits the ability to explore trade-offs and synergies across the three sustainability pillars.
  5. Absence of a generic and transferable framework
    - Existing models are often case-specific and lack generalizability.
    - Few attempts have been made to build a modular, multi-domain architecture that can be adapted across sectors.

Table 4.2 summarizes how the present research addresses these limitations through the development of a modular, systemic, and interdisciplinary FRISE framework.

**Table 4.2- Research gaps and modeling opportunities addressed by this thesis**

| Domain / Theme                     | Identified Gap                                                           | Modeling Opportunity                                                                                        | Corresponding Thesis contribution                                              |
|------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Chemical / Energy Risk Modeling    | Static probabilistic methods; weak link to management and sustainability | Develop a dynamic RA–SM structure that models feedback between safety barriers, investment, and degradation | RA and SM modules (Ch.6) and their integration via the glue layer (Ch.5)       |
| Hydrogen Safety and Sustainability | Fragmented models lacking socio-technical integration                    | Combine risk, management, economic, environmental, and social dimensions under Systems Thinking             | Hydrogen applications (Ch.7) using the full FRISE framework                    |
| Fire Safety Engineering (FSE)      | Trade-offs between sustainability and safety poorly quantified           | Apply feedback-based CLDs and graph analysis to evaluate                                                    | Fire safety applications (Ch.8) with cross-modular sustainability–safety loops |

| Domain / Theme             | Identified Gap                                                  | Modeling Opportunity                                                                        | Corresponding Thesis contribution                                        |
|----------------------------|-----------------------------------------------------------------|---------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
|                            |                                                                 | sustainability–safety interdependence                                                       |                                                                          |
| Socio-Technical Systems    | Human, cultural, and perception factors treated qualitatively   | Represent culture, trust, and communication as endogenous variables within dynamic networks | SOC and SM modules (Ch.6) and graph-based influence analysis (Ch.5)      |
| Sustainability Integration | Economic, environmental, and social pillars unbalanced          | Integrate ALARP, CBA, EI, and LQI as dynamic decision anchors for multi-criteria assessment | Decision anchor integration (Ch.4 & Ch.5)                                |
| Cross-Sectoral Modeling    | Lack of transferable, generic frameworks                        | Develop a modular, graph-based system adaptable to different industries                     | Generic framework architecture (Ch.5) and cross-domain validation (Ch.9) |
| Policy and Governance      | Limited systemic insight into leverage points and policy delays | Identify dominant feedback loops and systemic leverage points using graph theory            | Cross-modular feedback analysis (Ch.5 & Ch.9)                            |

The interdisciplinary approach adopted here laid the conceptual groundwork for the development of the FRISE framework introduced in Chapter 5. In the next chapter, this synthesis is operationalized into a methodological structure, where conceptual feedbacks become formalized connections, and theoretical insights evolve into a tangible modeling architecture capable of representing real-world complexity.

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## Chapter 5 – The FIRSE Research Framework

This chapter establishes the methodological core of the thesis. It translates the theoretical paradigms of Systems Thinking, Complexity, and Sustainability—developed in the preceding chapters—into a unified framework for modeling, integrating, and analyzing risk and safety in complex socio-technical systems. The chapter introduces the modular architecture of FRISE, composed of five interconnected components: Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC). These modules interact through a Systemic Glue Layer that captures feedbacks, interdependencies, and cross-domain relationships. The structure is formalized using Causal Loop Diagrams (CLDs) and Graph Theory (GT) metrics, enabling the identification of key leverage variables and dominant feedback loops without relying on full dynamic simulations. Additionally, the chapter defines the Decision Anchors—ALARP, CBA, EI, and LQI—as guiding principles that connect analytical outcomes with real-world safety and sustainability criteria.

### 5.1- Introduction

This chapter introduces the FRSIE Framework (*Feedback-based Risk and Safety Integration for Sustainability in Engineering*), the central methodological construct of the thesis. It operationalizes the conceptual and theoretical paradigms presented in Chapters 2–4 into a comprehensive modeling architecture.

FRSIE addresses the major research gaps identified in the literature: the fragmentation of Risk Assessment (RA) and Safety Management (SM) models, the weak integration of sustainability indicators, and the lack of feedback-based structures capable of representing dynamic socio-technical behavior. The framework unites these elements into a modular, scalable structure that links safety performance with sustainability outcomes across technical, economic, environmental, and social dimensions.

### 5.2- Conceptual overview

FRSIE translates the principles of Systems Thinking, Complexity, and Sustainability (3P model) into a system-of-systems architecture. It consists of five interconnected modules:

- 1- Risk Assessment (RA) – considers failure likelihood, hazard evolution, and risk reduction mechanisms;
- 2- Safety Management (SM) – captures organizational, cultural, and managerial responses to risk;

- 3- Economic (ECO) – evaluates cost–benefit dynamics, resource allocation, and profitability;
- 4- Environmental (ENV) – represents emissions, environmental degradation, and recovery processes; and
- 5- Social (SOC) – reflects trust, acceptance, and quality of life.

The integration of these modules forms the FRSIE architecture, a feedback-rich representation where variables co-evolve through dynamic interactions. Each module is conceptually autonomous but connected via cross-domain influence matrices—what is referred to as the “systemic glue layer.”

The design of FRSIE is guided by main four principles:

1. Modularity – each subsystem can be refined or expanded without altering the entire framework.
2. Dynamic representation – feedback loops, delays, and nonlinearities are explicitly modeled.
3. Cross-dimensional integration – coupling of safety, sustainability, and socio-economic drivers.
4. Scalability – adaptability to multiple engineering sectors (hydrogen, fire safety, energy).

The FRISE Framework embodies a conceptual synthesis of three interlinked paradigms—Systems Thinking, Complexity Theory, and Sustainability Science—applied to the domain of engineering risk and safety. It responds to the limitations of traditional, reductionist methodologies that address safety management, risk assessment, and sustainability in isolation. By adopting a systemic, feedback-oriented perspective, FRISE integrates these dimensions into a cohesive architecture that reflects the adaptive and co-evolutionary nature of socio-technical systems (Lane & Sterman, 2011; Leveson, 2011; D. H. Meadows, 2008).

The definition of system boundaries and the identification and classification of variables within the FRISE framework were informed by a lightweight expert elicitation process combining insights obtained during technical conferences, informal meetings with domain specialists, and a structured extraction of expert knowledge from the literature. Throughout the development of the framework and its application to hydrogen safety, fire safety engineering, and sustainability-related systems, discussions with researchers and practitioners helped refine the essential processes, feedback mechanisms, and sector-specific considerations that needed to be

represented. These exchanges, together with evidence synthesized from authoritative reports, empirical studies, and established modeling practices, supported the selection of relevant variables, the clarification of their roles and causal directions, and the delineation of system boundaries consistent with current expert understanding. This combined approach ensured that the modeling assumptions and structural components of the FRISE framework are aligned with prevalent expert perspectives and the state of the art in each domain.

### **5.2.1- Systems Thinking as the Structural Logic of FRISE**

The structural logic of FRISE is rooted in the Systems Thinking paradigm, which recognizes that the behavior of a system arises not from the sum of its parts but from the interconnections and feedbacks among them (Checkland, 1981; D. Meadows, 1999). In risk and safety contexts, this perspective allows the identification of reinforcing and balancing feedback loops that govern system stability or fragility.

For example, reinforcing loops may represent *learning and investment cycles* where increased safety culture leads to improved performance, which further strengthens trust and compliance. Conversely, balancing loops may represent *risk mitigation mechanisms* or the depletion of safety resources. Such feedback structures are key to explaining emergent properties, such as resilience or systemic collapse, which are not predictable from linear analyses alone (Sterman, 2002).

Within FRISE, Systems Thinking is operationalized through CLDs that map the cause–effect relations among variables in the risk, safety, and sustainability domains. These diagrams serve as the qualitative backbone of the framework, later translated into quantitative models using SD and GT approaches (Zio, 2016).

### **5.2.2- Complexity as the Behavioral Foundation of FRISE**

Modern engineering systems—such as hydrogen supply chains, energy infrastructures, or fire safety ecosystems—are examples of complex adaptive systems (Rasmussen, 1997; Leveson, 2011). They comprise multiple interacting components—technical, human, organizational, and environmental—whose interactions generate nonlinear behaviors and unintended consequences.

The FRISE Framework explicitly acknowledges this complexity by modeling interdependencies between its five subsystems: Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC). Each subsystem functions as a dynamic entity with internal feedbacks but also interacts with others through coupling variables such as *investment*, *trust*, *resource consumption*, and *environmental impact*.

These cross-domain couplings are formalized in the systemic glue layer, a conceptual construct that represents the exchange of information and influence among modules. The glue layer forms a network of dependencies, where the state of one subsystem affects the equilibrium of others, thus mirroring real-world complexity (Hollnagel, Woods & Leveson, 2006). For instance, a reduction in safety investment (ECO–SM interaction) may increase accident probability (RA), degrade environmental quality (ENV), and reduce public confidence (SOC), forming a reinforcing negative cycle.

The modeling of these complex feedbacks allows FRISE to go beyond the limitations of linear cause–effect frameworks and to explore emergent systemic behaviors, such as resilience thresholds, tipping points, or oscillatory safety performance under policy delays (Meadows, 1999; Sterman, 2002).

### **5.2.3- Sustainability as the Integrative Driver of FRISE**

While Systems Thinking provides structure and Complexity Theory defines behavior, Sustainability supplies the integrative purpose of the FRISE Framework. Engineering systems are not isolated technical entities but socio-technical infrastructures embedded in ecological and economic contexts (Elkington, 1997; Renn, 2008). Thus, decisions regarding safety investments, risk mitigation, or technological innovation must consider trade-offs among economic viability, environmental stewardship, and social acceptance—the three pillars of sustainability (Sterling, 2003; United Nations, 2015).

FRISE operationalizes sustainability through the inclusion of sustainability anchors—ALARP (As Low As Reasonably Practicable), CBA (Cost–Benefit Analysis), EI (Environmental Index), and LQI (Life Quality Index)—which act as dynamic reference points linking each module’s performance to broader societal objectives.

- Economic dimension (ECO): guided by CBA, assessing resource allocation efficiency.

- Environmental dimension (ENV): represented by EI, quantifying environmental degradation and recovery.
- Social dimension (SOC): measured through LQI, reflecting well-being and risk acceptance.
- Risk and Safety dimensions (RA, SM): constrained by ALARP, ensuring acceptable safety levels.

By embedding these anchors within the feedback architecture, FRISE ensures that safety decisions evolve adaptively with economic, environmental, and social conditions, thus transforming sustainability from an external constraint into an emergent system outcome.

#### **5.2.4- The Modular Architecture of FRISE**

The integration of the three paradigms manifests in the modular configuration of FRISE (see Figures 5.1-5.2). The framework is composed of five primary modules:

1. Risk Assessment (RA) – quantifies hazard likelihood, system vulnerability, and control-barrier performance.
2. Safety Management (SM) – represents management, culture, and feedback learning mechanisms that modulate system behavior.
3. Economic (ECO) – models investment flow, profitability, and resource distribution affecting safety and sustainability.
4. Environmental (ENV) – monitors emissions, compliance, and ecological recovery capacity.
5. Social (SOC) – captures trust, public perception, and acceptance dynamics within the socio-technical system.

These modules are interconnected through the systemic glue layer, which defines bidirectional cause–effect relationships and captures systemic coupling (Fig. 5.2). Graph-theory-based influence matrices later quantify the relative weight of these connections, enabling structural assessment and leverage-point detection.

This modular design makes FRISE scalable, adaptable, and transferable across sectors—supporting domain-specific model development such as hydrogen safety (Chapter 7), fire safety engineering (Chapter 8), and energy sustainability transitions (Chapter 9).

### **5.2.5- From Concept to Implementation**

The conceptual overview of FRISE provides the foundation for its operational development. The next stages—detailed in Sections 5.3 through 5.9—translate this conceptual architecture into a formal modeling framework using System Dynamics for time-dependent simulation and Graph Theory for structural quantification. These methods allow the identification of dominant feedback loops, virtuous and vicious cycles, and policy leverage points, supporting decision-making for sustainable safety management.

Through its modular yet integrated structure, FRISE establishes the methodological bridge between the theoretical insights presented in Chapters 2–4 and the model-based applications developed in Chapters 6–9.

### **5.3- The FRISE Framework: Structure and Stages**

The FRISE Framework represents the central methodological innovation of this thesis. It translates the conceptual paradigms of Systems Thinking (Checkland, 1981; Meadows, 2008), Complexity (Rasmussen, 1997; Leveson, 2011), and Sustainability (Elkington, 1997; Renn, 2008) into a structured, multi-layered methodology for analyzing and improving safety–sustainability performance in complex engineering systems.

FRISE evolves through four integrated stages (Figure 5.1), each corresponding to a distinct phase of theoretical grounding, model development, system integration, and application. Fig. 5.1 illustrates the four developmental stages of the FRISE Framework, from conceptual foundations to domain-level implementation. Each stage specifies its key inputs, main activities, and outputs, highlighting the transition from theoretical paradigms to modular framework development, analytical quantification, and policy-oriented applications. The feedback arrow from Stage IV to Stage I represents the iterative learning cycle and continuous refinement intrinsic to the FRISE approach, reinforcing its feedback-based and adaptive character.

The three vertical columns — Inputs, Main Activities, and Outputs — represent the flow of information and transformation within the framework: (1) Inputs summarize the knowledge or structures inherited from the preceding stage; (2) main Activities describe the methodological processes carried out within each stage; and (3) outputs denote the tangible products or insights generated, which become the inputs for the next phase. This structure clarifies how FRISE

evolves logically and systematically from conceptualization to application, maintaining coherence throughout the research process. The iterative feedback arrow connecting Stage IV to Stage I symbolizes this self-adaptive learning capability, whereby new empirical knowledge and cross-domain experiences continually refine the theoretical and methodological foundations. Thus, the FRISE Framework embodies not only a modeling methodology, but also a learning system — one that evolves in parallel with the complex systems it seeks to represent.

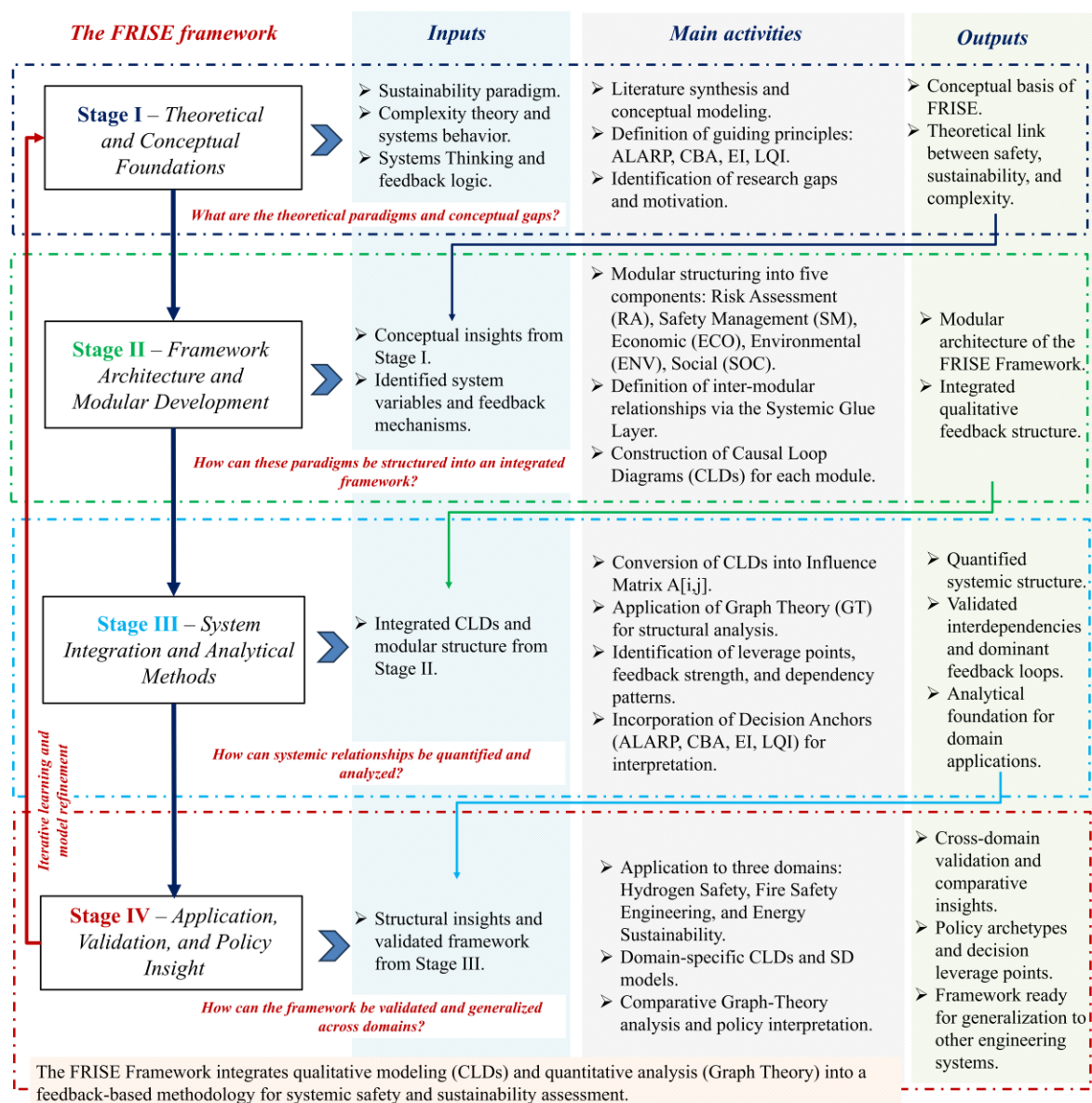


**Fig. 5.1- The FRISE Framework: from theoretical foundations to application and validation**

### 5.3.1- Stage I – Theoretical and Conceptual Foundations

The first stage establishes the intellectual scaffolding of FRISE. It consolidates the theoretical paradigms of Systems Thinking, Complexity, and Sustainability into a unified vision of engineering systems as adaptive socio-technical structures. In this stage, concepts such as feedback loops, delays, and nonlinearity (Forrester, 1961; Meadows, 1999) are identified as critical mechanisms shaping risk evolution. The stage also emphasizes that sustainability in engineering must integrate the economic, environmental, and social dimensions of system performance (Elkington, 1997; Sterling, 2003), while safety emerges as an *emergent system property* rather than a fixed objective (Leveson, 2011; Vanderhaegen, 2015).

### 5.3.2- Stage II – Framework Architecture and Modular Development

Building upon this conceptual foundation, Stage II develops the modular architecture of FRISE. The framework is structured around five interdependent modules—RA, SM, ECO, ENV, and SOC—that collectively capture the main dimensions of sustainability-oriented safety management.

Each module operates semi-autonomously, containing its own internal feedback structure, but interacts dynamically with other modules through shared variables (e.g., investment, compliance, trust, emission rate). These interconnections are coordinated through a systemic glue layer, which ensures data and feedback consistency across the system.

This modular design enables flexibility and scalability: modules can be expanded, combined, or simplified depending on the application domain (hydrogen systems, fire safety, energy transition). The modularization ensures that FRISE remains both conceptually coherent and operationally adaptable.

### 5.3.3- Stage III – System Integration and Analytical Methods

Stage III integrates all modules into a unified analytical platform. The framework employs CLDs for qualitative feedback mapping and GT for quantitative structural analysis. SD modeling is applied in subsequent application chapters to simulate dynamic behavior within specific engineering domains.

To quantify the structural interdependencies, GT is applied to translate CLDs into a directed influence matrix. The matrix  $A = [a_{ij}]$  quantifies the strength and direction of influence



between variables, enabling a numerical representation of system connectivity. Through centrality analysis (in-degree, out-degree, betweenness, eigenvector), the framework identifies dominant feedback loops and key leverage variables—those parameters whose modification produces the greatest systemic improvement (Zio, 2016).

This analytical integration allows FRISE to evolve from a conceptual model into a decision-support tool capable of identifying policy leverage points, systemic vulnerabilities, and potential virtuous or vicious cycles within safety–sustainability systems.

#### **5.3.4- Stage IV – Application, Validation, and Policy Insight**

The final stage operationalizes FRISE through simulation and comparative validation. The framework is applied to three engineering domains—hydrogen safety, fire safety engineering, and energy sustainability—selected for their diverse yet interconnected risk profiles. In each domain, feedback models derived from the FRISE architecture are implemented in *Vensim* and *MATLAB* environments.

Structural and behavioral validation confirm the robustness and transferability of FRISE. The outputs of this stage generate policy insights and governance guidelines, identifying leverage points for improving systemic resilience while maintaining sustainability trade-offs (ISO 31000, 2018; Zio, 2016).

#### **5.4- Structural Composition of the Modules**

The FRISE Framework is composed of five interacting modules—RA, SM, ECO, ENV, and SOC—each representing a key dimension of systemic sustainability in engineering systems. While each module can function autonomously, the strength of the framework lies in their interconnection through feedback relationships, mediated by the *Systemic Glue Layer*.

Figure 5.2 illustrates the modular architecture of the FRISE Framework, emphasizing the five interrelated components and their integration through the Systemic Glue Layer. The configuration captures the essential feedback mechanisms linking safety, economic performance, environmental impact, and social acceptance within complex engineering systems. The arrows represent both direct and cross-modular feedbacks, symbolizing how each subsystem dynamically influences the others through shared variables and decision anchors. This structure serves as the foundation for the analytical processes discussed in the following sections.

These relationships ensure that variations within one module propagate throughout the system, reproducing the complex, adaptive behavior observed in real-world engineering domains (Rasmussen, 1997; Leveson, 2011; Vanderhaegen, 2015; Zio, 2016). Each module is linked to one or more of the sustainability anchors—ALARP, CBA, EI, and LQI- which provide the evaluative criteria for performance and decision-making. The sections below describe the internal logic of each module, its main feedback loops, and its coupling mechanisms with the rest of the framework.

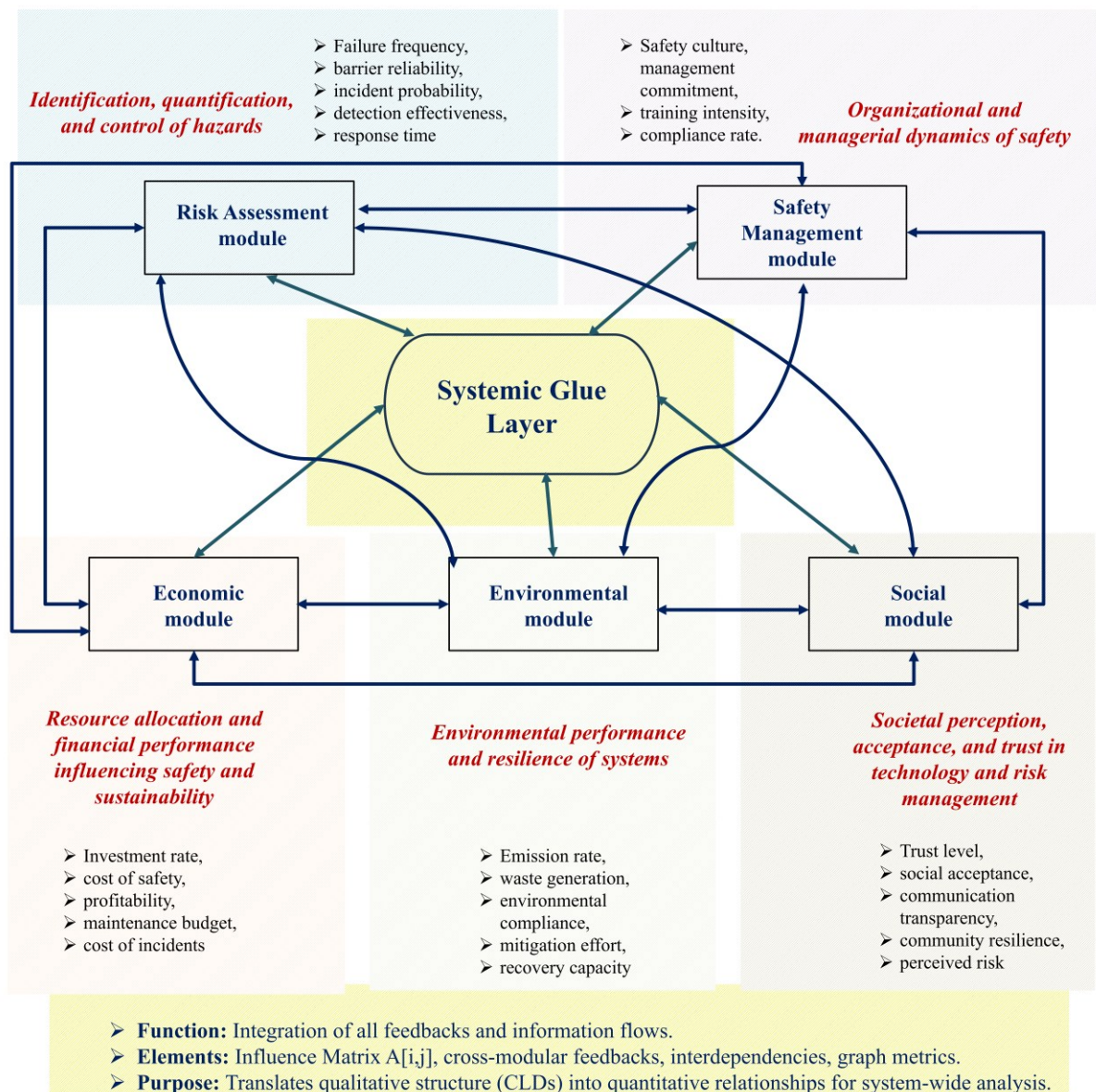


Fig. 5.2- Modular architecture of the FRISE framework

#### **5.4.1- The Risk Assessment (RA) Module**

The RA module captures the dynamic behavior of hazard identification, risk evolution, and mitigation effectiveness. It represents the technical and probabilistic aspects of system safety, incorporating feedback mechanisms that connect hazard occurrence, barrier reliability, and system resilience (Aven, 2015; ISO 31000, 2018).

RA module integrates the following core feedback loops:

1. Reinforcing loop ( $R_1$  – degradation loop): Component wear or operational degradation increases failure likelihood, leading to higher risk exposure.
2. Balancing loop ( $B_1$  – mitigation loop): Risk perception triggers preventive measures—inspection, maintenance, or redundancy—which reduce overall risk levels.
3. Balancing loop ( $B_2$  – regulatory compliance loop): As risk increases, stricter regulatory enforcement emerges, improving barrier performance and reducing residual risk.

Additionally, the RA module is connected through the following cross-modular connections:

- Receives investment input from ECO and managerial response from SM.
- Feeds risk perception into SOC and environmental consequences into ENV.

The associated sustainability anchor for this RM module is the ALARP (As Low As Reasonably Practicable) principle which defines acceptable risk thresholds and informs optimization between technical safety investment and residual risk.

#### **5.4.2- The Safety Management (SM) Module**

The SM module represents the organizational and managerial dimension of safety, encompassing leadership, culture, learning, and compliance. It models how proactive management, communication, and system learning feedbacks strengthen or weaken safety performance over time (Hollnagel, Woods & Leveson, 2006; Leveson, 2011).

SM module integrates the following core feedback loops:

1. Reinforcing loop ( $R_2$  – safety culture loop): Strong safety culture promotes adherence to procedures, reducing incidents and reinforcing organizational learning.
2. Balancing loop ( $B_3$  – erosion loop): In periods of budget constraint, safety training and oversight may decline, increasing latent vulnerabilities.
3. Reinforcing loop ( $R_3$  – learning and adaptation loop): Each incident or near miss generates lessons that improve safety behavior and prevent recurrence.

Additionally, the SM module is integrated through the following cross-modular connections:

- Exchanges resources with ECO (investment) and influences RA (barrier reliability).
- Enhances social trust and legitimacy in SOC.
- Affects environmental integrity in ENV through operational discipline.

For the SM module, the associated sustainability anchors are both ALARP and CBA, which jointly guide management priorities, balancing investment against achievable safety improvement.

#### **5.4.3- The Economic (ECO) Module**

The ECO module captures the financial and resource-allocation processes that underpin safety and sustainability decisions. It models profitability, operational costs, investment efficiency, and risk-reduction expenditures (Zio, 2016; Reniers & Khakzad, 2022).

ECO module integrates the following core feedback loops:

1. Reinforcing loop ( $R_4$  – growth and reinvestment): Improved profitability enables reinvestment in safety, technology, and environmental recovery, creating a virtuous safety–economy cycle.
2. Balancing loop ( $B_4$  – cost–constraint loop): Rising safety or environmental costs may reduce profit margins, discouraging long-term investment.
3. Reinforcing loop ( $R_5$  – reputation and market confidence): Good safety and environmental performance enhance reputation, increasing market competitiveness and financial return.

Additionally, the ECO module is integrated through the following cross-modular connections:

- Provides investment capital to RA and SM modules.
- Receives feedback on environmental penalties from ENV and trust impacts from SOC.

The associated sustainability anchor is the CBA (Cost–Benefit Analysis), which quantifies trade-offs between safety investment, environmental compliance, and financial viability.

#### **5.4.4- The Environmental (ENV) Module**

The ENV module addresses the interactions between system operations and the surrounding environment. It captures emissions, pollution, compliance with environmental standards, and recovery efforts after incidents (OECD, 2018; Zi, 2016).

ENV module integrates the following core feedback loops:

1. Balancing loop ( $B_5$  – mitigation and compliance loop): Higher emissions trigger mitigation efforts and stricter enforcement, improving environmental performance.
2. Reinforcing loop ( $R_6$  – degradation loop): Persistent environmental neglect amplifies degradation, leading to reduced resilience and social backlash.
3. Reinforcing loop ( $R_7$  – innovation loop): Investments in cleaner technologies decrease pollution and enhance long-term sustainability.

Additionally, the ENV module is integrated through the following cross-modular connections:

- Receives operational inputs from SM (discipline and control) and investment from ECO.
- Sends signals to SOC (public perception) and ECO (economic penalties or incentives).

The associated sustainability anchor is an EI (Environmental Index) which quantifies environmental performance and recovery capacity, serving as a feedback control variable within the system.

#### **5.4.5- The Social (SOC) Module**

The SOC module represents public perception, stakeholder trust, and societal acceptance. It captures how transparency, participation, and communication influence collective attitudes toward safety and sustainability (Renn, 2008; United Nations, 2015).

SOC module integrates the following core feedback loops:

1. Reinforcing loop ( $R_8$  – trust and legitimacy loop): Transparent communication and good performance increase trust, which reinforces regulatory support and compliance.
2. Balancing loop ( $B_6$  – social pressure loop): Perceived risk or environmental harm triggers activism and policy pressure, prompting stricter regulations.
3. Reinforcing loop ( $R_9$  – awareness and co-evolution loop): Education and risk communication increase societal awareness, aligning stakeholder behavior with sustainable practices.

Additionally, the SOC module is integrated through the following cross-modular connections:

- Receives information from RA (perceived risk), ENV (environmental impact), and SM (organizational transparency).
- Influences ECO through market reputation and S through compliance motivation.

The associated sustainability anchor is the LQI (Life Quality Index) reflects social well-being and acceptance, dynamically linked to safety and sustainability performance.

#### 5.4.6- Cross-Modular Synergies and Feedback Typologies

When integrated through the *Systemic Glue Layer*, the five modules collectively exhibit multi-layered feedback typologies, including:

- Technical feedbacks, linking safety reliability and risk evolution.
- Economic feedbacks, connecting investment and cost–benefit performance.
- Environmental feedbacks, governing degradation–recovery dynamics.
- Social feedbacks, shaping trust, legitimacy, and compliance behavior.

Table 5.1 shows a summary of module functions and anchors within the FRISE framework. The interplay of these feedback types produces emergent systemic properties such as resilience, adaptability, and sustainability (Hollnagel et al., 2006; Leveson, 2011; Zio, 2016). By mapping and quantifying these relationships through graph-theoretical metrics, the FRISE Framework identifies dominant loops (e.g., virtuous safety–investment cycles) and critical vulnerabilities (e.g., domino degradation feedbacks), enabling proactive, evidence-based decision-making across multiple domains.

**Table 5.1- Summary of Module Functions and Anchors**

| Module | Main Function                           | Key Feedback Loops                                                               | Cross-Link Variables               | Decision Anchor |
|--------|-----------------------------------------|----------------------------------------------------------------------------------|------------------------------------|-----------------|
| RA     | Hazard likelihood, mitigation           | R <sub>1</sub> degradation, B <sub>1</sub> mitigation                            | Investment (ECO), Compliance (SM)  | ALARP           |
| SM     | Organizational learning, safety culture | R <sub>2</sub> culture, B <sub>3</sub> erosion, R <sub>3</sub> learning          | Trust (SOC), Environment (ENV)     | ALARP, CBA      |
| ECO    | Investment, profitability               | R <sub>4</sub> growth, B <sub>4</sub> cost, R <sub>5</sub> reputation            | SM (budget), ENV (penalties)       | CBA             |
| ENV    | Emissions, recovery                     | B <sub>5</sub> mitigation, R <sub>6</sub> degradation, R <sub>7</sub> innovation | SM (discipline), SOC (reputation)  | EI              |
| SOC    | Trust, acceptance                       | R <sub>8</sub> trust, B <sub>6</sub> social pressure, R <sub>9</sub> awareness   | RA (risk perception), ENV (impact) | LQI             |

#### 5.5- The “Glue Layer” and Cross-Modular Integration

The conceptual power of the FRISE Framework lies in its capacity to integrate the five domain modules through a Systemic Glue Layer that formalizes the cross-modular feedback structure. This layer functions as both the structural backbone and the information exchange hub of the framework, enabling dynamic coupling among technical, organizational, and societal processes. It transforms the FRISE Framework from a set of modular representations into a cohesive system-of-systems model, reflecting the real-world interdependencies of complex

engineering domains (Forrester, 1961; Leveson, 2011; Zio, 2016). The conceptual role of the Systemic Glue Layer therefore extends beyond structural connectivity—it establishes the basis for dynamic information exchange and adaptive feedback among all FRISE modules. Through this cross-modular coupling, the framework evolves from a collection of disciplinary models into an integrated, feedback-driven system capable of representing emergent behavior across technical, organizational, and societal dimensions.

To ensure that the interconnections among modules are empirically grounded and enriched by the specific feedback effects identified within each domain application, the Cross-Modular Integration is developed in Chapter 9, following the implementation of all individual FRISE applications. This sequencing guarantees that the integration process reflects validated intra-modular behaviors and supports a comprehensive synthesis of systemic feedbacks, thereby strengthening the framework's overall coherence and realism.

#### **5.5.1- Concept and Purpose of the Glue Layer**

In socio-technical systems, individual subsystems rarely operate in isolation: financial investment affects safety management, environmental performance shapes social trust, and public acceptance influences regulatory compliance. The Glue Layer captures these cross-domain relationships, acting as an interface matrix through which variables, parameters, and decisions propagate among modules (Vanderhaegen, 2015; Zio, 2016).

Conceptually, it represents a network of bidirectional feedbacks, where each connection signifies a measurable influence—positive or negative—between components. For instance, an increase in safety investment ( $ECO \rightarrow SM$ ) may reduce failure probability ( $RA$ ) but simultaneously decrease short-term profitability ( $ECO \rightarrow RA$ ). Conversely, improved environmental compliance ( $ENV \rightarrow SOC$ ) can enhance public trust ( $SOC \rightarrow ECO$ ), generating reinforcing virtuous cycles.

The Glue Layer therefore ensures that safety and sustainability decisions are not compartmentalized but dynamically balanced across all subsystems—a central tenet of Systems Thinking and Complexity Science (Checkland, 1981; Rasmussen, 1997; Meadows, 2008).

### 5.5.2- Mathematical Representation

To operationalize these cross-modular interactions, the Glue Layer is represented as a directed influence matrix,  $A = [a_{ij}]$ , where each element  $a_{ij}$  quantifies the influence of variable  $i$  on variable  $j$ . The values of  $a_{ij}$  are dimensionless and normalized in the range  $[-1, +1]$  (Eq. 5.1)

$$a_{ij} = \begin{cases} +1, & \text{strong positive influence (reinforcing feedback)} \\ 0, & \text{no direct influence} \\ -1, & \text{strong negative influence (balancing feedback)} \end{cases} \quad (5.1)$$

This matrix formulation captures the interconnected topology of the FRISE Framework and serves as the foundation for subsequent graph-theoretical analysis. The matrix is both sparse (not all variables are directly linked) and asymmetric (the influence from  $i$  to  $j$  may differ from that of  $j$  to  $i$ ), reflecting real-world asymmetries such as regulatory lag or investment delay.

For computational purposes, the Glue Layer connects not only the five primary modules but also the sub-variables within each module, producing a multi-layered graph structure. This configuration allows the derivation of system-wide dependency metrics, structural hierarchies, and leverage points.

### 5.5.3- Graph-Theoretical Interpretation

The directed graph corresponding to matrix  $A$  enables quantitative assessment of systemic behavior using Graph Theory (GT) metrics (Zio, 2016). Each node represents a variable or module, while edges represent causal relationships with direction and sign (Table 5.2). The following centrality measures are particularly relevant:

1. Out-degree centrality ( $C_{out}$ ):  
Measures a variable's *influence capacity*—the number of outgoing connections and their weight.  
High  $C_{out}$  variables act as leverage points, capable of driving large-scale system change (e.g., *Safety Investment, Management Commitment*).
2. In-degree centrality ( $C_{in}$ ):  
Quantifies a variable's *dependency level*—the number and strength of incoming influences.  
Variables with high  $C_{in}$  are sensitive indicators, reflecting the overall system state (e.g., *Public Trust, Environmental Recovery*).
3. Betweenness centrality ( $C_b$ ):  
Identifies intermediary variables that mediate information flow between modules. These are often governance or policy-related variables linking economic and safety decisions (e.g., *Regulatory Compliance*).
4. Eigenvector centrality ( $C_e$ ):  
Captures systemic dominance—variables connected to other highly influential nodes.



High  $C_e$  values indicate strategic points for policy intervention (e.g., *Safety Culture*, *Sustainability Investment*).

**Table 5.2- Key Graph Theory Metrics and Interpretation**

| Metric                | Definition                         | Interpretation in FRISE                | Example Variable      |
|-----------------------|------------------------------------|----------------------------------------|-----------------------|
| Out-degree centrality | Number of outgoing links           | Influence capacity / leverage variable | Safety Investment     |
| In-degree centrality  | Number of incoming links           | Dependency / sensitivity               | Public Trust          |
| Betweenness           | Frequency in shortest paths        | Mediator / policy interface            | Regulatory Compliance |
| Eigenvector           | Connectedness to influential nodes | Systemic dominance                     | Safety Culture        |

This approach provides a quantitative complement to qualitative systems modeling (Forrester, 1961; Meadows, 1999), enhancing interpretability and allowing the detection of dominant feedback structures without requiring extensive numerical data.

#### 5.5.4- Feedback Typologies and Dynamic Behavior

The Glue Layer encompasses two fundamental feedback typologies—reinforcing (positive) and balancing (negative)—which govern the dynamic evolution of the system (Meadows, 2008; Sterman, 2002).

- Reinforcing feedbacks (R-loops): Amplify system behavior, leading to growth or escalation. Examples include the Safety Culture–Trust Loop and the Investment–Innovation Loop.
- Balancing feedbacks (B-loops): Regulate growth and maintain stability. Examples include the Risk Mitigation–Barrier Reliability Loop and the Cost–Constraint Loop.

Together, these loops form the dynamic architecture of the FRISE Framework, driving system evolution toward equilibrium, oscillation, or exponential growth depending on the strength and delay of interconnections. By applying both qualitative CLD interpretation and graph-based analysis, the framework captures transitions between these dynamic regimes, identifying thresholds beyond which safety performance, sustainability, or resilience may deteriorate.

#### 5.5.5- Functional Role in FRISE Applications

In subsequent chapters (7–9), the Glue Layer provides the mechanistic foundation for all domain applications:

- In hydrogen safety, it links process risk, investment, and public trust to predict adoption behavior.

- In fire safety engineering, it connects safety culture, resource allocation, and environmental impact within building performance design.
- In energy sustainability, it bridges economic growth, emissions, and social acceptance during hydrogen transition modeling.

In all cases, the Glue Layer ensures dynamic consistency among modules and maintains the conceptual coherence of FRISE across domains. It thus acts as the translation interface between theoretical complexity and applied modeling, allowing knowledge transfer across sectors while preserving systemic fidelity.

### **5.5.6- Summary**

The Systemic Glue Layer transforms the FRISE Framework from a modular collection of subsystems into a fully integrated system model. By formalizing interdependencies through an influence matrix and quantifying them via graph-theoretical metrics, it enables the detection of dominant leverage points and the analysis of emergent feedback patterns. In doing so, it embodies the core principle of Systemic Sustainability Engineering: that the resilience and sustainability of engineered systems emerge from the interaction of their parts—not their isolation (Leveson, 2011; Hollnagel et al., 2006).

Although the FRISE Framework can be extended into quantitative simulation through System Dynamics, in this thesis the core modular framework is analyzed using Graph Theory as the primary quantitative tool. The Glue Layer’s influence matrix forms the structural basis for evaluating system interdependencies, feedback density, and leverage points, without direct numerical simulation of dynamic behavior. This structural analysis informs the System Dynamics applications developed in later chapters, where domain-specific models are implemented and validated.

### **5.6- Decision anchors**

The final layer of the FRISE Framework integrates its analytical outputs into actionable decision-support criteria through the use of *Decision Anchors*. These anchors — ALARP (As Low As Reasonably Practicable), CBA (Cost–Benefit Analysis), EI (Environmental Index), and LQI (Life Quality Index) — serve as boundary conditions that guide safety and sustainability decisions, ensuring that system behavior remains aligned with both technical feasibility and societal expectations (Zio, 2016; Aven, 2015; ISO 31000, 2018).

Rather than static thresholds, in FRISE these anchors are modeled as dynamic variables that evolve with system feedbacks. They continuously adjust to changes in investment,

performance, and social context, thereby enabling adaptive governance and resilience-oriented decision-making (Leveson, 2011; Vanderhaegen, 2015).

By embedding these anchors directly within the feedback structure, the framework bridges the gap between system behavior analysis and decision rationalization, transforming abstract model results into context-sensitive recommendations.

#### **5.6.1- Role and Function of Decision Anchors in FRISE**

The Decision Anchors act as integrative filters that translate the outcomes of the five FRISE modules into measurable decision variables. They provide a multi-criteria reference system that enables the evaluation of trade-offs among safety, sustainability, and socio-economic performance. In complex engineering systems, no single performance indicator can capture the full spectrum of risks and trade-offs. The FRISE Framework therefore operationalizes these anchors as linked performance dimensions, expressed as time-dependent functions of system state variables (Eq. 5.2).

$$A(t) = f(RA(t), SM(t), ECO(t), ENV(t), SOC(t)) \quad (5.2)$$

Each anchor acts as a decision signal that constrains or reinforces system responses depending on performance evolution. Together, they form a multi-anchor decision space, enabling risk–sustainability under uncertainty.

#### **5.6.2- ALARP – Risk Tolerability and Optimization of Safety Investments**

The ALARP principle (As Low As Reasonably Practicable) provides the foundational anchor for risk tolerability within the FRISE Framework. It establishes that risk should be reduced until further reduction becomes grossly disproportionate to the benefit gained (Aven, 2015; ISO 31000, 2018).

In FRISE, ALARP is operationalized as a dynamic control threshold applied within the RA and SM modules. This allows FRISE to adapt safety-investment strategies as economic or social conditions change, ensuring decisions remain both rational and proportionate over time. ALARP thus connects technical safety management to economic feasibility and public perception, linking the microscopic behavior of the system to macroscopic policy thresholds (Rasmussen, 1997; Leveson, 2011).

#### **5.6.3- CBA – Economic Efficiency and Trade-Off Evaluation**

The CBA anchor provides the economic criterion that governs the allocation of resources across the FRISE system. It quantifies the ratio between the cost of safety measures and the expected

reduction in risk and loss, ensuring that investments in safety and sustainability yield optimal returns (Zio, 2016).

Within the ECO module, CBA operates as a feedback regulator between profitability and safety performance. Increases in safety investment improve reliability and sustainability, but excessive expenditure can erode financial resilience. The time dependence reflects delayed economic effects—such as learning, amortization, or recovery—thereby incorporating lagged feedbacks into financial decision-making. CBA thus ensures the system maintains economic sustainability while supporting long-term safety performance.

#### **5.6.4- EI – Environmental Integrity and Recovery Capacity**

The Environmental Index (EI) quantifies the ecological performance of the system, acting as a feedback measure of environmental degradation, compliance, and recovery (OECD, 2018; Zio, 2016). In the Environmental (ENV) module, EI is modeled as a continuous variable that responds to operational activity, mitigation policies, and recovery investment.

#### **5.6.5- LQI – Social Well-Being and Public Acceptance**

The Life Quality Index (LQI) measures the social dimension of sustainability within FRISE, focusing on human well-being, safety perception, and acceptance of technological risk (Renn, 2008; United Nations, 2015). In the Social (SOC) module, LQI evolves through feedbacks involving safety performance, economic stability, and environmental health.

Improved safety outcomes enhance trust and life expectancy, while environmental degradation or economic instability reduce overall quality of life. The LQI is expressed as a composite indicator considering life expectancy, safety performance, and environmental quality. By embedding LQI within the FRISE feedback structure, the framework captures social dynamics as both an outcome and a driver of system change—reflecting that public perception and societal resilience are inseparable from technical and economic performance.

#### **5.6.6- Interactions among Decision Anchors**

The four anchors are not independent; they interact continuously through reinforcing and balancing loops mediated by the Glue Layer.

For example:

- A decrease in risk (RA) lowers ALARP-driven interventions but improves LQI through perceived safety.

- Investments justified by CBA may enhance EI via cleaner technologies and increase societal acceptance (SOC).
- Environmental improvements (EI) positively influence LQI, which in turn enhances compliance behavior in the Safety module (S).

This interconnectedness creates a multi-anchor feedback network, where the anchors collectively define a dynamic equilibrium of sustainability and safety. In this network, achieving balance requires iterative adaptation—an embodiment of the resilience engineering philosophy (Hollnagel et al., 2006; Zio, 2016).

By embedding these anchors, FRISE provides a decision-making compass that aligns quantitative system modeling with normative policy principles. Regulators can use FRISE outputs to assess when risk is ALARP-compliant, whether investments remain economically viable, how environmental degradation evolves, and how public trust is affected.

This transforms FRISE from a diagnostic tool into a prescriptive framework, capable of guiding adaptive governance for sustainability and resilience (Leveson, 2011; Renn, 2008). The anchor-based decision layer thus bridges the gap between systemic modeling and policy formulation, ensuring that engineering safety management remains socially legitimate, environmentally responsible, and economically sound.

### **5.7- Methodological workflow**

The development of the FRISE Framework (Feedback-based Risk Integration for Safety and Sustainability in Engineering) follows a systematic, multi-phase workflow designed to ensure conceptual coherence, analytical robustness, and applicability across engineering domains.

This workflow provides the operational pathway through which theoretical paradigms—Systems Thinking, Complexity, and Sustainability—are translated into a quantitative, feedback-based modeling structure capable of supporting decision-making under uncertainty (Forrester, 1961; Meadows, 2008; Leveson, 2011; Zio, 2016). Each phase of the methodology corresponds to a distinct research activity, from system conceptualization to simulation and validation, but all are interlinked through continuous feedback refinement.

The methodological development of the FRISE Framework follows a structured yet flexible workflow designed to translate theoretical paradigms into a feedback-based structural model of safety and sustainability. The process combines qualitative system modeling (CLDs) with

quantitative structural analysis (GT), allowing for the identification of dominant feedback loops, systemic dependencies, and leverage variables.

Unlike traditional dynamic simulation methods, this thesis applies System Dynamics modeling only in domain-specific applications (Chapters 7–9). For the core framework, the analysis remains structural, focusing on feedback topologies and influence propagation using network metrics.

Figure 5.3 summarizes the methodological workflow of the FRISE Framework, illustrating the sequential development of the model from boundary definition to validation and the iterative refinement loop that ensures its adaptability. The process consists of five main stages, arranged in a feedback-oriented sequence rather than a linear hierarchy. This cyclical structure reflects the iterative nature of systemic model development and the adaptive logic of the framework. The methodological workflow comprises five iterative stages, shown schematically in Figure 5.3:

1. System Boundary Definition – delineate the technical, managerial, and societal limits of the system.
2. Variable Identification and Classification – extract and categorize key system variables from literature and expert judgment.
3. Causal Mapping – construct CLDs for each FRISE module and integrate them through the Systemic Glue Layer.
4. Influence Matrix and Graph Theory Analysis – translate causal maps into quantitative matrices and compute network metrics (centrality, feedback density, connectivity).
5. Structural Validation and Insight Extraction – verify structural coherence, identify dominant feedbacks, and synthesize cross-domain insights.

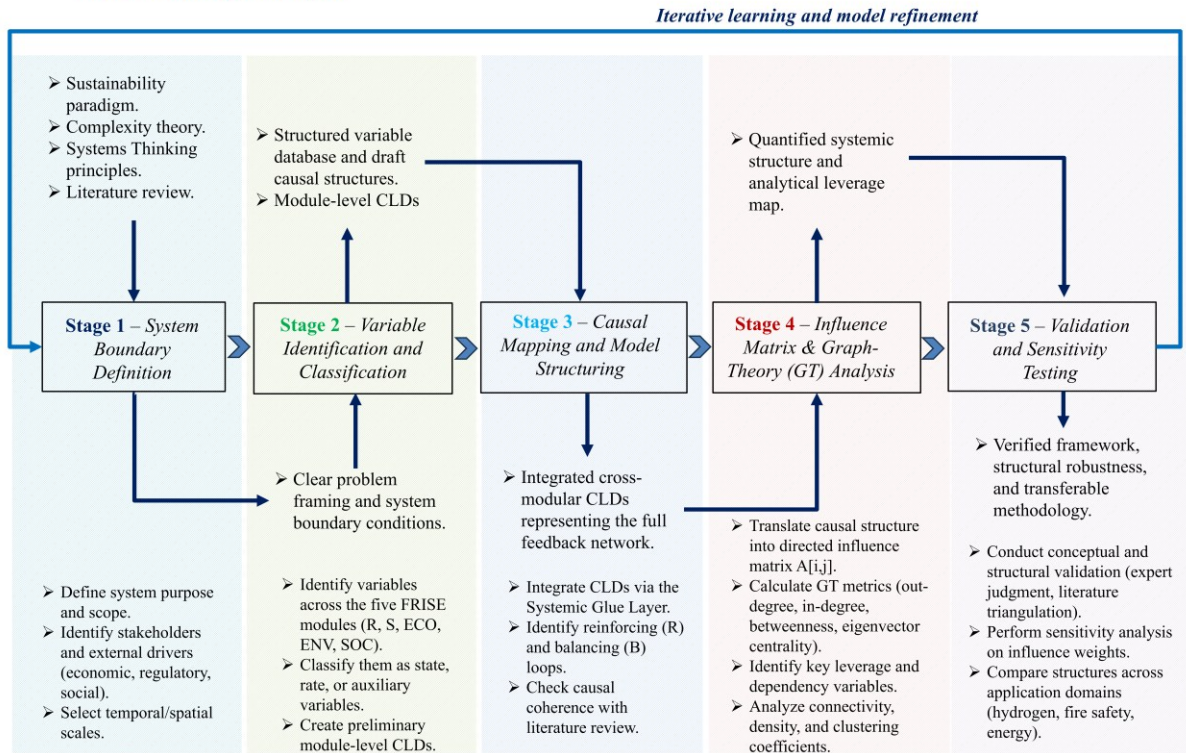


Fig. 5.3- Methodological workflow of the FRISE framework.

### 5.7.1- Stage 1 – System Boundary Definition

The first stage establishes the conceptual and operational boundaries of the system to be modeled.

Boundaries are defined by the problem scope (e.g., hydrogen safety, fire safety, or energy transition), the temporal and spatial scales, and the external factors influencing system performance (Checkland, 1981; Rasmussen, 1997).

Key activities include:

- Identifying system purpose and primary stakeholders;
- Defining control variables, external drivers, and boundary conditions;
- Mapping the level of aggregation required (process, organizational, or sectoral scale).

This phase ensures that the FRISE model remains both focused and representative, capturing the essential dynamics without excessive complexity.

### 5.7.2- Stage 2 – Variable Identification and Classification

Once system boundaries are established, the next step involves identifying relevant variables across the five FRISE modules.

Variables are classified into three categories:

1. State variables: dynamic quantities that evolve over time (e.g., risk level, safety culture, trust).
2. Rate variables: control flows influencing the rate of change (e.g., investment rate, emission rate).
3. Auxiliary variables: influencing or moderating factors (e.g., public perception, policy enforcement).

This classification facilitates the construction of Causal Loop Diagrams (CLDs), enabling a clear representation of system structure and the causal relationships between components (Meadows, 1999; Sterman, 2002).

### **5.7.3- Stage 3 – Causal Mapping and Model Structuring**

The third stage focuses on constructing Causal Loop Diagrams (CLDs) to map cause–effect interactions and identify reinforcing (R) and balancing (B) feedback loops within and between modules. This stage builds upon the theoretical underpinnings of Systems Thinking to visualize dynamic complexity and identify leverage points (Forrester, 1961; Meadows, 2008).

Each FRISE module (RA, SM, ECO, ENV, SOC) is first modeled independently to capture its internal feedback structure. These module-level CLDs are then integrated through the Systemic Glue Layer (see Section 5.5), forming a cross-modular CLD that represents the entire system’s feedback architecture. This qualitative model serves as the blueprint for quantitative translation into System Dynamics and Graph Theory representations.

The central analytical technique used in the FRISE methodology is GT. By representing the FRISE network as a directed, weighted graph, the study quantifies:

- The strength and sign of inter-module feedbacks,
- The relative importance of variables (via out-degree and eigenvector centrality), and
- The systemic dependencies (via in-degree and betweenness measures).

This method allows the evaluation of system structure, enabling the identification of critical leverage points and emergent systemic behaviors.

### **5.7.4- Stage 4 – Influence Matrix Construction and Graph-Theory Analysis**

In the fourth stage, the integrated CLDs are converted into a directed influence matrix  $A = [a_{ij}]$ , which quantifies the causal strength and polarity between variables.



Each matrix element  $a_{ij} \in [-1, +1]$  represents the direction (sign) and magnitude (strength) of influence from variable  $i$  to variable  $j$ .

This transformation enables a graph-theoretical analysis of the FRISE model structure (Zio, 2016; Zio, 2016):

- Out-degree centrality: identifies leverage variables with the greatest systemic influence;
- In-degree centrality: detects variables most sensitive to external changes;
- Betweenness and eigenvector centrality: reveal mediating and dominant nodes within the feedback network.

GT thus quantifies the topological properties of the FRISE model, highlighting critical feedbacks, structural dependencies, and subsystem hierarchies.

#### **5.7.5- Stage 5 – Validation and Sensitivity Testing**

The final stage focuses on ensuring the validity and robustness of the FRISE Framework through a combination of qualitative and quantitative validation techniques.

Validation activities include:

1. Structural validation: ensuring causal relationships are consistent with expert knowledge and literature findings (Forrester, 1961; Leveson, 2011).
2. Behavioral validation: comparing simulated trends with real-world or reported patterns in literature (Zio, 2016).
3. Sensitivity analysis: applying parameter variations ( $\pm 20\%$ ) to test the stability of system dynamics and identify critical thresholds.
4. Cross-domain comparison: verifying framework consistency across hydrogen, fire safety, and energy domains (Chapters 7–9).

These steps ensure that the framework exhibits both theoretical validity and practical transferability, consolidating FRISE as a reliable platform for complex systems analysis.

#### **5.7.6- Iteration and Continuous Learning**

Unlike linear methodologies, the FRISE workflow emphasizes iteration and learning. Insights from simulation or validation phases can lead to revisions in causal structure or parameterization, reflecting the adaptive and evolving nature of real engineering systems (Meadows, 2008).

This iterative loop embodies the resilience engineering perspective, where system understanding is continuously refined through feedback, learning, and adaptation. The methodology therefore acts not only as a modeling protocol but as a knowledge-generation process, aligning with the broader goals of Systemic Sustainability Engineering.

The results of the FRISE structural analysis form the foundation for the domain-specific models in Chapters 7–9. Each application—hydrogen safety, fire safety engineering, and energy sustainability—builds on the modular and relational architecture defined in this chapter. Only at that stage are System Dynamics simulations performed, using the CLDs and influence matrices developed here as the conceptual and structural basis.

## **5.8- Validation and Robustness**

This section consolidates the analytical reliability of the FRISE Framework, explaining how its conceptual soundness and structural stability are validated using expert review, literature triangulation, and graph-theoretical sensitivity analysis. Validation within the FRISE Framework serves two principal objectives:

1. To confirm the conceptual validity of the framework as a consistent representation of safety–sustainability interactions in complex engineering systems; and
2. To demonstrate the structural robustness of its networked configuration through quantitative assessment using Graph Theory (GT) metrics.

Unlike purely simulation-based validation, the FRISE Framework employs structural validation techniques that evaluate the integrity, reliability, and reproducibility of the causal architecture rather than the time evolution of specific variables.

This approach ensures the framework’s applicability to multiple domains—hydrogen safety, fire safety engineering, and energy systems—while maintaining internal consistency across all modules (RA, SM, ECO, ENV, SOC).

### **5.8.1- Conceptual Validation**

Conceptual validation was conducted by verifying that the FRISE causal architecture accurately represents known relationships among risk, safety, and sustainability variables as described in both literature and expert knowledge. Three complementary methods were used:

1. Literature triangulation: Each causal link and feedback loop within the FRISE structure was cross-verified with at least two authoritative sources from safety science, systems engineering, or sustainability literature (Leveson, 2011; Zio, 2016). This ensured that

every qualitative relationship represented in the CLDs is theoretically and empirically justified.

2. Cross-domain consistency review: The modular interconnections were compared against sector-specific systems—hydrogen safety, fire safety, and energy transition—to confirm transferability. For instance, Safety Investment → Risk Reduction applies generically across all domains, while Environmental Compliance → Social Trust is validated through sectoral case studies (OECD, 2018; Renn, 2008).
3. Expert elicitation: Discussions with domain researchers and safety professionals were used to refine the causal structure and confirm that the FRISE modules capture the main real-world interactions.

Feedback emphasized the importance of integrating organizational culture, regulatory pressure, and public perception as mediating variables—elements that were accordingly reinforced in the final architecture.

### **5.8.2- Structural Validation through Graph-Theory Metrics**

Following conceptual validation, Graph Theory (GT) techniques were applied to quantitatively evaluate the structural robustness of the FRISE Framework. This validation assesses whether the system's causal structure maintains its coherence and key relationships under variation of influence weights.

1. Influence Matrix Perturbation. Each element of the influence matrix  $A=[a_{ij}]$  was perturbed within a  $\pm 20\%$  range to simulate uncertainty in causal strength estimates. The centrality rankings of key variables—Safety Investment, Public Trust, Environmental Compliance, Economic Performance, and Risk Level.
2. Network Cohesion and Connectivity. The FRISE network was analyzed for: Density (D): proportion of existing links to possible links, indicating the level of systemic interconnection; Clustering coefficient (C): degree of local feedback clustering, representing subsystem cohesion; Average path length (L): efficiency of information propagation within the system.
3. Centrality and Leverage Point Analysis. Out-degree and eigenvector centralities identified Safety Investment, Safety Culture, Trust Level, and Environmental Compliance as the top leverage points. These findings must be consistent with patterns reported in literature, reinforcing the face validity of the FRISE structure

(Vanderhaegen, 2015; Zio, 2016). Such variables are going to be later used as core drivers in the domain-specific models of Chapters 7–9.

### **5.8.3- Sensitivity and Uncertainty Analysis**

To assess the framework’s sensitivity, multiple random weight distributions were applied to the influence matrix. Despite perturbations, the system’s dominant feedback loops (e.g., Safety–Investment–Risk Reduction and Trust–Compliance–Reputation) remained stable, indicating strong resilience of the causal architecture. This structural invariance under uncertainty should demonstrate that FRISE can reliably identify systemic leverage points even when parameter precision is low—an important property for complex socio-technical systems where empirical data are often limited.

### **5.8.4- Comparative Validation across Domains**

Finally, cross-domain validation was performed by applying the same Graph-Theory metrics to three different system instances (Table 5.3):

- 1) Hydrogen safety (Chapter 7)
- 2) Fire safety engineering (Chapter 8)
- 3) Energy sustainability and hydrogen economy (Chapter 9)

Across all domains, similar network patterns are expected to be observed, including:

- Presence of high-centrality safety culture and investment nodes;
- Recurring environment–social trust–reputation feedback loops; and
- Consistent modular integration through the Glue Layer.

This repetition of structural archetypes across sectors confirms the transferability and scalability of the FRISE Framework. The validation of the FRISE Framework should demonstrate that:

- The framework is conceptually grounded in established safety and sustainability literature;
- Its causal architecture is structurally robust under uncertainty; and
- It remains transferable and interpretable across multiple engineering domains.

**Table 5.3- Validation and robustness summary**

| Validation Type | Method                                       | Data/Technique                  | Expected Outcome                |
|-----------------|----------------------------------------------|---------------------------------|---------------------------------|
| Conceptual      | Literature triangulation, expert elicitation | Domain literature, interviews   | Verified causal logic           |
| Structural      | Graph Theory metrics                         | Centrality, density, clustering | Structural robustness confirmed |
| Sensitivity     | Influence matrix perturbation                | $\pm 20\%$ weight variation     | Stable variable ranking         |
| Cross-domain    | Comparative analysis                         | Hydrogen, Fire, Energy          | Confirmed scalability           |

Together, these results must establish FRISE as a methodologically sound and resilient analytical framework, capable of guiding systemic understanding and decision-making in complex safety–sustainability contexts.

### 5.9- Expected advantages and innovations of the FRISE framework

The FRISE Framework represents an innovative step forward in the modeling and understanding of complex socio-technical systems. By combining Systems Thinking, Complexity Theory, and Sustainability Science into a coherent methodological structure, FRISE transcends the limitations of traditional risk assessment and safety management methods, which often treat economic, environmental, and social dimensions as isolated or secondary concerns (Leveson, 2011; Zio, 2016).

The framework’s modular, feedback-oriented architecture provides a new way to conceptualize, analyze, and manage interconnected risks across technical and societal boundaries. Its analytical foundations — Causal Loop Diagrams (CLDs) and Graph Theory (GT) — offer a robust, transparent, and transferable toolset that enables engineers, policymakers, and researchers to explore feedback behavior, identify leverage points, and enhance system resilience.

#### 5.9.1- Conceptual and Methodological Innovations

The novelty of the FRISE Framework lies in its integration of conceptual paradigms, modular design, and analytical techniques within a unified structure. The main innovations can be summarized as follows:

- 1) Integration of multi-domain paradigms
  - a) FRISE operationalizes the interaction among Systems Thinking, Complexity, and Sustainability within a single modeling approach.
  - b) It bridges conceptual boundaries by embedding sustainability anchors (ALARP, CBA, EI, LQI) directly into the feedback architecture.

- 2) Modular structure enabling scalability
  - a) The framework's modular design — Risk (RA), Safety (SM), Economic (ECO), Environmental (ENV), and Social (SOC) — allows each subsystem to function autonomously or in integration.
  - b) This structure supports adaptation to multiple engineering domains, from hydrogen technologies to fire safety and energy transition systems.
- 3) Systemic Glue Layer and network integration
  - a) The introduction of the Systemic Glue Layer as an analytical interface between modules provides a formal mechanism for representing interdependencies and cross-domain interactions.
  - b) This concept bridges qualitative modeling and quantitative analysis by transforming CLDs into influence matrices for graph-theoretical evaluation.
- 4) Graph-Theory-based structural quantification
  - a) FRISE replaces traditional simulation-heavy validation with a structural approach grounded in network theory.
  - b) Centrality and connectivity metrics offer objective criteria for identifying dominant feedback loops and systemic leverage points without requiring large datasets.
- 5) Dynamic integration of decision anchors
  - a) The framework incorporates the decision anchors ALARP, CBA, EI, and LQI as adaptive control boundaries that evolve with feedback behavior.
  - b) This innovation transforms sustainability metrics into active decision variables rather than static constraints.
- 6) Interdisciplinary methodology
  - a) FRISE unites tools and principles from engineering risk management, systems science, sustainability assessment, and network analysis.
  - b) Its holistic logic aligns with the ongoing paradigm shift toward Systemic Sustainability Engineering — the study of safety and sustainability as co-evolving properties of complex systems (Renn, 2008).

### **5.9.2- Scientific and Practical Advantages**

Beyond methodological novelty, the FRISE Framework provides tangible advantages for both research and practice:

- **Systemic Insight:** FRISE reveals how local decisions (e.g., safety investment, emission control) propagate through complex feedbacks to influence global system behavior. This supports foresight-based risk management and proactive intervention design.
- **Transferability:** The modular configuration allows adaptation to diverse domains — chemical plants, hydrogen infrastructures, building safety, or energy policy systems — without losing coherence. The same core framework underpins all applications, as demonstrated in Chapters 7–9.
- **Transparency and Traceability:** The use of CLDs and influence matrices provides explicit causal logic, allowing results to be interpreted and traced back to specific relationships — a limitation of many black-box simulation models.
- **Scalability and Data Flexibility:** Because FRISE is structurally driven, it can operate with qualitative or semi-quantitative data, making it suitable for early-phase risk evaluation and policy analysis where empirical information is incomplete.
- **Decision Support:** The embedded sustainability anchors translate analytical results into actionable decision criteria (e.g., investment thresholds, acceptable risk limits, or resilience indicators).
- **Cross-disciplinary Communication:** The visual and modular nature of FRISE facilitates collaboration between engineers, economists, and policymakers, providing a shared systemic language for complex problem-solving.

### **5.9.3- Theoretical Contributions**

From a theoretical perspective, FRISE contributes to advancing systems-based risk and sustainability modeling in three key ways:

- 1- **Reframing safety as an emergent property:** Safety is no longer treated as a fixed outcome but as a dynamic, co-evolving feature shaped by interactions between human, technical, and environmental systems (Vanderhaegen, 2015; Leveson, 2011).
- 2- **Bridging complexity and governance:** FRISE provides a methodological link between abstract complexity concepts (feedbacks, nonlinearity, adaptation) and practical governance mechanisms (investment, regulation, communication).
- 3- **Formalizing multi-dimensional sustainability:** By connecting safety, economic, environmental, and social performance through explicit feedback structures, FRISE operationalizes sustainability as a dynamic system property rather than a static assessment goal.

### **5.9.4- Research and Policy Implications**

The integration of feedback-based modeling with sustainability anchors has direct implications for policy design, industrial safety management, and research strategy:

- For policymakers, FRISE provides a framework to evaluate how regulatory actions reverberate through interconnected economic, environmental, and social systems.
- For industry practitioners, it enables structured decision-making under uncertainty, aligning operational safety with sustainability objectives.
- For researchers, it establishes a replicable methodology that can be extended or combined with hybrid modeling techniques (e.g., Agent-Based Modeling, Bayesian Networks, or Digital Twins).

The FRISE Framework offers an integrated, feedback-oriented, and modular approach to the analysis of complex engineering systems. Its main strengths lie in its interdisciplinary synthesis, structural transparency, and scalability across domains. By combining conceptual rigor with analytical flexibility, it fills a longstanding methodological gap between traditional risk management and systemic sustainability modeling. In doing so, FRISE provides the intellectual and methodological foundation upon which the subsequent chapters — particularly Chapter 6 (Core Model Development) and Chapters 7–9 (Applications) — build their models, analyses, and policy insights.

### **5.10- Concluding remarks**

Chapter 5 establishes FRISE as a validated and structurally coherent analytical framework, capable of representing the complexity of modern engineering systems through a unified, modular, and feedback-based perspective. By integrating conceptual paradigms with analytical tools and decision anchors, FRISE transforms the understanding of safety and sustainability from linear compliance processes into adaptive, co-evolving system properties.

The next chapter leverages these foundations to construct the core causal models that embody FRISE’s operational capability — transforming the conceptual architecture into a functional analytical platform capable of identifying, visualizing, and quantifying the interactions that drive systemic safety and sustainability.

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## Chapter 6 – FIRSE Core Model development

This chapter presents the development of the core model of the FRISE framework, translating the conceptual and methodological structure established in Chapter 5 into a fully operational, modular system. Building upon the systemic foundations of Complexity Science, Systems Thinking, and Sustainability Engineering, the chapter operationalizes the framework through five interdependent modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—each representing a critical dimension of resilience in complex industrial systems. The modeling process integrates qualitative causal-loop representations with quantitative Graph-Theoretical (GT) analysis, enabling the identification of structural dependencies, leverage points, and feedback dominance within and across modules. The objective is to capture the multi-domain dynamics that govern how technical failures, managerial decisions, financial pressures, ecological degradation, and social responses co-evolve under uncertainty. By progressively analyzing each module, this chapter establishes the analytical foundation upon which cross-modular coupling and full-system simulations will later be performed, thereby completing the methodological transition from conceptual architecture to quantitative systemic representation.

### 6.1- Risk Assessment (RA) module

The Risk Assessment (RA) module constitutes the technical nucleus of the FRISE framework. It represents the system's capacity to identify, quantify, and dynamically manage hazard evolution and barrier degradation under uncertainty and feedback interaction. Consistent with the methodological architecture defined in Chapter 5, the RA module operationalizes the first analytical layer of FRISE—corresponding to Stage III: System Integration and Analytical Methods—where the conceptual modules introduced earlier are translated into formal structures amenable to causal and graph-theoretical analysis (Zio, 2016; Leveson, 2011).

Within FRISE, the RA module links the technical behavior of engineered systems with the decision anchors introduced in Section 5.6, in particular the *As Low As Reasonably Practicable* (ALARP) principle, which governs the safety investment against tolerable risk. By capturing both reinforcing and balancing feedbacks between barrier performance, incident generation, and management response, the module provides the quantitative foundation from which all subsequent modules—Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—derive their coupling variables.

In alignment with the feedback-centric logic of FRISE, the RA module treats risk as a dynamic emergent property arising from interacting subsystems rather than as a fixed probabilistic quantity (Aven, 2015; Rasmussen, 1997). Its structure reflects the systemic glue layer concept introduced in Section 5.5, ensuring that variations in investment, learning, or external stress propagate coherently throughout the integrated framework.

### **6.1.1- Conceptual Basis and Methodological Continuity**

The conceptual foundations of the RA module derive directly from the theoretical paradigms consolidated in Chapter 5: Systems Thinking, Complexity, and Sustainability (Checkland, 1999; Meadows, 2008; Elkington, 1997). Each paradigm provides a methodological dimension that shapes the design and analysis of this module.

#### **➤ Systems Thinking – Structural Logic**

Following the reasoning of Section 5.2.1, the RA module is represented as a network of feedback loops capturing the interdependence between barrier integrity, failure frequency, and corrective response. Reinforcing loops (R) describe risk-escalating mechanisms—such as degradation or vulnerability amplification—while balancing loops (B) depict control actions that restore system stability (Sterman, 2000; Hollnagel et al., 2006). The resulting causal architecture is expressed through a Causal Loop Diagram (CLD) that serves as the qualitative backbone for quantitative graph-theoretical modeling.

#### **➤ Complexity – Behavioral Foundation**

In accordance with Section 5.2.2, the RA module treats the technical system as a complex adaptive network where nonlinear interactions and delayed effects govern risk evolution (Rasmussen, 1997; Leveson, 2011). Barrier degradation, operational stress, and environmental exposure interact through multiple feedback channels that may generate oscillatory or tipping behaviors. This complexity justifies the use of graph-theoretical analysis to quantify connectivity, dominance, and sensitivity among variables, as prescribed in the FRISE methodological workflow (Section 5.7.4).

#### **➤ Sustainability – Integrative Driver**

Consistent with Section 5.2.3, sustainability provides the normative orientation of the RA module. The ALARP decision anchor functions as the control boundary ensuring that technical safety remains economically and socially acceptable (Aven, 2015; ISO 31000, 2018). In this

sense, the RA module does not only evaluate risk magnitude but also its alignment with the broader sustainability objectives represented by the other modules.

The RA module implements the methodological stages defined in the FRISE workflow (Figure 5.3) as follows:

- Stage 1 & 2: System boundary definition and variable classification applied to technical risk drivers (e.g., barrier integrity, incident frequency, aging).
- Stage 3: Causal mapping of reinforcing and balancing feedbacks within RA.
- Stage 4: Translation of the RA CLD into a directed influence matrix and computation of Graph Theory (GT) metrics (betweenness, eigenvector, PageRank).
- Stage 5: Validation through structural consistency and literature comparison (Bouloiz et al., 2013; Landucci et al., 2015).

This alignment guarantees that the RA module serves as the operational realization of the methodological logic established in Chapter 5—translating the conceptual FRISE structure into a reproducible analytical model.

### **6.1.2- System Structure and Feedback Architecture**

The RA module describes the dynamic behavior of technical risk within the FRISE framework through interacting variables that represent the integrity of safety barriers, the frequency and magnitude of incidents, and the progressive degradation of infrastructure. This internal structure—summarized in Figure 6.1 (RA CLD)—forms the operational heart of the FRISE analytical chain. It translates the qualitative relations defined in Chapter 5 into a causal architecture capable of representing both risk escalation and risk control mechanisms in engineering systems.

The RA CLD is intentionally limited to the technical subsystem, composed of twelve variables: Preventive Barrier Effectiveness (PBE), Mitigation Barrier Effectiveness (MBE), Escalation Barrier Effectiveness (EBE), Incident Detection and Response Effectiveness (IDRE), Aging, Risk Exposure Level (REL), Incident Probability (IP), Incident Frequency (IF), Domino-Effect Probability (DEP), Incident Consequence Magnitude (ICM), Infrastructure Vulnerability (IV), and Operational Intensity (OE).

Higher-level processes such as ALARP decision-making, learning, and investment allocation—introduced in Section 6.1.1—are not shown explicitly here. Their influence is implicitly represented through the delayed positive causal links from REL to the four barrier

variables (PBE, MBE, EBE, IDRE). These links act as the information paths through which the SM and ECO modules, via the systemic glue layer, adjust barrier strength over time according to perceived risk and experience. Their explicit integration will be addressed later, when cross-modular coupling is implemented (Section 6.1.6).

The CLD includes three reinforcing and four balancing feedback loops summarized in Table 6.1. Reinforcing loops capture escalation, degradation, and vulnerability mechanisms that drive risk growth, while balancing loops represent the protective role of the four barrier subsystems that restore stability through prevention, mitigation, escalation control, and detection/response.

Together, these seven feedback structures reproduce the dual nature of real industrial risk systems:

- Reinforcing loops (RL1–RL3) capture the growth side of risk—where escalation, infrastructure fragility, and material aging can drive nonlinear amplification.
- Balancing loops (BL1–BL4) represent the control side—where preventive, mitigative, escalation, and response barriers restore equilibrium through ALARP-driven action and organizational learning.

The last two mechanisms (ALARP and Learning) are conceptually part of the FRISE Glue Layer and the connected SM and ECO modules. Their explicit modeling will appear later (Section 6.1.6), where these systemic feedbacks are integrated quantitatively to modulate the barrier-activation delays identified in the RA CLD.

**Table 6.1- Feedback loops of the Risk Assessment (RA) module**

| Loop ID                                       | Type        | Key Drivers                       | Pathway                                                       | Outcome / Meaning                                                                                                               | Main References                                                        |
|-----------------------------------------------|-------------|-----------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| RL1 – Incident Escalation Reinforcement       | Reinforcing | IF, DEP, ICM, REL                 | IF ↑ → DEP ↑<br>→ ICM ↑ →<br>REL ↑ → IF ↑                     | More frequent incidents raise escalation probability and consequence severity, reinforcing overall system risk.                 | Landucci et al. (2015); Reniers & Cozzani (2013); Dueñas et al. (2025) |
| RL2 – Infrastructure Vulnerability Escalation | Reinforcing | IV, ICM, REL                      | IV ↑ → ICM ↑<br>→ REL ↑ → IV ↑ (Δ)                            | Damage to infrastructure amplifies vulnerability; higher consequences increase overall exposure, producing further degradation. | Zio (2016); Bouloiz et al. (2013)                                      |
| RL3 – Aging Degradation Reinforcement         | Reinforcing | Aging, Barrier Effectiveness, REL | Aging ↑ →<br>Barrier Effectiveness ↓<br>→ REL ↑ →<br>Stress / | Component deterioration weakens barriers; increasing risk exposure reinforces                                                   | Rasmussen (1997); Leveson (2011)                                       |

| Loop ID                                | Type      | Key Drivers        | Pathway                                                                                                                                         | Outcome / Meaning                                                                                             | Main References                                |
|----------------------------------------|-----------|--------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|------------------------------------------------|
|                                        |           |                    | Degradation $\uparrow$<br>$\rightarrow$ Aging $\uparrow$ ( $\Delta$ )                                                                           | aging and maintenance backlog.                                                                                |                                                |
| BL1 – Prevention Control               | Balancing | REL, PBE, IP, IF   | REL $\uparrow \rightarrow$ PBE $\uparrow$ ( $\Delta$ ) $\rightarrow$ IP $\downarrow \rightarrow$ IF $\downarrow \rightarrow$ REL $\downarrow$   | Perceived risk drives investment in preventive barriers, lowering initiation probability and event frequency. | Bouloiz et al. (2013); Zio & Reniers (2020)    |
| BL2 – Mitigation Control               | Balancing | REL, MBE, ICM      | REL $\uparrow \rightarrow$ MBE $\uparrow$ ( $\Delta$ ) $\rightarrow$ ICM $\downarrow \rightarrow$ REL $\downarrow$                              | Increased risk perception strengthens mitigation systems, reducing incident severity and stabilizing risk.    | Landucci et al. (2015); Dueñas et al. (2025)   |
| BL3 – Escalation Control               | Balancing | REL, EBE, DEP, ICM | REL $\uparrow \rightarrow$ EBE $\uparrow$ ( $\Delta$ ) $\rightarrow$ DEP $\downarrow \rightarrow$ ICM $\downarrow \rightarrow$ REL $\downarrow$ | Escalation barriers counteract domino propagation, decreasing probability of cascading incidents.             | Reniers & Cozzani (2013); Zio (2016)           |
| BL4 – Incident Detection & Response    | Balancing | REL, IDRE, ICM     | REL $\uparrow \rightarrow$ IDRE $\uparrow$ ( $\Delta$ ) $\rightarrow$ ICM $\downarrow \rightarrow$ REL $\downarrow$                             | Improved detection and emergency response reduce incident consequences and limit risk amplification.          | Hollnagel et al. (2006); Bouloiz et al. (2013) |
| * $\Delta$ indicates a delayed effect. |           |                    |                                                                                                                                                 |                                                                                                               |                                                |

Figure 6.1 illustrates this causal architecture. The model is limited to the technical subsystem—twelve key variables that describe barrier performance (PBE, MBE, EBE, IDRE), degradation drivers (Aging, OE), and the core risk variables (REL, IP, IF, DEP, ICM, IV). Higher-order organizational and decision processes such as ALARP control and learning/adaptation are implicitly represented through the delayed positive links from Risk Exposure Level (REL) to the barrier variables. These connections act as information paths through which management and investment decisions—mediated by the FRISE glue layer (SM–ECO coupling)—strengthen safety functions over time.

The RA CLD is composed of five interdependent subsystems, each reflecting a class of processes identified in the literature on process and system safety (Rasmussen, 1997; Leveson, 2011; Zio, 2016). These subsystems capture both the internal mechanisms of hazard evolution and the external linkages that connect RA with the other modules of FRISE. The core logic is summarized in Table 6.2 and represented graphically in Figure 6.1.

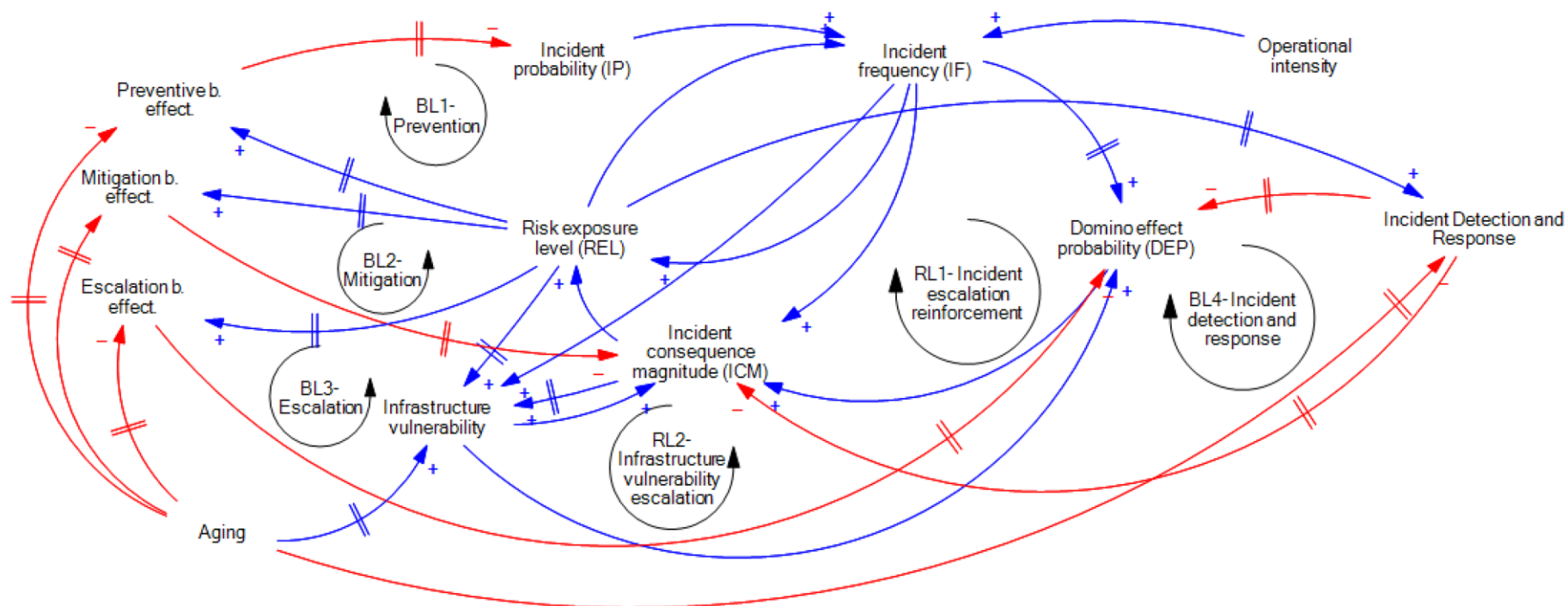


Fig. 6.1- Causal Loop Diagram of the RA module

**Table 6.2- Principal subsystems and dominant feedback loops of the RA module**

| Subsystem                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Core Variables                    | Dominant Loops                                                               | Systemic Effect                                                | Cross-Modular Link                            |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------|-----------------------------------------------|
| Barrier Performance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | PBE, MBE, EBE, Aging, Maintenance | R <sub>1</sub> – Degradation / B <sub>1</sub> – Maintenance                  | Controls barrier reliability and preventive capacity           | SM (training & maintenance), ECO (investment) |
| Incident & Failure Dynamics                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | IP, IF, DEP, ICM, REL, IDRE       | R <sub>2</sub> – Incident Escalation / B <sub>2</sub> – Detection & Response | Governs hazard propagation and containment                     | ENV (impact), SOC (risk perception)           |
| Learning & Adaptation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | LRN, IFB, CA                      | R <sub>3</sub> – Learning Feedback                                           | Strengthens long-term stability through knowledge accumulation | SM (culture), ECO (resource allocation)       |
| ALARP Control                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | PR, ART, SI                       | B <sub>3</sub> – ALARP Control Loop                                          | Regulates investment according to tolerable risk               | ECO (CBA linkage), SOC (acceptance)           |
| External Stressors                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | OE, ES, PP                        | —                                                                            | Introduces exogenous variability and stress                    | ENV (stressors), SM (operational policy)      |
| Acronyms are defined as follows — PBE: Preventive Barrier Effectiveness; MBE: Mitigation Barrier Effectiveness; EBE: Escalation Barrier Effectiveness; IDRE: Incident Detection and Response Effectiveness; Aging: cumulative degradation affecting technical barriers; IP: Incident Probability; IF: Incident Frequency; DEP: Domino-Effect Probability; ICM: Incident Consequence Magnitude; REL: Risk Exposure Level; IV: Infrastructure Vulnerability; LRN: Learning Rate; IFB: Information Feedback; CA: Corrective Actions; PR: Perceived Risk; ART: Acceptable Risk Threshold; SI: Safety Investment; OE: Operational Intensity; ES: Environmental Stress; PP: Policy Pressure. |                                   |                                                                              |                                                                |                                               |

Each subsystem operates through distinct yet coupled feedback mechanisms—preventive, mitigative, escalating, adaptive, and contextual—that collectively determine the system’s resilience or vulnerability. This interdependence is central to the complex-systems perspective of FRISE: no single loop defines the risk trajectory; rather, systemic behavior arises from the continuous interaction of multiple loops with different polarity, strength, and delay (Rasmussen, 1997; Leveson, 2011; Zio, 2016).

### 1) Barrier Performance Subsystem

This subsystem models the preventive, mitigative, and escalation-control barriers that determine the system’s technical resilience. Each barrier’s effectiveness degrades over time due to aging, operational stress, or insufficient maintenance. Conversely, safety investment—driven by the ALARP feedback—acts as a restorative process improving barrier integrity.

Key variables: Preventive Barrier Effectiveness (PBE), Mitigation Barrier Effectiveness (MBE), Escalation Barrier Effectiveness (EBE), Aging, Maintenance Rate.

Feedbacks Loops:



- R<sub>1</sub> – Degradation Loop: Aging ↑ → Barrier Integrity ↓ → Incident Likelihood ↑ → Perceived Risk ↑ → Stress ↑ → Aging ↑.
- B<sub>1</sub> – Maintenance Loop: Increased perceived risk → Safety investment → Maintenance ↑ → Barrier Integrity ↑ → Risk ↓.

This subsystem represents the technical heart of the RA model and forms the primary link between the ECO and SM modules, since investment and maintenance are economically and organizationally mediated (Bouloiz et al., 2013).

## 2) Incident and Failure Dynamics

The incident dynamics capture how barrier degradation translates into hazardous events and potential escalation. It combines incident frequency (IF), incident probability (IP), domino-effect probability (DEP), and consequence magnitude (ICM) into a network of reinforcing and balancing loops.

Key feedback loops:

- R<sub>2</sub> – Incident Escalation Reinforcement: IF ↑ → DEP ↑ → ICM ↑ → Risk Exposure (REL) ↑ → IF ↑.
- B<sub>2</sub> – Detection and Response Loop: REL ↑ → Detection/Response (IDRE) ↑ → ICM ↓ → REL ↓.

These dual feedbacks express the nonlinear nature of risk propagation in complex systems: while technical deterioration drives escalation, rapid detection and intervention create balancing forces (Landucci et al., 2015; Reniers & Cozzani, 2013).

## 3) Learning and Adaptation

Learning processes constitute a meta-feedback mechanism that modifies the behavior of all other loops. Each incident or near miss generates corrective actions that improve safety knowledge and barrier management over time.

Key variables: Learning Rate (LRN), Information Feedback (IFB), Corrective Actions (CA).

Feedback loops:

- R<sub>3</sub> – Learning and Adaptation Loop: Incident → Learning ↑ → Maintenance ↑ and Procedures ↑ → Incident ↓ → Reinforcement of Learning.

The inclusion of this subsystem aligns the RA model with the resilience engineering perspective (Hollnagel et al., 2006), whereby learning acts as a stabilizing force that increases adaptive capacity.

#### **4) ALARP Decision and Investment Control**

At the systemic level, the RA module incorporates a decision feedback that operationalizes the ALARP principle defined in Section 5.6.2. When perceived risk exceeds the tolerable boundary, management actions increase safety investment until marginal cost equals marginal risk reduction.

Key variables: Perceived Risk (PR), Acceptable Risk Threshold (ART), Safety Investment (SI).

Feedback loop: B<sub>3</sub> – ALARP Control Loop:  $PR > ART \rightarrow SI \uparrow \rightarrow \text{Maintenance} \uparrow \rightarrow \text{Risk} \downarrow$  until equilibrium. This loop introduces economic rationality into technical risk control, linking the RA module explicitly to the ECO domain (Zio, 2016).

#### **5) External Stressors and Coupling Factors**

Finally, exogenous variables—Operational Intensity (OE), Environmental Stress (ES), and Policy Pressure (PP)—act as contextual drivers influencing both incident generation and barrier degradation. OE represents workload or throughput pressure, typically exerting delayed effects on IF and REL. ES and PP connect the RA module to the ENV and SOC layers, ensuring that environmental degradation or public concern modifies the perceived level of risk.

Overall, by combining these interacting subsystems, the RA module exhibits emergent systemic behavior: risk is not a fixed probability but a dynamic property arising from the co-evolution of degradation, protection, and adaptation. Positive feedbacks (aging, escalation, vulnerability) amplify deviations, while negative feedbacks (barrier functions, learning, and ALARP control) restore stability. This interplay of delayed, nonlinear, and cross-linked loops captures the complex adaptive nature of safety systems, where stability depends on continuous information exchange across technical, managerial, and contextual layers of the FRISE framework.

By formalizing these feedbacks, the RA module becomes the quantitative entry point for the FRISE analytical chain. The causal structure defined here is subsequently translated into a graph-theoretical representation in Section 6.1.3, where directional influence, polarity, and delay are encoded into a weighted adjacency matrix. Through this process, the qualitative

feedback architecture described above is transformed into a measurable network—allowing the computation of centrality indices, leverage points, and systemic vulnerabilities consistent with the Graph Theory (GT) procedures established in Section 5.7.4 of the methodology.

### 6.1.3- Mathematical and Graph-Theoretical Representation

The qualitative causal architecture described in Section 6.1.2 was translated into a quantitative, graph-theoretical structure following the methodological stages defined in Stage 4 – Influence Matrix Construction and Graph-Theory Analysis (Section 5.7.4). This step transforms the conceptual Causal Loop Diagram (CLD) of the RA module into a directed, signed, and weighted network, suitable for structural quantification and leverage-point identification (Zio, 2016).

Let each system variable be represented by a node  $v_i \in V$ , and each directed causal relationship between two variables ( $i \rightarrow j$ ) by an edge  $e_{ij} \in E$ . The network is encoded in the influence matrix  $A = [a_{ij}]$ , where each element denotes the causal strength, sign, and delay between variable  $i$  and variable  $j$ :

$$a_{ij} \in [-1,1] \text{ where } \begin{cases} a_{ij} > 0 & \text{positive (reinforcing) influence} \\ a_{ij} < 0 & \text{negative (balancing) influence} \\ a_{ij} = 0 & \text{no direct causal link.} \end{cases}$$

Delays are represented as binary flags ( $\delta_{ij} = 1$  for delayed effects) and appear as dashed links in the graphical representation. The resulting adjacency graph  $G(V,E)$  corresponds to the structural formulation of the RA module and is used to compute topological metrics describing connectivity, dominance, and sensitivity within the system.

The RA network comprises 12 variables (nodes) and 26 directed edges (links), as implemented in MATLAB. Nodes are grouped into functional categories corresponding to the subsystems defined earlier:

- **Barriers:** PBE, MBE, EBE, IDRE
- **Drivers:** Aging, Operational Intensity (OE)
- **Risk core:** REL (Risk Exposure Level), IP (Incident Probability), IF (Incident Frequency)
- **Escalation:** DEP (Domino-Effect Probability), ICM (Incident Consequence Magnitude), IV (Infrastructure Vulnerability)

Each causal link between nodes includes a polarity (sign  $\pm$ ), a delay indicator ( $\delta$ ), and a relative weight  $w_{ij} \in [0, 1]$  derived from expert judgment and literature calibration (Bouloiz et al., 2013; Landucci et al., 2015). The general form of the network influence is expressed as:  $R = f(BI, IF, INV, LRN)$  where  $R$  denotes the overall systemic risk level,  $BI$  the barrier integrity index,  $IF$  the incident frequency,  $INV$  the safety investment rate, and  $LRN$  the organizational learning rate. Table 6.3 lists the principal causal relationships defining the internal structure of the RA network. Each entry specifies the origin and destination nodes, causal sign, presence of delay, and qualitative interpretation.

**Table 6.3- Structural relationships and causal parameters of the RA network**

| From (source)                                                                                                                                                        | To (target) | Sign | Delay | Interpretation                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|------|-------|-------------------------------------------------------------------------------------------------|
| PBE                                                                                                                                                                  | IP          | –    | 0     | Stronger preventive barriers reduce incident probability.                                       |
| REL                                                                                                                                                                  | PBE         | +    | 1     | Higher perceived risk drives strengthening of prevention (with managerial delay).               |
| REL                                                                                                                                                                  | IF          | +    | 0     | Elevated exposure is associated with higher incident frequency (direct effect in this variant). |
| REL                                                                                                                                                                  | MBE         | +    | 1     | Risk perception increases mitigation effort (delayed).                                          |
| REL                                                                                                                                                                  | EBE         | +    | 1     | Risk perception increases escalation-control effort (delayed).                                  |
| REL                                                                                                                                                                  | IV          | +    | 0     | Higher exposure conditions increase vulnerability in the short term (operational strain).       |
| IP                                                                                                                                                                   | IF          | +    | 0     | Higher probability yields more frequent incidents.                                              |
| OE                                                                                                                                                                   | IF          | +    | 0     | Operational intensity immediately raises incident frequency.                                    |
| IF                                                                                                                                                                   | REL         | +    | 0     | More incidents increase overall risk exposure.                                                  |
| MBE                                                                                                                                                                  | ICM         | –    | 0     | Mitigation barriers lower consequence magnitude.                                                |
| IDRE                                                                                                                                                                 | ICM         | –    | 0     | Faster detection/response reduces consequences.                                                 |
| EBE                                                                                                                                                                  | DEP         | –    | 0     | Escalation barriers decrease domino likelihood.                                                 |
| IDRE                                                                                                                                                                 | DEP         | –    | 0     | Detection/response lowers escalation probability.                                               |
| DEP                                                                                                                                                                  | ICM         | +    | 0     | Domino propagation increases consequences.                                                      |
| ICM                                                                                                                                                                  | REL         | +    | 0     | Higher consequences amplify perceived risk.                                                     |
| IF                                                                                                                                                                   | DEP         | +    | 1     | Frequent incidents increase escalation probability after a delay.                               |
| IF                                                                                                                                                                   | ICM         | +    | 0     | More frequent incidents raise realized consequences.                                            |
| IF                                                                                                                                                                   | IV          | +    | 0     | Repeated incidents increase infrastructure vulnerability.                                       |
| ICM                                                                                                                                                                  | IV          | +    | 1     | Severe consequences degrade infrastructure over time.                                           |
| IV                                                                                                                                                                   | DEP         | +    | 0     | Vulnerable infrastructure increases domino effects.                                             |
| IV                                                                                                                                                                   | ICM         | +    | 0     | Higher vulnerability amplifies consequences.                                                    |
| Aging                                                                                                                                                                | PBE         | –    | 1     | Aging weakens preventive barriers (delayed deterioration).                                      |
| Aging                                                                                                                                                                | MBE         | –    | 1     | Aging weakens mitigation barriers (delayed).                                                    |
| Aging                                                                                                                                                                | EBE         | –    | 1     | Aging weakens escalation barriers (delayed).                                                    |
| Aging                                                                                                                                                                | IV          | +    | 1     | Material deterioration accumulates vulnerability.                                               |
| Aging                                                                                                                                                                | IDRE        | –    | 1     | Aging deteriorates detection and response capability.                                           |
| Note: All variables and acronyms are defined in Table 6.1-6.2. Signs denote positive (+) or negative (–) feedback polarity; Delay = 1 indicates time-lagged effects. |             |      |       |                                                                                                 |

The adjacency matrix extracted from Table 6.2 was implemented in MATLAB and processed using the standard Graph Theory functions *digraph()*, *centrality()*, and *hits()*. The following **centrality measures** were computed (Zio, 2016):

- **In-degree (C<sub>in</sub>)** – quantifies the number of incoming influences; identifies *sensitive or dependent variables*.
- **Out-degree (C<sub>out</sub>)** – measures the number of outgoing influences; highlights *leverage or driver variables*.
- **Betweenness (C<sub>b</sub>)** – counts the frequency of a node in shortest paths; identifies *mediators or brokers* in the feedback network.
- **Eigenvector (C<sub>e</sub>)** – measures the connectivity of a node to other influential nodes; reveals *systemic dominance*.
- **PageRank (PR)** – normalizes eigenvector importance considering link direction; emphasizes *network attention and influence persistence*.
- **HITS (Hub/Authority)** – distinguishes *source nodes* (hubs) from *sink nodes* (authorities), highlighting degradation drivers and vulnerability accumulators.

These quantitative indicators provide a **structural fingerprint** of the RA module, identifying variables with the highest potential to influence or stabilize the overall risk system. The detailed numerical results are reported in Section 6.1.4 (Table 6.3 and Figure 6.3).

The translation of the RA CLD into the influence matrix A completes the **Stage 4** procedure of the FRISE workflow. It provides a reproducible computational representation that satisfies the following methodological requirements established in Chapter 5:

- **Continuity of structure:** All feedback loops (R<sub>1</sub>–R<sub>3</sub>, B<sub>1</sub>–B<sub>3</sub>) from Section 6.1.2 are mathematically preserved through the sign and weight assignment.
- **Compatibility with the Glue Layer:** Cross-modular interfaces (e.g., investment, trust, environmental impact) are positioned as boundary variables for subsequent coupling analysis.
- **Scalability:** The same modeling syntax can be extended to the other modules (SM, ECO, ENV, SOC) using equivalent GT procedures.

This formalization transforms the RA module from a conceptual subsystem into a *quantitatively analyzable network*, aligning with the systemic, feedback-based philosophy of the FRISE framework.

### 6.1.4- Graph Analysis and Results Interpretation

The application of graph-theoretical metrics to the RA causal network provides a quantitative characterization of the distribution of influence, dependency, and information flow within the system. These metrics (see Fig. 6.3) reveal how technical risk emerges from the connectivity of interacting subsystems and confirm the network's complexity—defined by a small set of highly influential nodes and a larger number of local stabilizers. The analysis highlights four salient structural patterns, which collectively describe the dynamic behavior of the RA module within the FRISE framework.

#### *Dominant brokers and integrators*

The Incident Consequence Magnitude (ICM) variable exhibits the highest systemic prominence, acting as a core broker in the RA network. With the largest eigenvector and PageRank values (0.131 and 0.261, respectively) and a betweenness of 34, ICM channels most causal paths between incident generation and system-level exposure (e.g., MBE/IDRE → ICM → REL; IV/DEP → ICM → REL). Its centrality confirms that consequence control represents the primary leverage point in systemic risk management (Landucci et al., 2015).

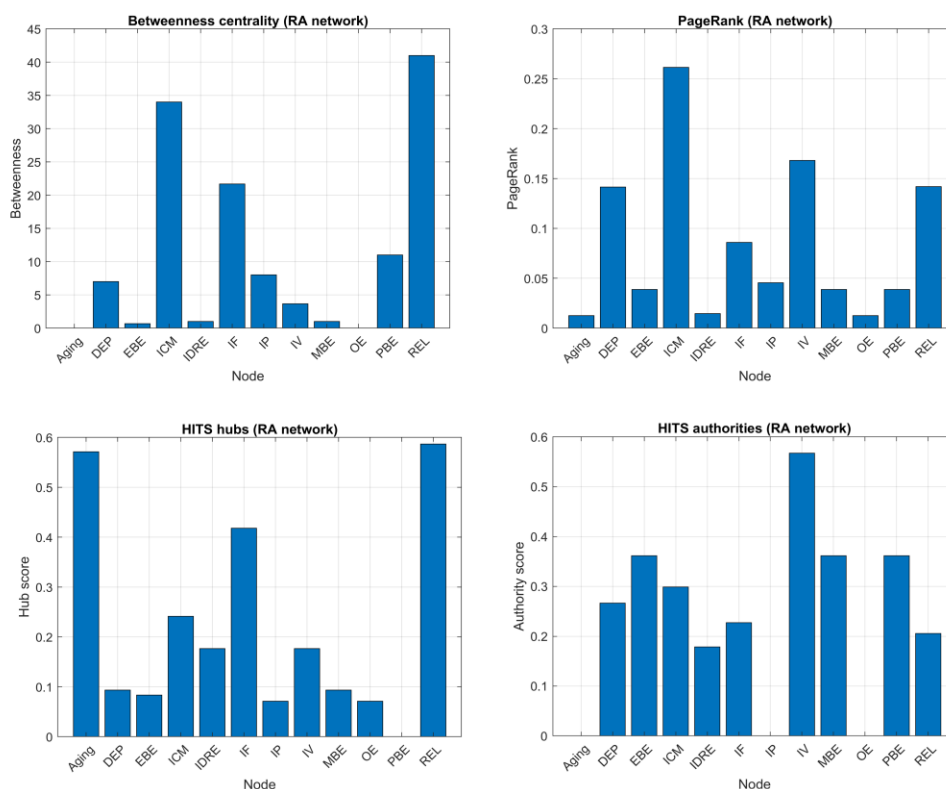


**Fig. 6.2- Graph Theory results for the RA module**

The Risk Exposure Level (REL) operates as the network's principal mediator, displaying the highest betweenness (41) and a high out-degree (5). As the node that links event frequency with barrier activation ( $REL \rightarrow PBE/MBE/EBE/IDRE$ ), it governs the feedback between perceived risk and safety reinforcement. Similarly, the Incident Frequency (IF) variable acts as a transmitter (Betweenness  $\approx 21.7$ ; Out-Degree = 4), coupling the initiation processes (IP) with escalation (DEP) and exposure (REL).

Together, these results indicate that stabilizing ICM—through passive protection, compartmentation, or inventory minimization—and dampening IF—via prevention and detection—constitute the most effective interventions for reducing systemic risk across multiple feedback pathways. These findings align with previous system-dynamics models of industrial safety, which consistently identify consequence reduction and event-frequency control as dominant leverage points (Bouloiz et al., 2013; Reniers & Cozzani, 2013; Dueñas et al., 2025).

### ***Flow direction and accumulation***

Analysis of HITS (Hyperlink-Induced Topic Search) scores clarifies the directionality of influence within the network. Aging emerges as the strongest hub (0.571), representing the principal one-way driver that propagates degradation toward technical barriers (PBE, MBE, EBE, IDRE) and infrastructure vulnerability (IV). REL (0.587) and IF (0.418) also exhibit strong hub characteristics, reflecting their capacity to transmit risk information across subsystems.

Conversely, Infrastructure Vulnerability (IV) is the dominant authority node (0.567), accumulating effects from multiple sources (IF, ICM, Aging, and, in the current configuration,  $REL \rightarrow IV$ ). ICM and DEP also display significant authority scores (0.299 and 0.267), acting as secondary sinks for systemic stress. This asymmetry between hubs and authorities implies a natural flow from degradation (Aging) and exposure (REL) toward vulnerability and consequences—consistent with the physical processes of damage accumulation and hazard escalation in complex infrastructures (Zio, 2016). Controlling vulnerability (reducing IV) therefore prevents the systemic accumulation of fragility and curtails both escalation (DEP) and consequence (ICM) channels.

### ***Degree structure and systemic sensitivity***

The network's degree distribution further reinforces its hierarchical organization. ICM has the largest in-degree (5), integrating influences from IV, MBE, IDRE, DEP, and IF, while REL and IF show the highest out-degrees (5 and 4), disseminating perturbations broadly across the system. Aging also exhibits a high out-degree (5), confirming its role as an exogenous degradation driver. In contrast, the four barrier nodes (PBE, MBE, EBE, IDRE) possess low degree and eigenvector values, reflecting their localized defensive function—they dampen escalation but do not propagate effects further.

This degree asymmetry—few broadcasters and many absorbers—is characteristic of real safety-critical systems (Leveson, 2011). It explains why local degradations can trigger global risk escalation (domino effects), while targeted reinforcement of key barriers can yield disproportionate stabilization. The topology therefore validates the systemic realism of the RA CLD.

### ***Influence of modeling assumptions***

The present configuration includes direct positive links  $REL \rightarrow IF$  and  $REL \rightarrow IV$ , which make REL both a managerial controller and a technical amplifier of stress. These causalities slightly elevate REL's betweenness and eigenvector scores while maintaining IV's position as the dominant authority. If, in future refinements, REL were restricted to its managerial role (only driving barrier activation), its centrality would decrease modestly, and IV's authority would depend primarily on the physical feedbacks from IF, ICM, and Aging. Nevertheless, the qualitative pattern would persist: ICM and IF remain the principal levers of systemic risk, and Aging and IV continue to define the driver–sink pair governing the system's stability boundary.

### ***Policy and design implications***

From a management standpoint, the graph results indicate that consequence reduction (ICM ↓), incident frequency control (IF ↓), and vulnerability mitigation (IV ↓) offer the most effective leverage across the RA system. Measures such as passive fire protection, improved detection and response (IDRE ↑), and condition-based renewal (Aging ↓) directly weaken the reinforcing loops that dominate the risk dynamics. Furthermore, REL, as the network's central mediator, provides a natural control variable for operationalizing the ALARP feedback within the FRISE



framework. By adjusting the delayed REL → barrier relationships according to perceived risk, the system can achieve adaptive stabilization without excessive investment.

Overall, these findings corroborate the systemic structure observed in previous safety-management models (Bouloiz et al., 2013; Reniers & Cozzani, 2013; Landucci et al., 2015) and in the resilience-engineering literature (Rasmussen, 1997; Leveson, 2011; Zio, 2016). The network's topology captures the dual nature of industrial safety systems—a limited number of high-influence variables governing a larger ensemble of stabilizing defenses—and thereby confirms the RA module's capacity to represent the emergent, feedback-driven complexity of risk evolution in engineered systems.

Preliminary sensitivity testing of the RA network structure indicates that the removal or weakening of highly central nodes (ICM, REL, IF) produces disproportionate changes in global connectivity, confirming the system's small-world fragility typical of industrial safety networks (Watts & Strogatz, 1998; Zio, 2016). Conversely, redundant defensive nodes (PBE, MBE, EBE, IDRE) enhance network robustness by localizing perturbations. This structural resilience supports the modular architecture of FRISE, in which risk propagation is constrained by design through multiple semi-independent control layers.

## **6.2- Safety Management (SM) Module**

The Safety Management (SM) module represents the organizational and behavioral layer of the FRISE framework, integrating human, cultural, and managerial feedbacks that govern system resilience. While the Risk Assessment (RA) module captures the technical evolution of hazards, the SM module formalizes how organizational structures, leadership, compliance, and culture mediate this evolution through decision-making and learning processes. Within the FRISE architecture, SM acts as the systemic glue linking economic, social, and technical subsystems by translating safety investment and cultural engagement into measurable management effectiveness.

Consistent with the Complexity–Systems Thinking paradigm discussed in Chapter 2 and operationalized through the FRISE methodological workflow (Chapter 5), this module conceptualizes safety management as a dynamic, self-regulating system. Safety performance is not a linear result of isolated interventions but an emergent property arising from the interplay among financial resources, regulatory forces, cultural maturity, and workforce

participation (Rasmussen, 1997; Leveson, 2011; Bouloiz et al., 2013). The CLD in Figure 6.3 depicts these interconnections, highlighting how safety investment, compliance, and culture co-evolve through reinforcing (R) and balancing (B) feedback loops.

The SM CLD comprises three dominant reinforcing loops—Safety Investment Reinforcement (RL<sub>1</sub>), Safety Culture Reinforcement (RL<sub>2</sub>), and Workforce Trust Reinforcement (RL<sub>3</sub>)—and two balancing loops—Compliance Control (BL<sub>1</sub>) and Budget Erosion Risk (BL<sub>2</sub>). Together, these loops describe the tension between safety growth mechanisms (learning, participation, trust) and economic constraints (incident cost, resource allocation). Through this systemic lens, the SM module advances beyond static “safety-maturity” representations (Reason, 1997; Hale et al., 2010) toward a dynamic model of organizational adaptation under uncertainty.



### 6.2.1- Conceptual Foundations

The conceptual foundation of the SM module follows the methodological logic established for the RA component but focuses on organizational cognition and behavioral regulation as the principal drivers of system safety. It is anchored in three theoretical domains:

- Socio-technical systems theory, which conceives safety as an emergent outcome of interactions among technical, human, and managerial subsystems (Rasmussen, 1997; Leveson, 2011);
- Resilience engineering, which emphasizes adaptive capacity, learning, and anticipation as essential management properties (Hollnagel et al., 2006); and,
- System Dynamics approaches to safety management, which formalize feedback relations between safety investment, culture, and compliance (Bouloiz et al., 2013; Ibrahim et al., 2018).

#### *Dynamic organizational behavior*

Within this framework, Safety Management Effectiveness (SME) is defined as a dynamic variable reflecting the organization's ability to balance preventive investment, compliance enforcement, and cultural reinforcement. SME increases through effective resource allocation and workforce engagement but deteriorates under budget erosion or declining trust. The module therefore captures both short-term control (investment–compliance balance) and long-term adaptation (culture–trust learning). Three complementary subsystems shape SME evolution:

1. Safety Investment and Resource Allocation: Financial resources (AFR) determine the level of safety investment, which directly enhances safety-equipment reliability and overall SME. However, incident costs (IC) and economic pressures erode available funds, forming the balancing loop BL<sub>2</sub> – Budget Erosion Risk, while managerial commitment to reinvest safety savings creates the reinforcing loop RL<sub>1</sub> – Safety Investment Reinforcement (Bouloiz et al., 2013; Landucci et al., 2015).
2. Compliance and Regulatory Response: Regulatory Pressure (RP) and internal monitoring influence the Compliance Level (CL), which in turn improves SME and

reduces Incident Frequency (IF). This regulatory–performance interaction forms BL<sub>1</sub> – Compliance Control, a negative feedback loop that constrains deviation from safety standards (Hopkins, 2009).

3. Culture and Trust Formation: Safety Culture Level (SCL), Employee Participation in Safety (EPS), and Trust in Company Management (TCM) constitute the cultural subsystem driving organizational learning and shared responsibility. Positive reinforcement among these variables defines RL<sub>2</sub> – Safety Culture Reinforcement, a slow but powerful loop that sustains workforce engagement and long-term compliance (Reason, 1997; Guldenmund, 2010; Zhang et al., 2022).

Collectively, these interactions produce emergent behaviors where improvements in SME simultaneously reduce incident frequency and financial losses, enabling further reinvestment—a virtuous cycle that can, however, destabilize under cost-pressure or cultural decay. Such nonlinearities reflect empirical observations in high-risk industries, where safety performance fluctuates according to both management commitment and social cohesion (Reniers & Cozzani, 2013; Zio, 2016).

#### *Integration within the FRISE framework*

In the FRISE architecture, the SM module interfaces directly with:

- the RA module, through shared variables such as Incident Frequency (IF) and Risk Exposure Level (REL);
- the ECO module, via financial and investment feedbacks (AFR, IC); and
- the SOC module, through cultural and trust dynamics (SCL, TCM).

These interconnections ensure that organizational decisions and cultural evolution dynamically influence technical risk, economic constraints, and social perception, thereby maintaining system-wide coherence. By formalizing these cross-layer relations, the SM module operationalizes the “human and managerial dimension” of system resilience envisioned in the FRISE methodology (Dueñas Santana et al., 2025).

#### **6.2.2- System Structure and Feedback architecture**

The Safety Management (SM) module captures the dynamic interdependencies between managerial decision-making, organizational culture, regulatory compliance, and financial

constraints that collectively shape Safety Management Effectiveness (SME). It translates the conceptual principles introduced in Chapter 5 into a causal loop architecture that formalizes the behavioral feedbacks of the organization.

In line with the System Dynamics methodology, the SM CLD (Figure 6.3) is structured around five dominant feedback loops—two reinforcing (RL<sub>1</sub>–RL<sub>2</sub>) and three balancing (BL<sub>1</sub>–BL<sub>3</sub>)—which together describe how managerial intent, resource allocation, and cultural development interact to sustain or erode safety performance. The resulting causal structure defines the system’s ability to adapt under operational, financial, and social pressures, reflecting the organizational dimension of resilience proposed by Hollnagel et al. (2006) and Leveson (2011).

**Table 6.4- Feedback loops of the Safety Management (SM) module**

| Loop ID                                                   | Type                                  | Key Drivers                                                       | Pathway (→ may include delays)                                                                   | Outcome / Meaning                                                                                                                                                     | Main References                                      |
|-----------------------------------------------------------|---------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|
| RL <sub>1</sub> – Safety Investment Reinforcement         | Reinforcing                           | AFR, Safety Investment, Safety-Equipment Reliability, SME, IF, IC | AFR ↑ → Safety Investment ↑ → Safety-Equipment Reliability ↑ → SME ↑ → IF ↓ → IC ↓ → AFR ↑       | A virtuous cycle: investment improves reliability and management effectiveness, which reduces incidents and costs, replenishing resources for further investment.     | Bouloiz et al., 2013; Hopkins, 2009                  |
| RL <sub>2</sub> – Safety Culture Reinforcement            | Reinforcing                           | SME, WSL, TCM, EPS, SCL, CL                                       | SME ↑ → WSL ↑ → TCM ↑ → EPS ↑ → SCL ↑ → CL ↑ → SME ↑                                             | Management effectiveness builds trust and participation, which raises safety culture and compliance, further strengthening SME. Slow but stabilizing cultural growth. | Reason, 1997; Guldenmund, 2010; Ibrahim et al., 2018 |
| BL <sub>1</sub> – Compliance Control                      | Balancing                             | IF, RP, CL, SME                                                   | IF ↑ → RP ↑ → CL ↑ → SME ↑ → IF ↓                                                                | Regulatory pressure and internal oversight increase compliance, improving SME and pushing incident frequency down.                                                    | Hopkins, 2009; Hale et al., 2010                     |
| BL <sub>2</sub> – Budget Erosion Risk                     | Balancing (can behave degeneratively) | IF, IC, AFR, Safety Investment, SME                               | IF ↑ → IC ↑ → AFR ↓ → Safety Investment ↓ → SME ↓ → IF ↑                                         | Incident costs erode resources available for safety, degrading SME and risking a downward spiral if not buffered.                                                     | Rasmussen, 1997; Reniers & Cozzani, 2013             |
| BL <sub>3</sub> – Reliability–Incident Control (implicit) | Balancing                             | Safety-Equipment Reliability, SME, IF                             | Safety-Equipment Reliability ↓ → SME ↓ → IF ↑ → (triggers corrective investment) → Reliability ↑ | Time-dependent corrective loop: deterioration raises incidents, which elicits renewed investment/maintenance to restore reliability.                                  | Bouloiz et al., 2013; Zio, 2016                      |

| Loop ID                                                                                                                                                                                                                                                                                               | Type | Key Drivers | Pathway (→<br>may include<br>delays) | Outcome / Meaning | Main<br>References |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|-------------|--------------------------------------|-------------------|--------------------|
| Acronyms: AFR—Available Financial Resources; SME—Safety Management Effectiveness; IF—Incident Frequency; IC—Incident Costs; RP—Regulatory Pressure; CL—Compliance Level; SCL—Safety Culture Level; EPS—Employee Participation in Safety; TCM—Trust in Company Management; WSL—Workforce Safety Level. |      |             |                                      |                   |                    |

The first reinforcing mechanism, RL<sub>1</sub> – Safety Investment Reinforcement, establishes a self-amplifying relation between available financial resources (AFR), safety investment, and SME. When AFR rises, larger investments improve equipment reliability and managerial oversight, thereby reducing incident frequency (IF) and associated costs (IC). As incident losses decrease, resources are replenished, sustaining a virtuous cycle of proactive investment. This process has been described in the literature as a positive safety-economy coupling, where strategic investment produces compound gains in both safety and productivity (Bouloiz et al., 2013). However, its strength depends on avoiding response delays and financial pressure that may otherwise erode SME over time.

A second reinforcing process, RL<sub>2</sub> – Safety Culture Reinforcement, describes the evolution of organizational trust and workforce engagement. Higher SME enhances the workforce's perception of safety (WSL), fostering trust in company management (TCM) and participation in safety activities (EPS). The resulting improvement in the Safety Culture Level (SCL) and compliance (CL) further reinforces SME, closing a long-term adaptive loop. This structural feedback expresses the social-cognitive dimension of safety recognized by Reason (1997) and Guldenmund (2010): safety performance becomes an emergent property of learning, trust, and participation rather than of formal procedures alone. The timescale of RL<sub>2</sub> is slower than that of financial loops but provides the damping and resilience necessary for sustainable performance (Ibrahim et al., 2018).

Balancing feedbacks counteract these reinforcements by introducing control and constraint mechanisms. BL<sub>1</sub> – Compliance Control links increasing incident frequency to stronger regulatory and internal oversight. Rising IF triggers higher regulatory pressure (RP), which enhances compliance (CL) and improves SME, thereby lowering IF. This negative feedback stabilizes the system by enforcing adherence to standards and preventing unsafe drift, consistent with the regulation-performance loop discussed by Hopkins (2008) and Landucci et al. (2015). Yet, excessive regulatory pressure without cultural reinforcement may generate compliance fatigue or bureaucratic stagnation (Hale et al., 2010).

Economic constraints are represented by BL<sub>2</sub> – Budget Erosion Risk, which closes the counter-loop to RL<sub>1</sub>. When incidents occur, their costs (IC) reduce AFR, leading to decreased safety investment and deterioration of SME, which in turn increases IF. Intended as a stabilizing mechanism, it may instead evolve into a degenerative spiral if financial depletion outpaces recovery, a phenomenon of structural vulnerability reported by Rasmussen (1997) and Reniers & Cozzani (2013). Maintaining budgetary buffers or dynamic allocation mechanisms thus becomes a managerial leverage point to preserve systemic equilibrium.

An additional implicit loop, BL<sub>3</sub> – Operational Feedback and Equipment Degradation, connects SME, equipment reliability, and IF. As technical performance declines due to wear or operational stress, SME decreases and IF rises; in response, maintenance and investment activities are triggered, restoring reliability. This delayed negative feedback introduces adaptivity and aligns with the maintenance-based stabilization processes found in dynamic safety models (Bouloiz et al., 2013; Zio, 2016).

The collective behavior emerging from these loops defines a multi-layered adaptive architecture in which financial, regulatory, and cultural subsystems interact continuously. The interplay between RL<sub>1</sub> and BL<sub>2</sub> delineates the economic boundary of safety evolution, where time-delayed investment adjustments can produce oscillations in SME and IF. Simultaneously, the coupling between RL<sub>2</sub> and BL<sub>1</sub> establishes the organizational stability boundary, where cultural maturity internalizes compliance norms and mitigates over-regulation. These dual stabilizing structures illustrate how SME arises as a non-linear function of tangible resources (investment, equipment reliability, compliance) and intangible assets (trust, participation, culture).

In the FRISE framework, the SM module therefore acts as a systemic regulator that converts managerial knowledge and organizational learning into measurable safety performance. It mediates between the technical layer (RA module) and the socio-economic domains (ECO and SOC modules), ensuring that decision feedbacks are both economically sustainable and socially legitimate. The resulting causal architecture demonstrates that the resilience of the entire FRISE system depends not only on technical reliability but also on the adaptive capacity of management structures and cultural mechanisms—a finding consistent with the broader



systems-thinking literature on complex socio-technical systems (Leveson, 2011; Hollnagel et al., 2006; Dueñas Santana et al., 2025).

**Table 6.5- Principal subsystems and dominant feedback loops of the SM module**

| Subsystem                          | Core Variables                                                | Dominant Loops                    | Systemic Effect                                                                                              | Cross-Modular Link                                                   |
|------------------------------------|---------------------------------------------------------------|-----------------------------------|--------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|
| Investment & Resources             | AFR, Safety Investment, Safety-Equipment Reliability, SME, IC | RL <sub>1</sub> , BL <sub>2</sub> | Governs the financial boundary of safety performance: investment-led improvement versus cost-driven erosion. | ECO (budget, costs), RA (IF as driver of IC)                         |
| Compliance & Regulation            | RP, CL, SME, IF                                               | BL <sub>1</sub>                   | Stabilizes performance via standards and oversight; counters drifts into unsafe operation.                   | RA (IF feedback), SOC/ENV (external legitimacy, regulatory pressure) |
| Culture, Trust & Participation     | WSL, TCM, EPS, SCL, CL, SME                                   | RL <sub>2</sub>                   | Builds long-term adaptive capacity; internalizes safety norms and reduces reliance on punitive control.      | SOC (acceptance, trust), ECO (resource prioritization)               |
| Operational Reliability (implicit) | Safety-Equipment Reliability, SME, IF                         | BL <sub>3</sub>                   | Introduces time-dependent corrective dynamics via maintenance/renewal; prevents runaway degradation.         | RA (aging, reliability effects), ECO (maintenance funding)           |

### 6.2.3- Mathematical and Graph-Theoretical Representation

The Causal Loop Diagram (CLD) of the Safety Management (SM) module was translated into a directed weighted graph to enable structural analysis and ensure methodological consistency with the approach used for the Risk Assessment (RA) module. This translation formalizes the causal relationships described in Section 6.2.2 into a quantitative framework suitable for graph-theoretical evaluation. Each causal interaction between management, cultural, and financial variables was represented as a directed edge  $e_{ij}$  linking nodes  $v_i$ (source) and  $v_j$ (target), characterized by a sign (positive or negative), a delay (0 = immediate, 1 = delayed), and a normalized weight  $w_{ij} \in [-1,1]$ . The resulting adjacency matrix  $\mathbf{A}_{SM} = [w_{ij}]$  therefore captures both the polarity and temporal structure of managerial influence pathways.

The network representation of the SM system comprises key variables describing the economic, behavioral, and regulatory subsystems: Available Financial Resources (AFR), Safety Investment Level (SIL), Safety Equipment Reliability (SER), Safety Management Effectiveness (SME), Incident Frequency (IF), Incident Costs (IC), Regulatory Pressure (RP), Compliance Level (CL), Safety Culture Level (SCL), Workforce Safety Level (WSL), Trust in Company Management (TCM), and Employee Participation in Safety (EPS). These variables

form a medium-density directed graph, consistent with the complexity observed in managerial and socio-organizational systems (Bouloiz et al., 2013; Zhang et al., 2022). The structural organization emphasizes three interdependent subsystems:

- a. the investment chain, which translates financial resources into improved equipment reliability and SME;
- b. the compliance–culture engine, which couples regulatory control with trust, participation, and learning; and
- c. the budget–risk feedback, where incidents erode available resources and trigger renewed investment and oversight.

Delays were assigned to processes where effects unfold over time—such as the influence of investment on equipment reliability, the reinforcement of safety culture through employee participation, and the consolidation of trust into management performance. These delayed causalities are essential for reproducing the oscillatory and adaptive behaviors typical of socio-technical management systems (Rasmussen, 1997; Leveson, 2011).

The sign structure of the SM network reveals a balanced mix of reinforcing and balancing feedbacks, reflecting the dynamic tension between proactive growth (investment, culture reinforcement) and stabilizing constraints (budget erosion, compliance control). Although no quantitative results are discussed here, the structural mapping anticipates SME as a central integrator variable, aggregating effects from financial, cultural, and regulatory pathways. The corresponding graph model ( $G_{SM}$ ) therefore represents the managerial layer of the FRISE framework, bridging economic drivers, organizational learning, and risk control. The complete list of causal relationships and their qualitative parameters is summarized in Table 6.6, which provides the foundation for subsequent graph-theoretical analysis in Section 6.2.4.

**Table 6.6- Structural relationships and causal parameters of the SM network**

| From (source) | To (target) | Sign | Delay | Interpretation                                                            |
|---------------|-------------|------|-------|---------------------------------------------------------------------------|
| AFR           | SIL         | +    | 0     | Greater financial availability enables higher safety investment.          |
| SIL           | SER         | +    | 1     | Investments improve equipment reliability after a delay.                  |
| SER           | SME         | +    | 1     | Enhanced reliability increases safety management effectiveness (delayed). |
| IC            | SME         | –    | 0     | Incident costs negatively affect management effectiveness.                |
| CL            | IF          | –    | 0     | Stronger compliance reduces incident frequency.                           |
| CL            | SME         | +    | 0     | Compliance enforcement improves SME.                                      |
| CL            | WSL         | +    | 1     | Improved compliance fosters workforce safety perception (delayed).        |
| SCL           | WSL         | +    | 0     | Mature safety culture promotes safer workforce behavior.                  |

| From (source)                                                                                                                                                                                                                                                                                        | To (target) | Sign | Delay | Interpretation                                                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|------|-------|---------------------------------------------------------------------------------|
| WSL                                                                                                                                                                                                                                                                                                  | TCM         | +    | 1     | Positive workforce safety perception strengthens trust in management (delayed). |
| TCM                                                                                                                                                                                                                                                                                                  | EPS         | +    | 0     | Higher trust enhances employee participation in safety initiatives.             |
| EPS                                                                                                                                                                                                                                                                                                  | SCL         | +    | 1     | Increased participation reinforces the safety culture (delayed).                |
| SCL                                                                                                                                                                                                                                                                                                  | CL          | +    | 1     | Stronger safety culture improves compliance levels over time (delayed).         |
| WSL                                                                                                                                                                                                                                                                                                  | IF          | –    | 0     | Safer workforce behaviors reduce incident frequency.                            |
| TCM                                                                                                                                                                                                                                                                                                  | SME         | +    | 0     | Trust in management directly enhances safety performance.                       |
| SME                                                                                                                                                                                                                                                                                                  | IF          | –    | 1     | Effective management reduces incident frequency (delayed).                      |
| IF                                                                                                                                                                                                                                                                                                   | IC          | +    | 0     | More incidents increase associated costs.                                       |
| IF                                                                                                                                                                                                                                                                                                   | RP          | +    | 0     | Higher incident frequency raises regulatory pressure.                           |
| IC                                                                                                                                                                                                                                                                                                   | AFR         | –    | 0     | Incident costs erode available financial resources.                             |
| RP                                                                                                                                                                                                                                                                                                   | SME         | +    | 0     | Regulatory oversight supports safety management.                                |
| RP                                                                                                                                                                                                                                                                                                   | CL          | +    | 1     | Regulatory pressure improves compliance over time (delayed).                    |
| Notes: Signs denote feedback polarity (+ positive, – negative); a delay value of 1 indicates a time-lagged causal effect. All variables are defined in Table 6.4-SM. This structural mapping underpins the graph-theoretical model of the SM module used for quantitative analysis in Section 6.2.4. |             |      |       |                                                                                 |

#### 6.2.4- Graph analysis and results interpretation (SM module)

The graph-theoretical metrics for the Safety Management (SM) network quantify how managerial, cultural, and financial influences propagate across the organizational layer of FRISE. The results reveal a topology with a small set of broadcast controllers (notably CL, RP, TCM) and a small number of absorbing/aggregation nodes (chiefly SME and, to a lesser extent, IF), consistent with system-dynamics accounts of organizational safety where a few levers govern broad behavioral change (Reason, 1997; Bouloiz et al., 2013; Zhang et al., 2022).

##### *Dominant integrators and brokers*

Safety Management Effectiveness (SME) emerges as the central integrator of the network: it has the highest in-degree (5), high eigenvector centrality ( $\approx 0.148$ ), and strong PageRank ( $\approx 0.188$ ), alongside a very large betweenness ( $\approx 42.5$ ). This indicates that many causal pathways converge into SME (from SER, CL, TCM, RP, IC), and that SME relays effects toward incident control (SME→IF). Functionally, SME aggregates financial (AFR→SIL→SER), compliance (CL), regulatory (RP), and trust-culture (TCM) inputs, then projects them onto incident reduction. This structural role matches the conceptual definition of SME as the managerial “resultant” of investment, compliance, and culture (Hale et al., 2010; Leveson, 2011).

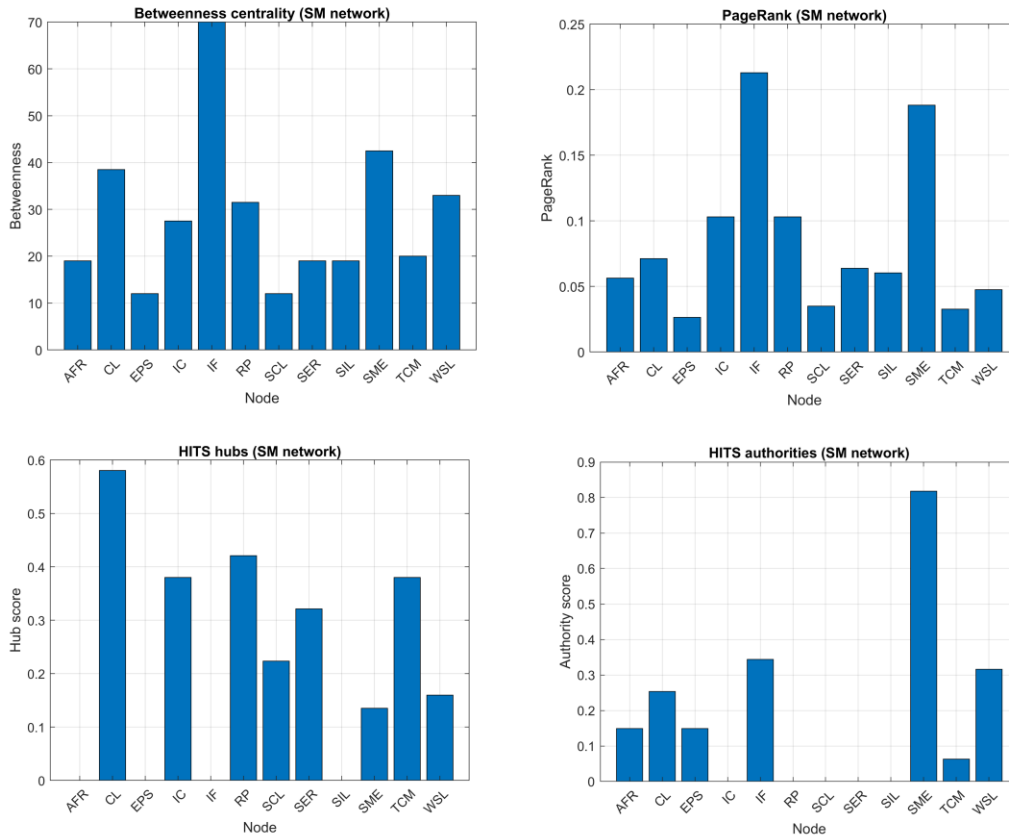


**Fig. 6.4- Graph Theory results for the SM module**

Incident Frequency (IF) shows the highest betweenness in the SM network ( $\approx 70$ ) and the top PageRank ( $\approx 0.213$ ), positioning IF as the principal broker linking management performance to economic consequences and oversight ( $IF \rightarrow IC$ ,  $IF \rightarrow RP$ ) and feeding back into the investment chain (via  $IC \rightarrow AFR$ ). Even though IF is “technical” in the RA layer, within SM it functions as a behavioral outcome that redistributes influence into costs and regulation—precisely the cross-modular coupling FRISE intends (Rasmussen, 1997; Reniers & Cozzani, 2013).

Compliance Level (CL) also ranks among the most influential transmitters (betweenness  $\approx 38.5$ ; out-degree 3; eigenvector  $\approx 0.146$ ). CL broadcasts managerial influence into SME and IF, and, through WSL, into the trust–participation–culture chain. This confirms compliance as a short-to-medium-term lever that stabilizes performance (Hopkins, 2009; Landucci et al., 2015).

### ***Flow direction and accumulation (HITS)***

HITS scores clarify who pushes and who absorbs influence. On the hub side, CL ( $\approx 0.581$ ) and RP ( $\approx 0.421$ ) are the strongest broadcasters, with TCM ( $\approx 0.380$ ) and IC ( $\approx 0.380$ ) contributing

significant outbound flow; SER ( $\approx 0.321$ ) and SCL ( $\approx 0.223$ ) support the technical and cultural legs of the system. On the authority side, SME is the dominant sink ( $\approx 0.818$ ), followed by IF ( $\approx 0.344$ ) and WSL ( $\approx 0.316$ ). This hub–authority asymmetry confirms a directional cascade: compliance/regulatory pressure and trust drive influence outward; SME, IF, and workforce state accumulate and express it as performance (Guldenmund, 2010; Zhang et al., 2022).

### ***Degree structure and subsystem sensitivity***

Degree patterns reinforce these roles. SME has the largest in-degree (5), integrating multiple precursors; CL (out-degree 3) and RP/TCM (out-degree 2) disseminate changes across the network. The investment chain appears as a sequenced pathway (AFR→SIL→SER→SME) with delays (SIL→SER; SER→SME), which explains why financial shocks may exhibit lagged effects on performance. The culture engine (WSL→TCM→EPS→SCL→CL→...→SME) contains several slow links (WSL→TCM; EPS→SCL; SCL→CL), consistent with empirical observations that cultural maturation is slower but stabilizing (Reason, 1997; Hale et al., 2010).

### ***Management implications***

Three levers stand out. First, compliance/regulatory control (CL, RP) are high-hub variables: strengthening them yields rapid, system-wide effects and contributes to IF↓ via SME↑. Second, trust-based engagement (TCM→EPS→SCL) provides medium-term stabilization: improving WSL and TCM increases SME both directly and indirectly (through CL), buffering against budget-driven oscillations (Bouloiz et al., 2013). Third, incident-cost containment (IF→IC→AFR) protects the investment pipeline: controlling IF prevents budget erosion, maintaining AFR→SIL→SER→SME continuity. Altogether, the results validate the SM CLD as a realistic socio-technical regulator that converts organizational action into measurable reductions in incident risk, consistent with the literature on dynamic safety management and resilience engineering (Hollnagel et al., 2006; Leveson, 2011; Zio, 2016).

## **6.3- Economic (ECO) Module**

The Economic (ECO) module constitutes the financial and market pillar of the FRISE framework. It captures how profitability, resource allocation, and market reputation interact dynamically with safety performance and managerial behavior. In this layer, economics is not

treated as an exogenous constraint but as an endogenous component of system resilience—continuously shaped by investment decisions, regulatory costs, and incident outcomes.

The module therefore formalizes the economic metabolism of the entire FRISE system, linking safety improvement to value generation and financial sustainability. The ECO subsystem extends the dynamic perspective adopted in the Risk Assessment and Safety Management modules by describing how financial outcomes evolve through feedback between costs, profits, and reputation. Profitability is influenced simultaneously by operational efficiency, regulatory and insurance burdens, and the financial consequences of incidents. These, in turn, depend on the level of safety investment and performance achieved by the technical and managerial subsystems. Hence, the ECO module provides the quantitative bridge through which the benefits of reduced risk or improved culture can be evaluated in economic terms.

Within the FRISE architecture, the ECO component serves a dual function. First, it measures the economic return of safety decisions—how investments, operational costs, and market effects translate into profitability and available financial resources. Second, it introduces budgetary and market feedbacks that constrain or reinforce the behavior of the other modules. Through this two-way coupling, the framework ensures that safety evolution remains economically viable while economic pressures remain responsive to safety performance.

This approach integrates principles of systems thinking and resilience engineering into financial analysis, emphasizing adaptability rather than static optimization (Rasmussen, 1997; Hollnagel et al., 2006; Leveson, 2011). The causal structure of the ECO module, illustrated in Figure 6.5, contains interlinked relationships among Available Financial Resources (AFR), Safety Investment Level (SIL), Incident Costs (IC), Operational Costs (OpC), Profitability (P), Market Reputation and Share (MRS), Regulatory Fees, and Insurance Premiums. Together, these variables define the pathways through which economic performance feeds back into safety decisions and vice versa. The system captures both short-term financial control and long-term economic reinforcement, reflecting the trade-off between cost efficiency and sustainable risk reduction (Bouloiz et al., 2013; Landucci et al., 2015).

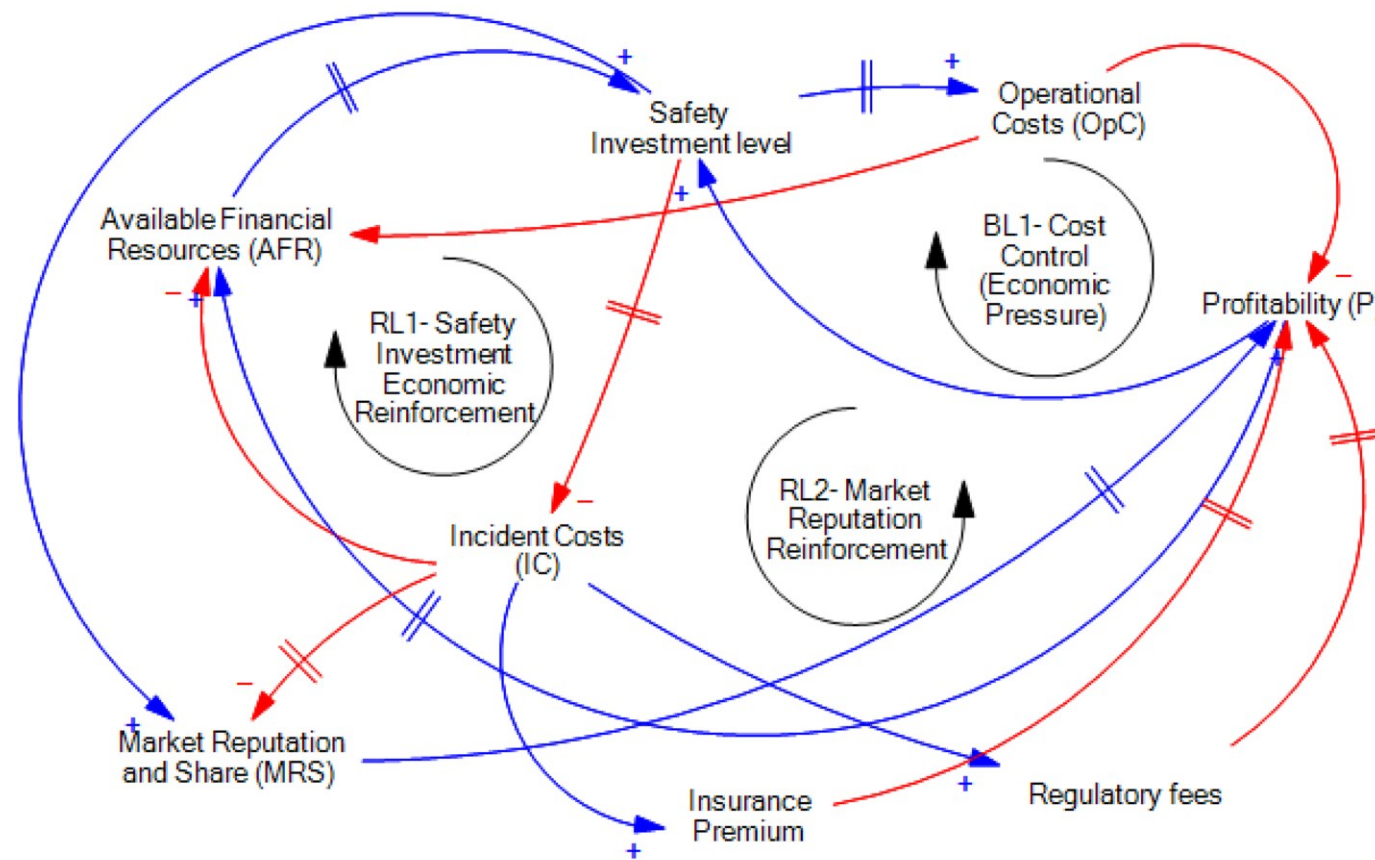


Fig. 6.5- Causal Loop Diagram of the ECO Module

### 6.3.1- Conceptual Foundations

The conceptual foundation of the ECO module is grounded in dynamic industrial economics and systemic safety management theory. Economic performance in complex socio-technical systems is not merely a result of external market conditions but emerges from the same adaptive feedbacks that govern safety, learning, and trust (Rasmussen, 1997; Leveson, 2011).

Accordingly, the module integrates the notions of profitability, investment, and reputation into a single feedback-driven structure that interacts continuously with the technical (RA) and organizational (SM) domains.

Three theoretical premises underpin this representation. First, financial sustainability is an emergent property of balanced feedback between cost control and reinvestment (Hollnagel et al., 2006). Second, the relationship between safety and profitability is non-linear—moderate investments can yield compounding economic benefits, whereas under-investment triggers long-term degradation of both safety and financial outcomes (Bouloiz et al., 2013; Reniers & Cozzani, 2013). Third, intangible factors such as corporate reputation and market confidence act as amplifiers of resilience, mediating how stakeholders perceive and reward safety performance (Zio, 2016).

In operational terms, the ECO module conceptualizes Profitability (P) as the principal economic control variable governing the flow of resources within the enterprise. Profitability increases when incident costs, regulatory fees, and insurance premiums decline, and when market reputation and operational efficiency improve. Higher profitability expands Available Financial Resources (AFR), which support new safety investments and technology upgrades. Conversely, cost pressures—operational expenses, accident losses, or reputational damage—reduce AFR and limit the capacity to invest, generating delayed and potentially destabilizing responses. This conceptualization ensures that the ECO layer mirrors real-world decision dynamics, where financial indicators both reflect and influence organizational priorities.

It also provides the analytical bridge for cross-modular coupling:

- with the RA module, through Incident Costs as an outcome of technical failures;
- with the SM module, through Safety Investment as a managerial decision variable; and



- with the SOC module, through Market Reputation as a proxy for social acceptance.

By embedding these linkages, the ECO module completes the representation of the economic dimension of systemic resilience within FRISE.

### **6.3.2- System Structure and Feedback Architecture**

The internal logic of the Economic (ECO) module captures the interaction between profitability, resource allocation, and external market factors that together determine the economic sustainability of safety management. It formalizes the dynamic interdependencies between investment, costs, and market performance, describing how financial signals both constrain and reinforce safety decisions.

The corresponding Causal Loop Diagram (CLD) presented in Figure 6.5 translates the conceptual foundations outlined previously into an explicit feedback architecture composed of two reinforcing and one balancing loops. These loops collectively define the economic boundary of the FRISE framework—where short-term efficiency pressures and long-term reinvestment dynamics interact to govern systemic resilience.

The first reinforcing mechanism,  $RL_1$  – Safety-Investment Economic Reinforcement, links profitability to safety expenditure and financial recovery. As Available Financial Resources (AFR) increase, management expands Safety Investment Level (SIL), which reduces Incident Costs (IC) through improved reliability and operational performance. Lower IC directly enhances Profitability (P), allowing AFR to recover, thus closing a self-amplifying financial loop. This virtuous cycle expresses the economic rationality of prevention: every monetary unit allocated to safety yields multi-domain benefits, simultaneously reducing losses, regulatory burdens, and insurance premiums (Bouloiz et al., 2013; Landucci et al., 2015).

However, the reinforcing effect depends critically on managerial timing—delays in investment or profit realization can create oscillatory or unstable behaviour, highlighting the need for adaptive budget control (Rasmussen, 1997). The second reinforcing mechanism,  $RL_2$  – Market-Reputation Reinforcement, describes how incident outcomes influence corporate reputation and, in turn, market share and profitability.

Reduced IC and enhanced safety performance improve Market Reputation and Share (MRS), which strengthens stakeholder trust and customer confidence. A stronger reputation increases

profitability and stimulates further investment in safety, completing a long-term reputational feedback.

This loop integrates the economic and social dimensions of FRISE by recognizing that market legitimacy and brand equity amplify resilience beyond pure financial indicators (Reniers & Cozzani, 2013; Zio, 2016). The reputational path evolves more slowly than direct cost feedbacks but contributes substantially to long-term stability by internalizing safety as a strategic asset.

Counterbalancing these reinforcements, the BL<sub>1</sub> – Cost Control (Economic Pressure) loop introduces a stabilizing but potentially restrictive mechanism. When operational or safety expenditures rise, Operational Costs (OpC) increase and Profitability (P) declines. In response, organizations implement cost-control measures that reduce investment and operating expenses. If moderation is maintained, the loop ensures economic discipline; however, excessive austerity can weaken SIL and reverse the benefits achieved by RL<sub>1</sub> and RL<sub>2</sub>.

This trade-off between immediate cost reduction and deferred risk is a well-known systemic tension in industrial safety economics (Hopkins, 2009; Hollnagel et al., 2006). Within FRISE, BL<sub>1</sub> thus represents the economic counterpart to the regulatory and cultural balancing loops found in the SM and RA modules. Together, RL<sub>1</sub>, RL<sub>2</sub>, and BL<sub>1</sub> form a triadic structure governing the evolution of profitability and financial resilience.

When safety investment and reputation management are coordinated, profitability stabilizes at a sustainable level; when budgetary pressure dominates, the system tends toward cyclical contraction. This architecture reflects the empirical observation that firms achieve enduring safety performance only when economic incentives and risk-management objectives are structurally aligned (Bouloiz et al., 2013; Leveson, 2011).

**Table 6.7- Feedback loops of the Economic (ECO) module**

| Loop ID                                                                                                                                                                           | Type        | Key Drivers     | Pathway (→ may include delays)                    | Outcome / Meaning                                                                                           | Main References                             |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|-----------------|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------|---------------------------------------------|
| RL <sub>1</sub> – Safety-Investment Economic Reinforcement                                                                                                                        | Reinforcing | AFR, SIL, IC, P | AFR ↑ → SIL ↑ → IC ↓ → P ↑ → AFR ↑                | Economic virtuous cycle in which reinvestment in safety reduces losses and increases profitability.         | Bouloiz et al., 2013; Landucci et al., 2015 |
| RL <sub>2</sub> – Market-Reputation Reinforcement                                                                                                                                 | Reinforcing | IC, MRS, P      | IC ↓ → MRS ↑ → P ↑ → AFR ↑ → SIL ↑ → IC ↓         | Reputation gains from improved safety strengthen profitability and further support safety investment.       | Reniers & Cozzani, 2013; Zio, 2016          |
| BL <sub>1</sub> – Cost Control (Economic Pressure)                                                                                                                                | Balancing   | OpC, P, SIL     | OpC ↑ → P ↓ → Cost Control ↑ → SIL ↓ → IC ↑ → P ↓ | Financial discipline mechanism that restrains overspending but can induce under-investment if over-applied. | Hopkins, 2009; Hollnagel et al., 2006       |
| Acronyms: AFR – Available Financial Resources; SIL – Safety Investment Level; IC – Incident Costs; P – Profitability; OpC – Operational Costs; MRS – Market Reputation and Share. |             |                 |                                                   |                                                                                                             |                                             |

**Table 6.8- Principal subsystems and dominant feedback loops of the Economic module**

| Subsystem                                 | Core Variables  | Dominant Loops                    | Systemic Effect                                                                                                             | Cross-Modular Link                                   |
|-------------------------------------------|-----------------|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|
| Financial Resources and Investment        | AFR, SIL, IC, P | RL <sub>1</sub> , BL <sub>1</sub> | Governs the flow of capital between profit generation and safety expenditure; defines the economic boundary of resilience.  | RA (IC as risk output); SM (SIL as investment input) |
| Market Reputation and External Perception | IC, MRS, P      | RL <sub>2</sub>                   | Integrates social and market feedbacks into financial performance; amplifies long-term sustainability.                      | SOC (public trust and acceptance)                    |
| Operational Cost and Regulatory Pressure  | OpC, P, AFR     | BL <sub>1</sub>                   | Balances profitability with expenditure; constrains unsustainable growth and links financial control to operational safety. | SM (cost allocation), ENV (regulatory fees)          |

The integration of these loops produces a dynamic economic architecture in which profitability both drives and results from safety performance. The ECO module therefore provides the financial closure of the FRISE framework: safety-related improvements in the RA and SM layers translate into economic gains, while the resulting profitability determines future investment capacity. Through this reciprocal coupling, the model captures the essential principle of economic resilience—that sustained safety is contingent on adaptive financial feedbacks rather than fixed budgets.

By embedding economic feedback within the same systemic logic as technical and managerial processes, the FRISE framework offers a unified representation of how risk reduction, organizational learning, and financial viability co-evolve in complex industrial systems.

### 6.3.3- Mathematical and Graph-Theoretical Representation

The Causal Loop Diagram (CLD) of the Economic (ECO) module was converted into a weighted directed graph  $G_{ECO}$  in order to formalize the causal dependencies between financial, operational, and reputational variables and to enable subsequent quantitative analysis using graph-theoretical metrics. This translation follows the same methodological principles applied in the Risk Assessment (RA) and Safety Management (SM) modules but introduces a crucial enhancement: the inclusion of edge weights that express the relative financial intensity of each causal pathway.

In the economic subsystem, relationships differ markedly in magnitude and immediacy. For example, an increase in *Operational Costs* (OpC) immediately reduces *Profitability* (P) with a high elastic effect, whereas the influence of *Market Reputation and Share* (MRS) on profitability operates more slowly and with smaller amplitude. To capture this heterogeneity, each directed edge  $e_{ij}$  was characterized not only by polarity (+ or −) and delay (0 = instantaneous, 1 = lagged), but also by a relative weight  $w_{ij} \in \{1,2,3\}$ . Weights were assigned through expert judgement informed by system-dynamics and safety-economics literature (Bouloiz et al., 2013; Reniers & Cozzani, 2013; Landucci et al., 2015), where monetary flows and cost elasticities provide a natural basis for ordinal ranking.

The resulting adjacency matrix  $A_{ECO} = [w_{ij}]$  represents both the structural and quantitative features of the ECO system. Each node corresponds to a core variable in the economic loop: Available Financial Resources (AFR), Safety Investment Level (SIL), Operational Costs (OpC), Profitability (P), Incident Costs (IC), Market Reputation and Share (MRS), Insurance Premiums (Ins), and Regulatory Fees (RegF). The directed edges define how capital and information circulate between these variables, closing the reinforcing and balancing loops described in Section 6.3.2.

The introduction of weighted edges allows the analysis to distinguish between strong financial couplings (e.g.,  $AFR \rightarrow SIL$ ,  $OpC \rightarrow P$ ,  $IC \rightarrow AFR$ ) and secondary or delayed effects (e.g.,  $IC \rightarrow MRS$ ,  $RegF \rightarrow P$ ). This differentiation enhances the explanatory power of graph metrics—

particularly betweenness and PageRank—by aligning structural prominence with economic significance. In the adjacency representation, the weights serve as proportional coefficients for link importance, while the delays introduce temporal separation between short-term cash-flow dynamics and long-term market responses.

Although the same metrics employed in the RA and SM analyses (in- and out-degree, betweenness, closeness, eigenvector, PageRank, and HITS) will later be applied to  $G_{ECO}$ , their interpretation here will reflect the financial meaning of connectivity—*how profit, cost, and investment influence propagate through the economic network*. Quantitative results from the MATLAB implementation will be discussed in Section 6.3.4.

**Table 6.9- Structural relationships and causal parameters of the Economic (ECO) network**

| From (source) | To (target) | Sign | Delay | Weight | Interpretation                                                                             | Supporting references                         |
|---------------|-------------|------|-------|--------|--------------------------------------------------------------------------------------------|-----------------------------------------------|
| AFR           | SIL         | +    | 1     | 3      | Greater available financial resources enable higher safety investment after budget cycles. | Bouloiz et al., 2013; Reniers & Cozzani, 2013 |
| SIL           | OpC         | +    | 1     | 2      | Safety investment moderately increases operational costs through maintenance and training. | Hale et al., 2010; Bouloiz et al., 2013       |
| OpC           | P           | –    | 0     | 3      | Higher operational costs immediately reduce profitability.                                 | Bouloiz et al., 2013; Landucci et al., 2015   |
| OpC           | AFR         | –    | 0     | 3      | Rising costs deplete financial reserves and cash flow.                                     | Bouloiz et al., 2013                          |
| P             | AFR         | +    | 1     | 3      | Increased profitability restores financial resources after fiscal delay.                   | Bouloiz et al., 2013                          |
| P             | SIL         | +    | 1     | 3      | Profits stimulate subsequent safety investment in the next budgeting period.               | Bouloiz et al., 2013; Reniers & Cozzani, 2013 |
| SIL           | IC          | –    | 1     | 3      | Investment reduces incident costs through prevention and reliability improvement.          | Bouloiz et al., 2013; Landucci et al., 2015   |
| IC            | AFR         | –    | 0     | 3      | Incident losses directly diminish available resources.                                     | Bouloiz et al., 2013                          |
| SIL           | MRS         | +    | 1     | 2      | Visible investment enhances market reputation over time.                                   | Reniers & Cozzani, 2013                       |
| IC            | MRS         | –    | 1     | 2      | Accidents erode market reputation with a lag.                                              | Reniers & Cozzani, 2013; Zio, 2016            |
| MRS           | P           | +    | 1     | 3      | Improved reputation increases market share and profitability.                              | Reniers & Cozzani, 2013; Zio, 2016            |
| IC            | Ins         | +    | 0     | 2      | Higher incident frequency raises insurance premiums.                                       | Hopkins, 2009; Bouloiz et al., 2013           |
| Ins           | P           | –    | 0     | 2      | Increased insurance costs reduce profitability.                                            | Hopkins, 2009; Bouloiz et al., 2013           |
| IC            | RegF        | +    | 1     | 2      | More incidents lead to higher regulatory fees and penalties after administrative delay.    | Landucci et al., 2015                         |
| RegF          | P           | –    | 0     | 2      | Regulatory payments lower net profit.                                                      | Landucci et al., 2015; Hopkins, 2009          |

| From<br>(source)                                                                                                                                                                                                                                                                                                                                                                                  | To<br>(target) | Sign | Delay | Weight | Interpretation | Supporting<br>references |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|------|-------|--------|----------------|--------------------------|
| Notes: (1) Signs indicate feedback polarity (+ positive, – negative); Delay = 1 denotes lagged effects such as budget cycles or market responses. (2) Weights (1–3) reflect relative causal strength: 3 = strong/primary economic coupling, 2 = moderate/secondary influence. (3) All relationships are grounded in the literature on dynamic safety management and safety economics cited above. |                |      |       |        |                |                          |

Table 6.9 summarizes all structural relationships incorporated into the model, including their polarity, delay, assigned weight, and the literature supporting each causal assumption. This table provides full traceability for subsequent quantitative analyses and cross-module comparisons.

The graph-theoretical formalization of the ECO module thus provides a rigorous quantitative scaffold for analyzing the propagation of financial and reputational effects across the FRISE framework. Weighted causal relationships enable differentiation between fast, high-impact financial flows and slower, diffuse market or regulatory responses. This structure allows forthcoming analyses to evaluate how profitability, investment, and incident costs jointly influence system resilience—bridging technical safety and economic sustainability within a single systemic model.

### 6.3.4- Graph Analysis and Results Interpretation

The graph-theoretical assessment of the Economic (ECO) module clarifies how financial, operational, and reputational drivers interact to shape the economic dynamics of the FRISE framework. The weighted-network analysis reveals a highly integrated but asymmetrical structure in which a few key variables—Safety Investment Level (SIL), Profitability (P), and Available Financial Resources (AFR)—govern the propagation of influence across the system. Their central positions confirm the expected configuration of a financial-feedback system in which profitability and investment jointly sustain resilience through continuous capital reinjection (Bouloiz et al., 2013; Landucci et al., 2015).

#### *Dominant financial brokers and integrators*

Among all nodes, SIL emerges as the principal broker and transmitter of influence. It exhibits the highest betweenness (28), the highest PageRank (0.252), and a strong eigenvector centrality (0.99). These indicators show that SIL connects nearly every major financial pathway, acting simultaneously as a receiver of funds and a distributor of economic effects. Functionally, SIL transmits the effect of AFR to operational and incident costs, while also contributing to market

reputation through visible investment and preventive actions. This structure mirrors the “virtuous cycle of safety investment” observed in system-dynamics models of industrial safety, where continuous reinvestment produces cumulative reductions in risk and cost (Bouloiz et al., 2013; Reniers & Cozzani, 2013).

Profitability (P) ranks second in both influence and connectivity (PageRank = 0.215, Betweenness = 20.5). As the most connected sink within the system (In-degree = 4), P aggregates effects from cost, reputation, insurance, and regulatory nodes, translating them into renewed financial resources and future investment. Its elevated eigenvector value (0.93) confirms its strong coupling with SIL and AFR, together forming the economic “core triad” that underpins self-reinforcing growth. This topology captures the empirical observation that profitability functions as both an outcome of safety and a driver of its continuation, reproducing the investment-performance feedback identified by Cozzani et al. (2015) and Zio (2016).

The third dominant node, AFR, serves as the central financial reservoir controlling liquidity within the system (Eigenvector = 1.00; PageRank = 0.167). With three inbound and one outbound link, AFR collects the outputs of profitability, operational costs, and incident costs, and redistributes them as new investment. Its moderate betweenness (4.5) but very high authority score indicate that AFR acts primarily as a stabilizing stock rather than an initiator, mediating the long-term capacity for resilience. In systemic terms, it represents the “financial inertia” of the enterprise: a delayed but decisive mechanism governing whether safety and profitability can be sustained through multiple budget cycles (Rasmussen, 1997).

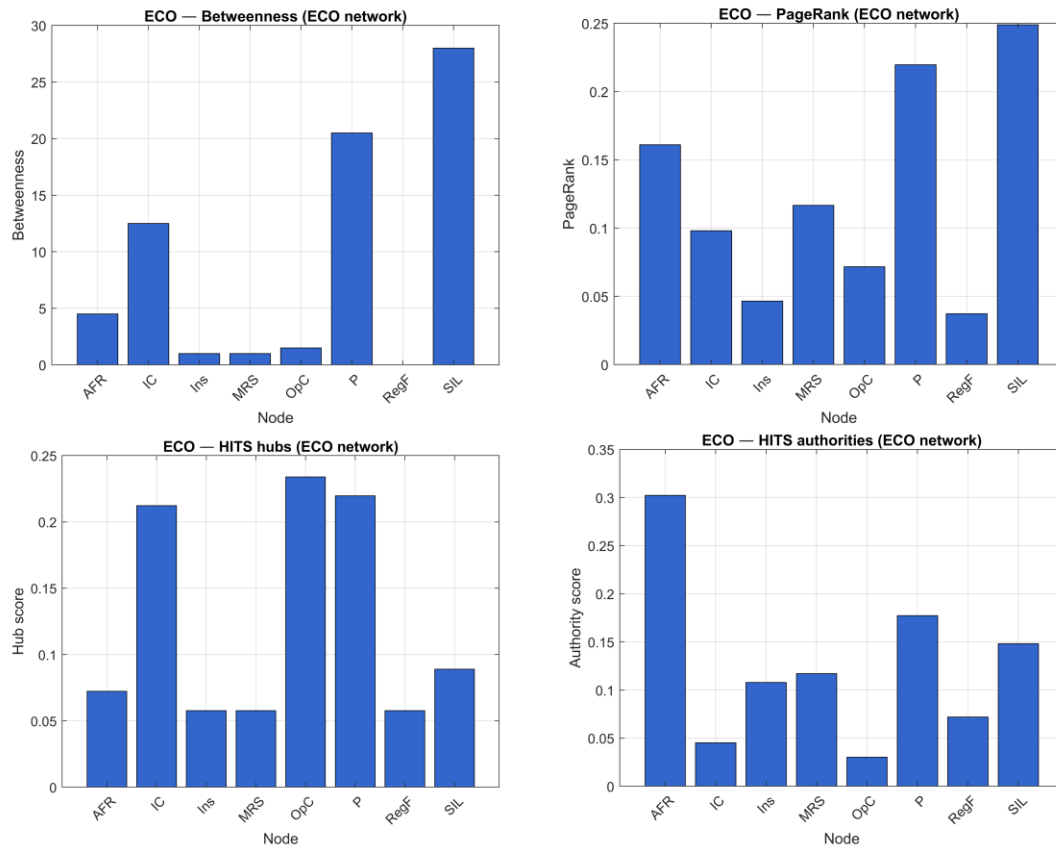


**Fig. 6.6- Graph Theory results for the ECO module**

### *Propagation and cost-constrained dynamics*

The intermediate variables—Operational Costs (OpC), Incident Costs (IC), and Market Reputation and Share (MRS)—form the channels through which economic effects propagate. OpC and IC have relatively modest PageRank values ( $\approx 0.09$ ) but distinct structural roles. OpC functions as the short-term balancing element that links investment to profitability, while IC aggregates losses from technical and managerial layers, broadcasting their financial consequences throughout the economic subsystem. IC's betweenness (12.5) and hub score (0.29) identify it as a critical transmission point for adverse effects: it converts operational degradation into financial loss, thereby closing the negative side of the safety–economy feedback. MRS, in contrast, operates over a longer temporal horizon, with a moderate eigenvector centrality (0.77) and PageRank (0.11). It embodies the reputational mechanism that amplifies profitability when safety performance is visible and credible. Although weaker than direct financial links, this reputational pathway provides structural damping by restoring investor and stakeholder confidence after adverse events (Reniers & Cozzani, 2013).



### ***Directional flow and hub–authority structure***

The HITS algorithm confirms the directional asymmetry of financial information flow. The strongest hubs—IC (0.29), OpC (0.19), and P (0.15)—act as the primary broadcasters of influence, pushing cost and profit signals toward the rest of the system. Conversely, the leading authorities—AFR (0.26) and P (0.17)—serve as receivers that accumulate and normalize these signals. This dual configuration reflects a well-balanced economic mechanism in which costs act as stressors and profits as absorbers, maintaining systemic equilibrium. The hub–authority pattern also delineates the boundaries of the balancing loop ( $BL_1$ ) identified earlier: rising costs increase economic pressure, reducing profitability and available funds, until investment and reputation restore the financial balance.

### ***Network reachability and harmonic closeness***

The harmonic closeness (Fig. 6.7) distribution provides complementary insight into how rapidly financial signals can propagate across the ECO system. The highest harmonic closeness value is observed for Incident Costs (IC) (0.35), followed by Safety Investment Level (SIL) (0.28) and Profitability (P) (0.21). This ordering indicates that IC is the most immediately responsive node within the economic network. Any perturbation affecting incident frequency or severity rapidly manifests as cost fluctuations that propagate through the financial chain, influencing liquidity (AFR) and profitability almost instantaneously.

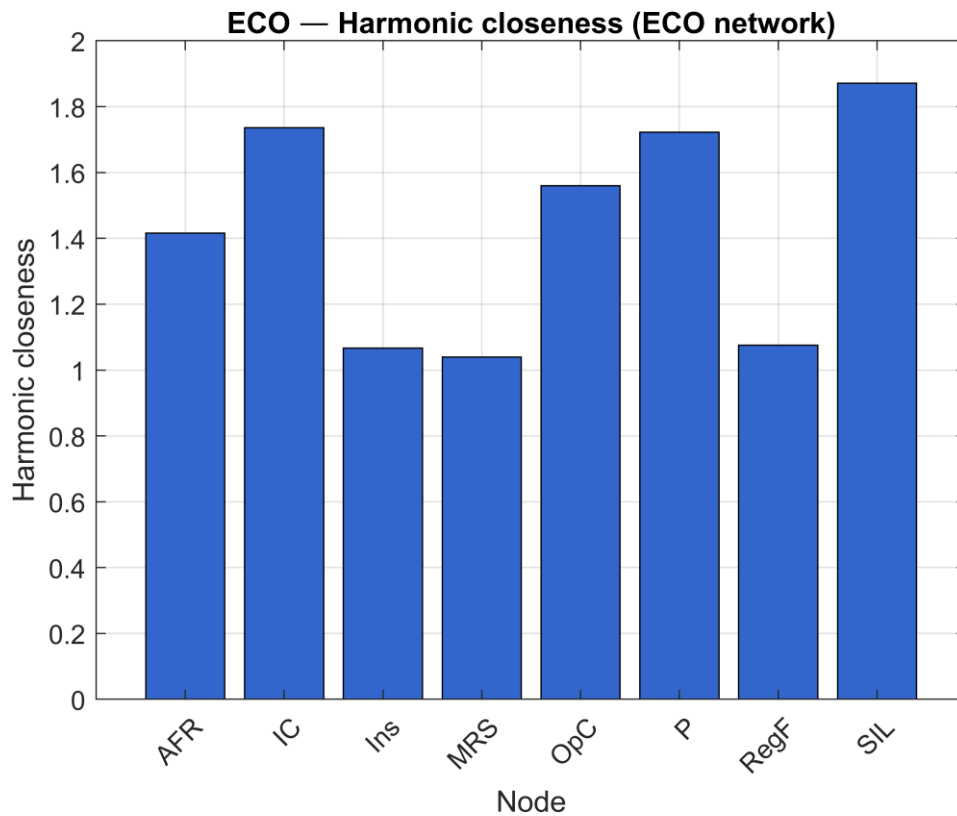


**Fig. 6.7- Harmonic closeness for the ECO module**

The high harmonic closeness of SIL reflects its dual role as both a receptor and transmitter of monetary feedbacks: it reacts quickly to variations in available resources and profitability while simultaneously exerting downstream influence on costs and reputation. In contrast, the moderate closeness of P and MRS suggests that these nodes participate in longer feedback paths, consistent with the delayed realization of profits and reputational gains in real financial cycles. Lower closeness scores for AFR and OpC confirm their peripheral, slower-acting nature as financial stock and cost-accumulation mechanisms rather than active transmitters.

From a systemic viewpoint, these closeness patterns reveal a multi-speed financial architecture. Rapid local responses occur through IC and SIL—capturing the short-term coupling between safety performance and financial exposure—while slower, more inertial processes dominate in AFR and P. Such a configuration is advantageous for stability: fast-reacting cost nodes provide early warning and dynamic sensitivity, whereas slower capital nodes ensure damping and financial continuity. The coexistence of these temporal layers reflects the adaptive nature of the economic subsystem, in which short-term operational variations and long-term profitability trends interact to sustain resilience (Bouloiz et al., 2013; Hollnagel et al., 2006; Rasmussen, 1997).

### *Systemic interpretation and resilience perspective*

The topology revealed by the ECO network demonstrates a self-regulating yet inherently fragile structure. Reinforcing feedbacks dominate the upper layer of the system ( $AFR \rightarrow SIL \rightarrow P \rightarrow AFR$ ), sustaining growth through profitability and reinvestment. Balancing loops emerge through cost pathways ( $SIL \rightarrow OpC \rightarrow P \downarrow$ ;  $IC \rightarrow AFR \downarrow$ ), preventing uncontrolled expansion but also introducing vulnerability to delayed corrective actions. The network's resilience therefore depends on the synchronization of these loops: when the reinforcing cycle outpaces the balancing corrections, the system accumulates profit and reinvestment capacity; when cost feedbacks become dominant, liquidity contraction may inhibit safety spending. The moderate delays encoded in the graph (especially in  $P \rightarrow SIL$  and  $SIL \rightarrow IC$ ) produce realistic oscillatory behavior characteristic of industrial economic systems (Bouloiz et al., 2013; Hollnagel et al., 2006).

From a management standpoint, the graph metrics indicate three leverage priorities for economic resilience. First, maintaining continuous safety investment (SIL) is crucial, as its high centrality implies that small fluctuations propagate widely through both cost and profit channels. Second, monitoring and controlling cost nodes (OpC, IC) is essential to avoid liquidity erosion. Third, strengthening market reputation (MRS) serves as a long-term buffer that stabilizes profitability against transient financial shocks. Collectively, these findings confirm that the economic resilience of the FRISE framework arises from a balanced interplay between fast-acting financial feedbacks and slower reputational and regulatory responses.

### *Synthesis*

Taken together, the harmonic closeness patterns reinforce the earlier conclusion that the ECO module operates as a two-tier financial system. Fast-propagating feedbacks (IC and SIL) ensure responsiveness to operational disturbances, while slower accumulative nodes (P and AFR) secure economic equilibrium over time. This structural duality allows the system to balance agility and stability—an essential property of resilient financial management within the FRISE framework.

The ECO network analysis establishes a consistent quantitative foundation for understanding how financial and safety subsystems co-evolve. The dominance of SIL, P, and AFR forms a coherent financial core that sustains reinforcement through reinvestment, while IC and OpC

operate as critical balancing elements moderating growth. Reputational and regulatory nodes contribute secondary stabilization. This configuration captures the essence of economic resilience: profitability and investment acting as mutually reinforcing drivers, tempered by feedback from operational efficiency and cost control. Within the FRISE architecture, the ECO module thus performs the role of a dynamic financial regulator, converting safety performance into sustainable economic value and ensuring the long-term viability of the integrated socio-technical system.

#### **6.4- Environmental (ENV) module**

The Environmental (ENV) module represents the ecological and regulatory dimension of the FRISE framework, describing how industrial operations interact dynamically with environmental quality, compliance mechanisms, and natural recovery processes. Its main objective is to capture the nonlinear evolution of environmental degradation and sustainability as a function of emissions, operational intensity, and control effectiveness. In contrast to static environmental risk assessments that rely on fixed pollutant thresholds, this module adopts a feedback-based, systemic formulation consistent with the dynamic environmental governance perspective (Sterman, 2002; Zhang et al., 2022).

Within the FRISE architecture, the ENV module performs a dual role. First, it internalizes the environmental consequences of industrial activity by quantifying the reinforcing feedbacks that drive pollution accumulation and ecosystem degradation. Second, it integrates the balancing forces of regulatory intervention and ecological recovery that promote stabilization toward sustainable operating conditions. Through this integration, the ENV module bridges technical and socio-economic dynamics—translating operational stress and compliance behavior from the SM and ECO modules into environmental outcomes, and feeding back regulatory and sustainability information to those same modules. The result is a closed-loop representation of environmental resilience, where degradation and recovery coexist within a bounded adaptive system (Zio, 2016; Leveson, 2011).

The module is conceptually aligned with the planetary boundaries and industrial ecology frameworks (Rockström et al., 2009; Ellen MacArthur Foundation, 2019), but it operationalizes these principles at the system-dynamics level. Environmental degradation is treated not as an exogenous constraint but as an endogenous process evolving under feedback control. The inclusion of time delays and regulatory adaptation ensures that short-term

fluctuations in emissions or compliance do not directly translate into irreversible environmental collapse. Instead, the ENV module models sustainability as an emergent property of the interaction between industrial activity, environmental feedback, and institutional response—an approach consistent with resilience theory and adaptive governance literature (Folke et al., 2010; Holling, 2001).

Figure 6.8 illustrates the causal structure of the ENV system, highlighting the main reinforcing and balancing feedbacks that govern environmental behavior. Reinforcing processes describe how pollution accumulation intensifies degradation, while balancing loops represent compliance enforcement and ecosystem recovery. The combined action of these loops forms the environmental subsystem of the FRISE framework, ensuring that ecological variables evolve coherently with economic and social domains.

#### **6.4.1- Conceptual Foundations**

The conceptual formulation of the ENV module builds upon the methodological principles outlined in Chapter 5, particularly the feedback-centric modeling and systemic coupling approaches. In this context, the environment is viewed as a dynamic subsystem governed by interdependent flows of emissions, damage, recovery, and compliance. Its structure is defined around three fundamental paradigms: (i) environmental degradation reinforcement, (ii) regulatory and compliance control, and (iii) ecosystem recovery and sustainability.

The first paradigm—environmental degradation reinforcement—captures the self-amplifying nature of industrial pollution. Increased operational intensity (OI) elevates the Pollution Emission Rate (PER), which in turn increases the Environmental Damage Level (EDL). Higher damage reduces environmental carrying capacity and further constrains natural recovery processes, thus establishing a reinforcing loop that embodies the principle of cumulative environmental stress (Renn & Klinke, 2013). This mechanism mirrors real-world observations in industrial ecology, where uncontrolled growth in emissions leads to nonlinear degradation of ecosystem services.

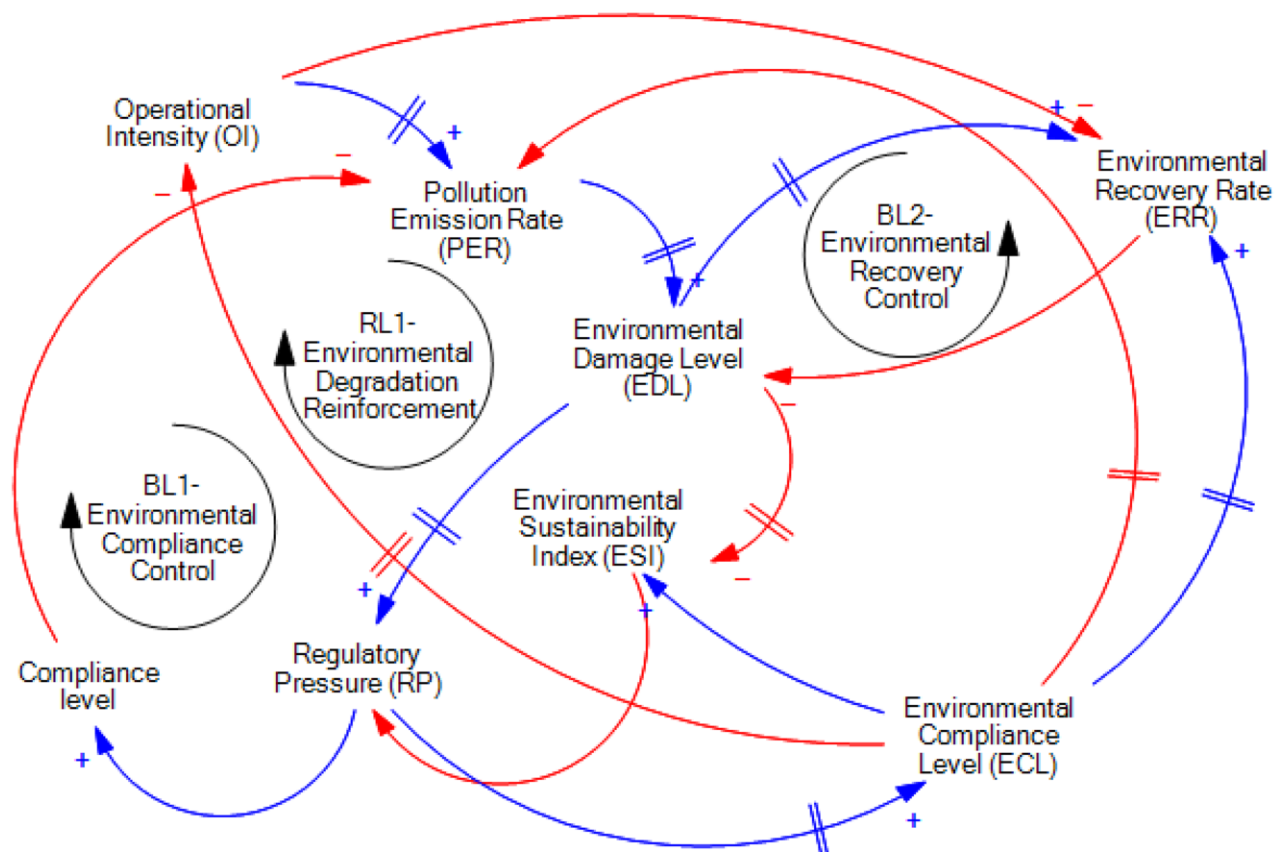


Fig. 6.8- Causal Loop Diagram of the ENV Module

The second paradigm—regulatory and compliance control—represents the institutional counterbalance to degradation. The Regulatory Pressure (RP) variable responds to increases in damage or sustainability deviation by enforcing stricter standards, thereby increasing the Environmental Compliance Level (ECL). Higher compliance moderates operational intensity and pollution emission, creating a balancing loop that mitigates degradation (Bouloiz et al., 2013). Delays in regulation or enforcement, however, can produce oscillatory environmental behavior, as short-term emission reductions are followed by slow policy relaxation—a phenomenon consistent with adaptive regulatory cycles observed in environmental governance (Stermann, 2002; Reniers & Cozzani, 2013).

The third paradigm—ecosystem recovery and sustainability—embodies the natural capacity of the environment to restore itself when stress is reduced. The Environmental Recovery Rate (ERR) acts as a restorative feedback, reducing EDL and increasing the Environmental Sustainability Index (ESI). This index measures the dynamic balance between degradation and recovery, providing an integrated indicator of system-level sustainability. By linking ERR and ESI, the module incorporates ecological resilience directly into the causal architecture (Folke et al., 2010; Zio, 2016). The inclusion of ERR introduces an additional balancing feedback that complements institutional regulation with biophysical self-regulation, representing the long-term stabilizing potential of ecosystems.

Together, these paradigms establish a coherent systemic basis for modeling environmental performance under continuous industrial activity. The ENV module thus extends the scope of the FRISE framework beyond technical and managerial domains, embedding environmental sustainability as a dynamically coupled layer. It provides the structural foundation for subsequent graph-theoretical analysis and quantitative evaluation of environmental resilience, which are developed in the following subsections.

#### **6.4.2- System Structure and Feedback Architecture**

The systemic structure of the Environmental (ENV) module formalizes the causal architecture through which industrial activity interacts with ecological and regulatory processes. As illustrated in Figure 6.10, this module integrates reinforcing and balancing feedbacks that represent the dual dynamics of environmental degradation and recovery. These interactions

give rise to nonlinear behaviors—such as pollution accumulation, delayed recovery, and oscillatory compliance response—typical of complex socio-environmental systems (Sterman, 2002; Folke et al., 2010).

At its core, the ENV module operates through three interdependent functional subsystems: (i) emission and degradation dynamics, (ii) regulatory compliance control, and (iii) ecological recovery and sustainability. Together, they describe the feedback mechanisms by which industrial operations influence the environment and, conversely, how environmental conditions constrain industrial behavior. The feedback structure ensures that degradation, regulation, and recovery are dynamically coupled—so that both anthropogenic and natural processes contribute to the emergent level of environmental sustainability.

The first subsystem, the Emission–Degradation Dynamics, captures how operational activities drive pollution emissions and subsequent environmental damage. Increases in Operational Intensity (OI) and Pollution Emission Rate (PER) escalate the Environmental Damage Level (EDL), forming a reinforcing feedback that amplifies environmental degradation. This process, represented by the  $RL_1$  – Environmental Degradation Reinforcement loop, reflects the structural coupling between industrial throughput and environmental impact (Renn & Klinke, 2013). Without balancing influences, this loop can drive uncontrolled environmental deterioration, reducing ecological resilience and exacerbating regulatory stress.

The second subsystem, Regulatory Compliance Control, represents the institutional mechanisms that counteract degradation through enforcement and adaptation. As environmental damage accumulates, Regulatory Pressure (RP) rises, stimulating higher Environmental Compliance Level (ECL) and stricter operational standards. Increased compliance lowers emissions and mitigates degradation, establishing the  $BL_1$  – Environmental Compliance Control loop. This balancing feedback mirrors the real-world function of environmental regulation, where enforcement intensity responds dynamically to deviations from sustainability targets (Bouloiz et al., 2013; Reniers & Cozzani, 2013). However, policy enforcement and compliance effectiveness are subject to delays, which may induce temporary overshoots or oscillations in pollution levels before stabilization occurs.

The third subsystem, Environmental Recovery and Sustainability, captures the natural and anthropogenic restorative processes that reduce accumulated damage. The Environmental Recovery Rate (ERR) counteracts degradation by converting damaged ecosystems into



restored or sustainable states. This balancing feedback, represented by BL<sub>2</sub> – Environmental Recovery Control, reduces EDL and improves the Environmental Sustainability Index (ESI) over time. The interaction between ERR and ESI reflects the adaptive capacity of ecosystems and their ability to buffer against external stressors (Folke et al., 2010; Holling, 2001). When recovery capacity is exceeded, however, the system can shift toward degraded equilibria—illustrating the limits of resilience under sustained industrial pressure.

The resulting feedback architecture exhibits a complex interplay between anthropogenic and ecological forces. Reinforcing degradation processes (RL<sub>1</sub>) compete with two counterbalancing loops (BL<sub>1</sub> and BL<sub>2</sub>), whose joint effectiveness determines whether the system converges toward sustainability or drifts toward collapse. Regulatory pressure acts as an intermediary variable linking social and institutional responses to environmental conditions, while ESI provides an aggregate measure of systemic performance. These dynamic relationships, summarized in Table 6.10, form the structural basis of the environmental subsystem within the FRISE framework.

**Table 6.10- Feedback Loops of the Environmental (ENV) Module**

| Loop ID                                                                                                                                                                                                                                             | Type        | Key Drivers       | Pathway                                                            | Outcome / Meaning                                                                                                                              | References                                      |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|-------------------|--------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|
| RL <sub>1</sub> – Environmental Degradation Reinforcement                                                                                                                                                                                           | Reinforcing | OI, PER, EDL      | OI ↑ → PER ↑ → EDL ↑ → ESI ↓ → RP ↑ → (OI maintained or increased) | Represents the self-reinforcing nature of industrial activity that accelerates environmental degradation and reduces sustainability over time. | Pizzol et al. (2017); Renn & Klinke (2013)      |
| BL <sub>1</sub> – Environmental Compliance Control                                                                                                                                                                                                  | Balancing   | RP, ECL, PER, EDL | EDL ↑ → RP ↑ → ECL ↑ → PER ↓ → EDL ↓                               | Regulatory mechanisms enforce compliance and reduce emissions in response to environmental degradation, restoring system balance.              | Bouloiz et al. (2013); Reniers & Cozzani (2013) |
| BL <sub>2</sub> – Environmental Recovery Control                                                                                                                                                                                                    | Balancing   | ERR, EDL, ESI     | EDL ↑ → ERR ↑ → EDL ↓ → ESI ↑                                      | Captures natural and engineered recovery processes that counteract environmental damage and restore sustainability.                            | Folke et al. (2010); Holling (2001); Zio (2016) |
| Acronyms: OI – Operational Intensity; PER – Pollution Emission Rate; EDL – Environmental Damage Level; ESI – Environmental Sustainability Index; RP – Regulatory Pressure; ECL – Environmental Compliance Level; ERR – Environmental Recovery Rate. |             |                   |                                                                    |                                                                                                                                                |                                                 |

The causal architecture defined by these loops provides the ENV subsystem with its self-regulatory and adaptive character. The reinforcing loop (RL<sub>1</sub>) continuously amplifies degradation as industrial activity grows, while the two balancing loops (BL<sub>1</sub> and BL<sub>2</sub>) introduce corrective forces that can restore equilibrium—through regulatory enforcement or natural recovery. The dynamic interplay among these loops determines the resilience of the environmental system and its ability to maintain long-term stability under uncertainty and external stressors.

From a systemic perspective, the ENV module illustrates how sustainability arises not from static optimization but from the ongoing feedback between human activity, ecological processes, and institutional adaptation. Regulatory and recovery mechanisms act as complementary stabilizers, each operating on distinct temporal scales—policy enforcement on the short-to-medium term and ecological regeneration on the long term. This layered temporal structure is a defining feature of environmental resilience and is consistent with adaptive cycles observed in socio-ecological systems (Holling, 2001; Folke et al., 2010).

**Table 6.11- Principal Subsystems and Dominant Feedback Loops of the Environmental (ENV) Module**

| Subsystem                             | Core Variables    | Dominant Loops                              | Systemic Effect                                                                        | Cross-Modular Link                                                        |
|---------------------------------------|-------------------|---------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Emission–Degradation Dynamics         | OI, PER, EDL      | RL <sub>1</sub> – Degradation Reinforcement | Drives pollution accumulation and environmental damage through operational activity.   | Linked to SM (Operational Intensity) and ECO (Production Pressure)        |
| Regulatory Compliance Control         | RP, ECL, PER, ESI | BL <sub>1</sub> – Compliance Control        | Stabilizes degradation through institutional regulation and enforcement of compliance. | Linked to SM (Compliance, RP) and SOC (Public Perception)                 |
| Recovery and Sustainability Processes | ERR, EDL, ESI     | BL <sub>2</sub> – Recovery Control          | Restores environmental conditions through natural and engineered recovery mechanisms.  | Linked to ECO (Investment in Recovery) and SOC (Sustainability Awareness) |

The structure summarized in Table 6.11 reveals the integrative nature of the environmental subsystem within the FRISE framework. Each of the three subsystems interacts with other modules—technical (RA), managerial (SM), and economic (ECO)—to produce emergent sustainability dynamics. Regulatory pressure connects the ENV module to the organizational decision-making of the SM layer, while sustainability indicators (ESI) feed back into economic and social considerations, influencing investment, public trust, and long-term policy adaptation.

By embedding environmental processes into the same feedback-driven architecture as safety and economic systems, the ENV module ensures coherence across the entire FRISE framework. It enables the quantitative study of coupled degradation–recovery behavior and provides a dynamic foundation for assessing environmental resilience in complex industrial systems.

### 6.4.3- Mathematical and Graph-Theoretical Representation

The mathematical representation of the Environmental (ENV) module translates the causal architecture of Figure 6.10 into a directed, weighted graph where nodes correspond to key environmental variables and edges encode the polarity, delay, and relative strength of their interactions. Following the methodology established in Section 5.7.3, each causal link is formalized through a five-element tuple  $(i, j, s, \delta, w)$ , where  $i$  and  $j$  denote the origin and destination nodes,  $s = \pm 1$  the sign of influence,  $\delta = 0, 1$  the presence or absence of a temporal delay, and  $w \in [1, 3]$  the normalized weight representing the magnitude of causal effect. This parameterization captures both the directionality and dynamical asymmetry inherent in environmental systems, where physical processes, regulatory responses, and natural recovery operate over distinct time horizons (Sterman, 2002; Zio, 2016).

The resulting signed digraph  $G_{ENV} = (V, E)$  includes eight variables representing the main environmental and regulatory factors: *Operational Intensity (OI)*, *Pollution Emission Rate (PER)*, *Environmental Damage Level (EDL)*, *Environmental Recovery Rate (ERR)*, *Environmental Sustainability Index (ESI)*, *Environmental Compliance Level (ECL)*, *Regulatory Pressure (RP)*, and *Compliance Level (CL)*. These variables interact through 16 directed edges that define the causal backbone of the ENV module. Reinforcing mechanisms (e.g.,  $OI \rightarrow PER \rightarrow EDL$ ) amplify degradation, while balancing mechanisms (e.g.,  $ECL \rightarrow PER \downarrow$ ;  $ERR \rightarrow EDL \downarrow$ ) introduce stabilizing feedback that governs long-term sustainability.

In graph-theoretical terms, the ENV system can be expressed through its weighted adjacency matrix  $A = [a_{ij}]$ , where each element  $a_{ij} = s_{ij}w_{ij}$  if a causal link exists from node  $i$  to node  $j$ , and  $a_{ij} = 0$  otherwise. Positive entries denote synergistic or aggravating effects, while negative values indicate mitigating or compensatory interactions. Temporal delays, represented by  $\delta_{ij} = 1$ , denote slower feedback propagation—typically associated with ecological regeneration, institutional response, or compliance improvement.

This formalization enables the computation of centrality metrics such as betweenness, eigenvector, and PageRank centralities, which quantify each variable's structural role in information transmission, influence propagation, and system stabilization. These metrics, computed in MATLAB using the algorithm described in Section 5.7.4, provide a quantitative basis for identifying leverage points in environmental governance and sustainability transitions. The complete causal structure and parameterization of the ENV network are summarized in Table 6.12.

**Table 6.12 – Structural Relationships and Causal Parameters of the Environmental (ENV) Network**

| From (source) | To (target) | Sign | Delay | Weight | Interpretation                                                                                                     | References                                       |
|---------------|-------------|------|-------|--------|--------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| OI            | PER         | +    | 1     | 2      | Higher operational intensity increases pollution emissions, reflecting industrial throughput effects.              | Pizzol et al. (2017); Renn & Klinke (2013)       |
| PER           | EDL         | +    | 1     | 2      | Pollution accumulation raises environmental damage levels after a temporal lag.                                    | Bouloiz et al. (2013)                            |
| EDL           | ERR         | +    | 1     | 2      | Greater damage stimulates recovery efforts (natural or technological), introducing a delayed restorative response. | Folke et al. (2010); Holling (2001)              |
| ERR           | EDL         | –    | 0     | 2      | Enhanced recovery directly mitigates environmental damage.                                                         | Holling (2001); Zio (2016)                       |
| OI            | ERR         | –    | 0     | 1      | Operational stress weakens recovery capacity, reflecting ecosystem overload.                                       | Sterman (2002).                                  |
| EDL           | ESI         | –    | 1     | 2      | Environmental degradation lowers sustainability performance with a time delay.                                     | Rockström et al. (2009).                         |
| ECL           | ESI         | +    | 0     | 2      | Improved compliance strengthens sustainability outcomes.                                                           | Bouloiz et al. (2013); Zio (2016)                |
| ESI           | RP          | –    | 0     | 2      | Greater sustainability reduces regulatory pressure and need for enforcement.                                       | Reniers & Cozzani (2013); Renn & Klinke (2013)   |
| EDL           | RP          | +    | 1     | 2      | Increased damage provokes stronger regulatory responses.                                                           | Sterman (2002); Zhang et al. (2020)              |
| RP            | CL          | +    | 0     | 1      | Regulatory pressure elevates compliance levels through enforcement.                                                | Bouloiz et al. (2013) ; Reniers & Cozzani (2013) |
| CL            | PER         | –    | 0     | 2      | Higher compliance reduces emissions by enforcing operational limits.                                               | Zhang et al. (2020); Folke et al. (2010)         |
| RP            | ECL         | +    | 1     | 2      | Institutional pressure increases organizational compliance over time.                                              | Reniers & Cozzani (2013) ;                       |

| From (source) | To (target) | Sign | Delay | Weight | Interpretation                                                                                  | References                          |
|---------------|-------------|------|-------|--------|-------------------------------------------------------------------------------------------------|-------------------------------------|
|               |             |      |       |        |                                                                                                 | Bouloiz et al. (2013)               |
| ECL           | PER         | –    | 1     | 2      | Improved environmental compliance reduces pollutant release.                                    | Bouloiz et al. (2013)               |
| ECL           | OI          | –    | 1     | 2      | Strong compliance decreases operational intensity by limiting production rates or resource use. | Zio (2016); Rockström et al. (2009) |
| ECL           | ERR         | +    | 1     | 2      | Effective compliance promotes recovery activities (e.g., remediation, ecosystem restoration).   | Folke et al. (2010); Holling (2001) |

This structural formulation of the ENV module captures the essential causal pathways governing the evolution of environmental performance under industrial operations. Reinforcing interactions (e.g., OI → PER → EDL) represent the pressure exerted by economic and production growth, while balancing influences (ECL → PER ↓; ERR → EDL ↓) embody regulatory and ecological resilience mechanisms. The inclusion of moderate to high weights (2–3) for most delayed processes reflects the strong but temporally lagged influence of both degradation and recovery pathways, consistent with empirical evidence from industrial ecology and environmental systems modeling (Sterman, 2002).

The formalized ENV network thus provides a robust quantitative foundation for subsequent analysis through graph-theoretical centrality metrics. In the next section, these results are interpreted to identify dominant nodes, influence pathways, and potential leverage points for enhancing environmental resilience and sustainability performance within the broader FRISE framework.

#### 6.4.4- Graph Analysis and Results Interpretation

The graph-theoretical analysis of the Environmental (ENV) module quantifies how influence, dependency, and feedback strength are distributed across the environmental causal network. The metrics obtained from the directed and weighted graph representation reveal a clear division between drivers of degradation, regulatory mediators, and restorative or absorptive sinks. These findings (Figure 6.9) provide insight into the structure of environmental resilience and the propagation of sustainability effects through the system.

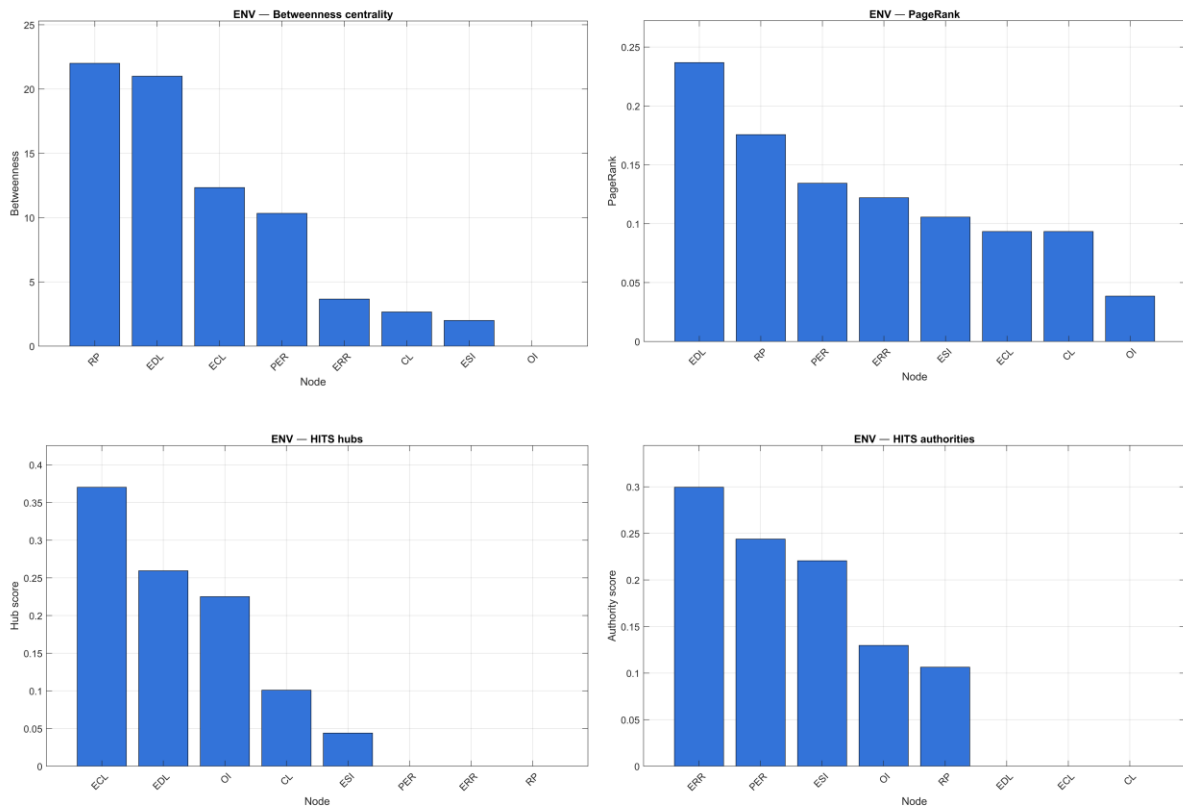


**Fig. 6.9- Graph Theory results for the ENV module**

### ***Dominant mediators and influence pathways***

Among all nodes, Environmental Damage Level (EDL) and Regulatory Pressure (RP) emerge as the dominant mediators of systemic behavior. EDL exhibits the highest betweenness centrality (21) and a high PageRank value (0.2368), confirming its role as the central broker between degradation and recovery subsystems. In the causal structure, EDL connects emissions (PER) to both the recovery rate (ERR) and the sustainability index (ESI), while also stimulating regulatory responses (EDL → RP). This position makes EDL the primary conduit for feedback transmission, where small perturbations in pollution or recovery processes propagate widely throughout the network. Similar findings in environmental systems modeling indicate that environmental damage accumulation functions as a structural leverage point — a variable through which both mitigation and policy interventions can most effectively reduce long-term ecological risk (Folke et al., 2010; Zio, 2016).

RP, in turn, exhibits the highest betweenness among regulatory variables (22) and a strong eigenvector centrality (0.993), signaling its function as a major mediator between environmental states and institutional responses. Positioned downstream of both EDL and ESI, RP drives compliance (RP → ECL) and links ecological degradation to managerial action. This

reinforces the notion that regulatory mechanisms serve as the primary adaptive control within the ENV subsystem, converting environmental information into behavioral constraints that shape operational and compliance dynamics (Renn & Klinke, 2013; Bouloiz et al., 2013).

### ***Degradation drivers and emission dynamics***

Pollution Emission Rate (PER) operates as the key source node for degradation processes. It holds moderate betweenness (10.3) but a relatively high eigenvector value (0.766), indicating that although it is not a central broker, it is closely connected to other influential nodes (EDL, RP, and ESI). This structure mirrors real industrial ecosystems, where emission intensity drives a cascade of secondary effects rather than serving as a systemic controller. Operational Intensity (OI), the exogenous driver of PER, shows low betweenness (0) and modest PageRank (0.0386), which aligns with its interpretation as an external input rather than an internally regulated variable. These results confirm that emission control — mediated through PER and OI — functions as a bottom-up driver of environmental pressure, whose downstream impacts are absorbed by regulatory and recovery mechanisms.

### ***Compliance and restoration subsystems***

The Environmental Compliance Level (ECL) exhibits a high out-degree (4) and betweenness of 12.3, indicating that it serves as a major transmitter of corrective influence. ECL affects both emissions and operational activity ( $ECL \rightarrow PER \downarrow$ ;  $ECL \rightarrow OI \downarrow$ ), and indirectly supports recovery processes ( $ECL \rightarrow ERR \uparrow$ ). Although its eigenvector value (0.546) and PageRank (0.093) are moderate, this node's large out-degree emphasizes its role as a systemic stabilizer that translates regulatory pressure into multiple corrective pathways. This mirrors the empirical role of compliance systems as distributed stabilizers in industrial environmental governance (Reniers & Cozzani, 2013; Bouloiz et al., 2013).

The Environmental Recovery Rate (ERR), on the other hand, presents high authority (0.299) and maximum eigenvector centrality (1), identifying it as a principal sink for incoming influences. ERR receives input from EDL (damage-induced recovery activation), OI (operational inhibition), and ECL (policy-enhanced recovery). The combination of these signals underscores ERR's function as a dynamic absorber that closes the feedback loop between degradation and restoration. This configuration confirms the recovery subsystem as a structural counterbalance to the reinforcement of environmental damage, consistent with resilience theory (Holling, 2001; Folke et al., 2010).

### ***Sustainability integration and system connectivity***

The Environmental Sustainability Index (ESI) holds an eigenvector centrality of 0.835 and PageRank of 0.106, suggesting its strong but indirect influence across multiple loops. ESI mediates between environmental state (EDL) and institutional behavior (RP), forming a crucial perceptual link that translates ecological performance into social and political action. Despite its lower betweenness (2), ESI's high eigenvector indicates connectivity with influential nodes, emphasizing its integrative role as an outcome variable in the long-term sustainability feedback. Conceptually, ESI reflects the “slow variable” of environmental adaptation, accumulating the net effects of damage, recovery, and policy compliance (Rockström et al., 2009).

### ***HITS structure and flow direction***

The HITS analysis reinforces this differentiation between source and sink dynamics. The highest hub score (0.370) belongs to ECL, which acts as a major dispatcher of influence through its multiple outgoing connections. Conversely, ERR (authority = 0.299), PER (authority = 0.244), and ESI (authority = 0.221) emerge as the main recipients of incoming effects — confirming that environmental recovery, pollution emissions, and sustainability performance are the primary endpoints of system behavior. The relatively low hub score of OI (0.225) and RP ( $\approx 0.0$ ) further supports their classification as exogenous and intermediate variables, respectively, rather than network sources.

### ***Systemic interpretation and harmonic structure***

The harmonic closeness centrality (Figure 6.10) provides an aggregate measure of information accessibility across the network. The values obtained (ranging from 0.84 for CL to 1.5 for ECL) indicate that most nodes are moderately well-connected, but delays and directional dependencies introduce asymmetries in response propagation. Variables with higher harmonic closeness — notably ECL (1.5) and EDL (1.29) — occupy positions of high topological efficiency, implying that corrective actions or changes in these variables rapidly influence the rest of the network. This property is characteristic of well-balanced environmental systems, where regulatory and damage variables form an efficient information core that maintains system responsiveness (Sterman, 2002; Zio, 2016).



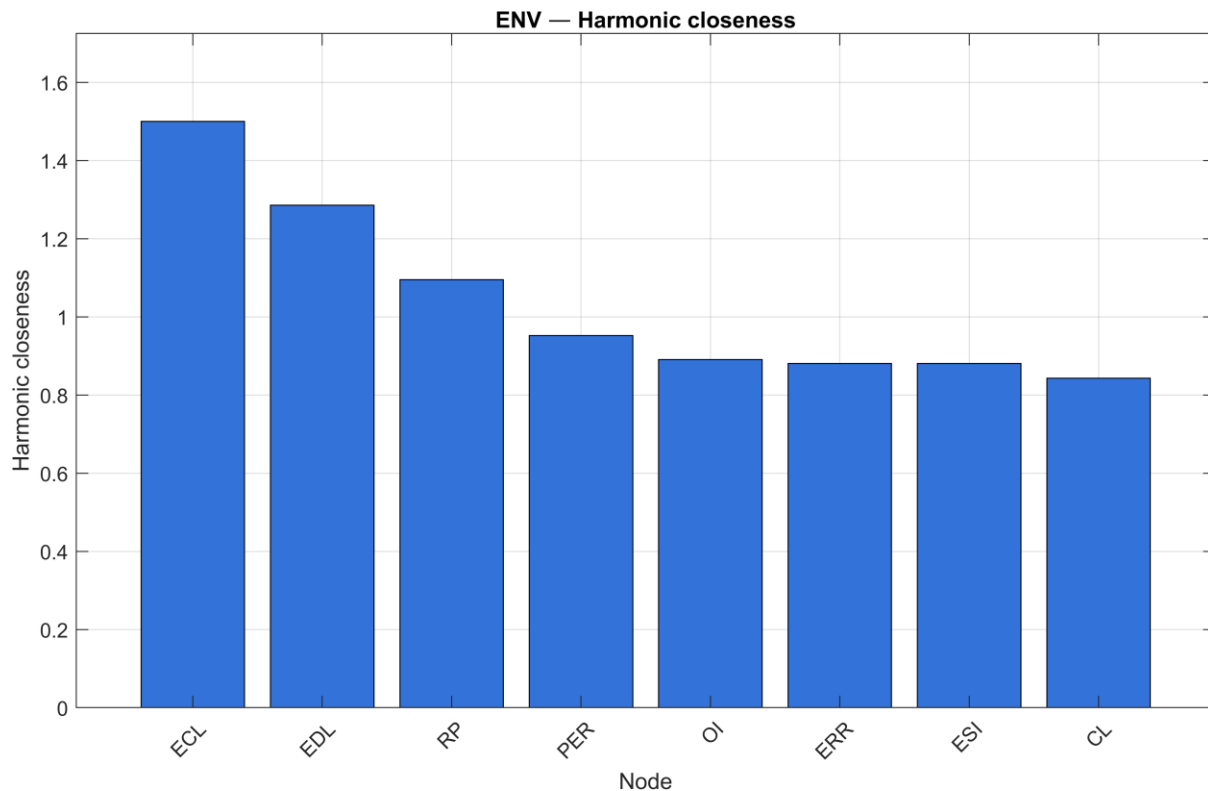


**Fig. 6.10- Harmonic closeness for the ENV module**

### ***Policy and systemic implications***

The quantitative topology of the ENV network underscores the importance of managing damage accumulation (EDL) and regulatory activation (RP) as leverage points for sustainable stability. High-centrality nodes such as EDL and RP represent strategic intervention points where relatively small adjustments in policy or operational parameters can yield disproportionately large systemic effects. Meanwhile, the stability of the entire network depends on maintaining the functional integrity of the recovery subsystem (ERR) and the compliance interface (ECL), both of which exhibit strong authority and hub properties, respectively.

From a resilience perspective, the ENV subsystem demonstrates a well-structured combination of reinforcement and balance: degradation drivers amplify short-term stress, while compliance and recovery dampen these effects over time. Such a structure corresponds to adaptive environmental governance systems where feedback, learning, and ecological processes interact to maintain sustainability within safe operating limits (Holling, 2001; Folke et al., 2010; Rockström et al., 2009).

## ***Summary***

Overall, the ENV module exhibits a robust yet tensioned architecture. Environmental Damage Level (EDL) and Regulatory Pressure (RP) dominate as systemic mediators, linking pollution and sustainability feedbacks, while Recovery Rate (ERR) and Compliance Level (ECL) serve as stabilizing nodes that absorb disturbances and restore balance. The combination of moderate harmonic connectivity and high betweenness among control variables confirms that the system is both responsive and adaptive, yet vulnerable to delays in feedback response. These findings reinforce the conceptual consistency of the FRISE framework, where the ENV subsystem functions as both a sink of degradation and a source of adaptive recovery, dynamically coupled to the technical, managerial, and economic domains of industrial safety and sustainability.

### **6.5- Social (SOC) module**

The Social (SOC) module represents the interface between the technical–managerial system and its broader societal environment. Within the FRISE framework, it captures how public perception, community resilience, and stakeholder trust dynamically influence — and are influenced by — the system’s safety performance, risk management, and transparency. In this sense, the SOC module operates as the societal feedback layer that transforms incident information, communication practices, and cultural values into adaptive behavioral and regulatory responses.

While traditional safety analyses often treat social impact as an external or post-incident consideration, this module integrates it directly into the systemic architecture. By doing so, it links risk communication, organizational legitimacy, and collective resilience with the internal management of safety and environmental performance. This integration allows for a bidirectional exchange of information and influence: incidents shape public attitudes and policy, while community expectations and regulatory pressures feed back into operational and investment decisions (Renn, 2008; Le Coze, 2019; Reniers & Cozzani, 2013).

The SOC module thus extends the FRISE system into the socio-technical domain, ensuring that human and institutional reactions to risk are explicitly modeled. Its inclusion addresses the social amplification of risk phenomena (Kasperson et al., 1988) and the dynamic interplay between trust, legitimacy, and communication (Earle, 2010; Slovic, 2016). In this context, social acceptance and stakeholder satisfaction are not static perceptions but evolving constructs governed by feedback loops that connect community response, regulatory attention, and organizational transparency.

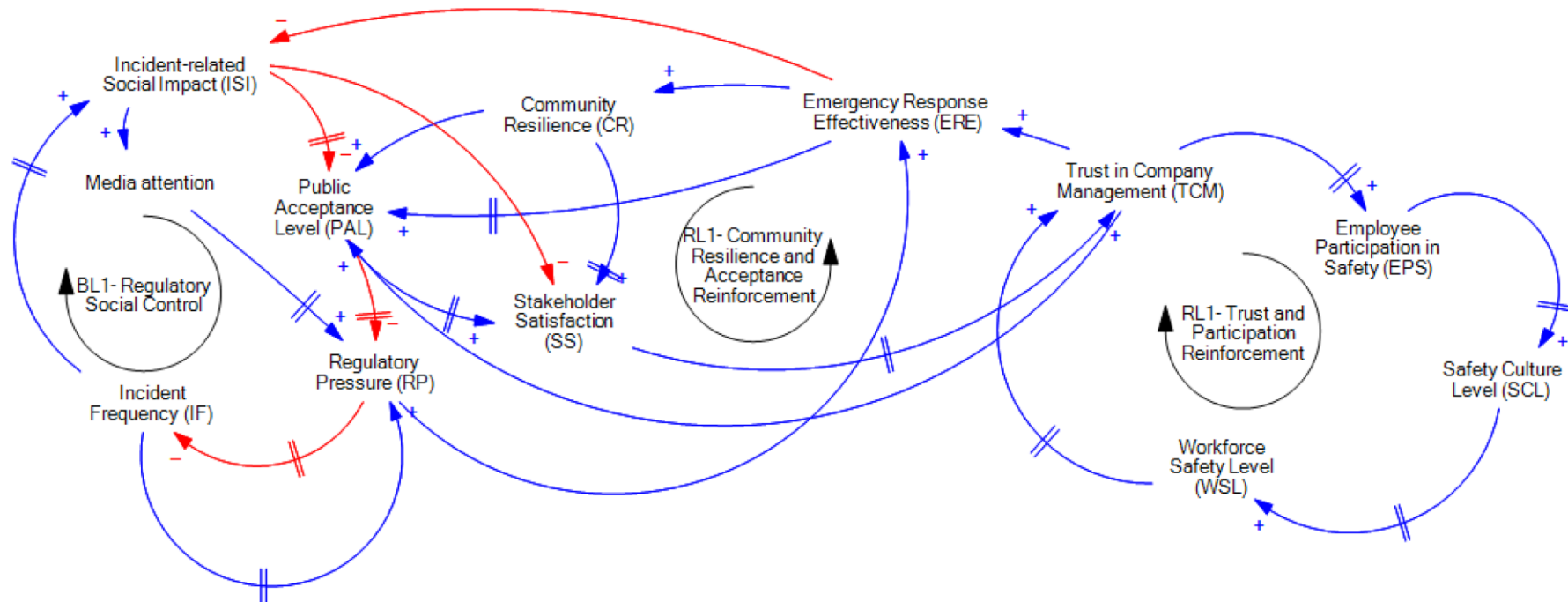


Fig. 6.11- Causal Loop Diagram of the SOC module

The causal structure of this subsystem is depicted in Figure 6.11, which presents the Causal Loop Diagram (CLD) of the Social Module. The diagram visualizes the interdependencies between incident-related social impact (ISI), public acceptance level (PAL), stakeholder satisfaction (SS), and community resilience (CR), alongside the mediating roles of regulatory pressure (RP), trust in company management (TCM), and employee participation in safety (EPS). The feedback loops illustrate how information and perception propagate across societal, organizational, and cultural levels, forming a self-regulating social system that either reinforces confidence or amplifies distrust following incidents.

### **6.5.1- Conceptual Foundations**

The conceptual structure of the SOC module is grounded in social systems theory and risk communication research, bridging individual, organizational, and collective dimensions of safety perception. It operationalizes the co-evolutionary relationship between industrial systems and their social environment through dynamic feedback processes that determine public trust, legitimacy, and resilience. At its core, the module incorporates three foundational paradigms:

- 1- **Perception–Response Coupling:** Risk perception and social response are modeled as dynamically interdependent processes. Incidents trigger public and media attention, which in turn shape the regulatory environment and influence organizational behavior. This reflexive process represents the social amplification of risk (Kasperson et al., 1988; Renn, 2008), where the societal consequences of accidents depend as much on information flow and trust as on physical damage.
- 2- **Trust and Legitimacy as Control Variables:** Trust in company management (TCM) and stakeholder satisfaction (SS) function as stabilizing social control mechanisms. High trust reduces perceived risk and mitigates escalation of regulatory or reputational pressure, while loss of trust amplifies media scrutiny and policy reaction. These variables embody the notion of “socio-political resilience” (Earle, 2010; Boholm, 2010), ensuring that the system adapts through transparency and engagement rather than coercion.
- 3- **Community Resilience and Participation:** The module embeds resilience theory (Hollnagel, 2014; Ferran-Alcázar et al., 2020) by treating community resilience (CR) and employee participation in safety (EPS) as adaptive capacities. These variables capture how learning, collective efficacy, and shared responsibility evolve following incidents, contributing to the long-term stability of the socio-technical system. As

feedback processes strengthen, social actors internalize safety norms, transforming external enforcement into self-regulation.

The resulting system architecture formalizes how incident-related social impact (ISI) and public acceptance level (PAL) interact with stakeholder satisfaction, regulatory pressure, and community resilience. This creates a dynamic continuum between external social perception and internal cultural adaptation. When coupled with the Safety Management (SM) and Environmental (ENV) modules, the SOC layer closes the feedback loop between technical performance, public confidence, and institutional legitimacy, achieving a full representation of sustainability as an emergent property of social–technical–organizational complexity.

### **6.5.2- System Structure and Feedback Architecture**

The internal architecture of the Social (SOC) module captures the adaptive dynamics between public perception, institutional response, and organizational communication. As part of the FRISE framework, it formalizes the sociotechnical feedback processes through which communities, regulators, and internal stakeholders co-evolve in response to safety events. The model assumes that risk communication, public trust, and community resilience emerge as dynamic state variables that influence—rather than merely reflect—system performance (Kasperson et al., 1988; Renn, 2008; Earle, 2010).

The structure of the SOC CLD (Figure 6.11) integrates three principal domains: (i) the social impact–acceptance subsystem, which links operational incidents to media attention, regulatory response, and public approval; (ii) the stakeholder trust–resilience subsystem, representing the long-term cultural reinforcement of confidence and participation; and (iii) the organizational interface, where communication and transparency mediate between technical safety performance and societal legitimacy.

Each of these domains is expressed as a network of causal feedback loops—some reinforcing, promoting social learning and adaptive trust; others balancing, ensuring corrective control and legitimacy restoration after disturbances. The loops are summarized in Table 6.13, while the subsystem interrelations and their cross-modular roles are presented in Table 6.14.

**Table 6.13 – Feedback Loops of the Social (SOC) Module**

| Loop ID                                                                                                                                                                                                                                                                                                                   | Type        | Key Drivers               | Pathway                                         | Outcome / Meaning                                                                                                                           | References                                                          |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|---------------------------|-------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|
| RL <sub>1</sub> – Community Resilience and Acceptance Reinforcement                                                                                                                                                                                                                                                       | Reinforcing | SS, CR, PAL               | SS ↑ → CR ↑ → PAL ↑ → SS ↑                      | Stakeholder satisfaction enhances community resilience and public acceptance, creating a virtuous cycle of confidence and social stability. | Kasperson et al. (1988); Earle (2010); Ferran-Alcázar et al. (2020) |
| RL <sub>2</sub> – Trust and Participation Reinforcement                                                                                                                                                                                                                                                                   | Reinforcing | TCM, EPS, SCL, WSL        | TCM ↑ → EPS ↑ → SCL ↑ → WSL ↑ → TCM ↑           | High trust in management stimulates employee participation and safety culture, reinforcing social cohesion within the organization.         | Hollnagel (2014); Le Coze (2019); Renn (2008)                       |
| BL <sub>1</sub> – Regulatory Social Control                                                                                                                                                                                                                                                                               | Balancing   | IF, RP, PAL               | IF ↑ → RP ↑ → PAL ↓ → RP ↑ (stabilization)      | Incidents raise regulatory pressure, which enforces compliance and curbs excessive social destabilization.                                  | Reniers & Cozzani (2013); Renn (2008); Boholm (2010)                |
| BL <sub>2</sub> – Media Amplification Control (implicit)                                                                                                                                                                                                                                                                  | Balancing   | ISI, Media Attention, PAL | ISI ↑ → Media Attention ↑ → PAL ↓ → RP ↑ → IF ↓ | Media-driven amplification enhances short-term awareness but eventually stabilizes as regulation curtails incident frequency.               | Kasperson et al. (1988); Slovic (2016)                              |
| BL <sub>3</sub> – Community Recovery and Legitimacy Loop (implicit)                                                                                                                                                                                                                                                       | Balancing   | CR, SS, RP                | CR ↑ → SS ↑ → RP ↓ → IF ↓ → CR ↑                | Social and institutional recovery reduce perceived risk and regulatory strain, restoring equilibrium after incidents.                       | Earle (2010); Renn (2008)                                           |
| Acronyms: SS – Stakeholder Satisfaction; CR – Community Resilience; PAL – Public Acceptance Level; TCM – Trust in Company Management; EPS – Employee Participation in Safety; SCL – Safety Culture Level; WSL – Workforce Safety Level; IF – Incident Frequency; RP – Regulatory Pressure; ISI – Incident Severity Index. |             |                           |                                                 |                                                                                                                                             |                                                                     |

The SOC system thus features a combination of rapid feedbacks—driven by media attention and regulatory responses—and slow, trust-based reinforcements that shape long-term resilience. Reinforcing loops (RL<sub>1</sub>–RL<sub>2</sub>) sustain cultural and relational growth, while balancing loops (BL<sub>1</sub>–BL<sub>3</sub>) act as social regulators preventing overreaction and instability. Together, these mechanisms form a socially adaptive control structure consistent with risk governance theory (Renn, 2008).

**Table 6.14 – Principal Subsystems and Dominant Feedback Loops of the SOC Module**

| Subsystem                                | Core Variables                | Dominant Loops                                                                       | Systemic Effect                                                                                                       | Cross-Modular Link                                                     |
|------------------------------------------|-------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Social Impact and Acceptance             | ISI, Media Attention, PAL, RP | BL <sub>1</sub> – Regulatory Social Control; BL <sub>2</sub> – Media Amplification   | Translates incidents into societal perception and regulatory behavior, linking technical events to public legitimacy. | RA (Incident Frequency, REL), ENV (Regulatory Pressure)                |
| Stakeholder Trust and Resilience         | SS, CR, TCM                   | RL <sub>1</sub> – Community Reinforcement; BL <sub>3</sub> – Recovery and Legitimacy | Enhances adaptive capacity and fosters collective learning; transforms external oversight into self-regulation.       | SM (Trust, Safety Culture), ECO (Investment, Reputation)               |
| Organizational Participation and Culture | TCM, EPS, SCL, WSL            | RL <sub>2</sub> – Trust and Participation Reinforcement                              | Promotes safety-oriented behavior through participatory engagement and shared responsibility.                         | SM (Safety Management Effectiveness), SOC (public legitimacy feedback) |

The social impact subsystem governs short-term reactions to incidents and their amplification through public and media attention. The trust–resilience subsystem manages the restoration of legitimacy and long-term stability through confidence-building and institutional learning. Finally, the participation–culture subsystem integrates internal employee engagement with external societal expectations, acting as the organizational bridge between technical performance and social trust.

Collectively, these subsystems define the SOC module as a societal feedback governor within the FRISE framework. Its interdependence with the SM and ENV modules ensures that public perception and trust dynamically shape compliance, investment, and risk reduction strategies—closing the loop between technical operations, organizational conduct, and social sustainability.

### 6.5.3- Mathematical and Graph-Theoretical Representation

The mathematical formalization of the Social (SOC) module translates the qualitative feedback structure of Figure 6.11 into a directed, signed, and weighted network  $G_{SOC} = (V, E)$  describing the dynamics of social perception, trust, and legitimacy. Each vertex  $v_i \in V$  represents a social or organizational variable, while each directed edge  $e_{ij} \in E$  corresponds to a causal influence from  $v_i$  to  $v_j$ . The edge polarity  $s_{ij} \in \{+1, -1\}$  denotes whether the interaction is reinforcing or mitigating, the delay parameter  $\delta_{ij} \in \{0, 1\}$  indicates whether the effect acts with a temporal lag, and the weight  $w_{ij} \in [1, 2]$  reflects the relative strength of

influence as estimated from the literature and expert elicitation (Renn 2008; Earle 2010; Ferran-Alcázar et al. 2020).

The resulting network comprises twelve key variables: *Incident Frequency (IF)*, *Incident-related Social Impact (ISI)*, *Media Attention (Media)*, *Public Acceptance Level (PAL)*, *Stakeholder Satisfaction (SS)*, *Community Resilience (CR)*, *Regulatory Pressure (RP)*, *Emergency Response Effectiveness (ERE)*, *Trust in Company Management (TCM)*, *Employee Participation in Safety (EPS)*, *Safety Culture Level (SCL)*, and *Workforce Safety Level (WSL)*. These variables together capture the circular interplay between external societal perception and internal organizational adaptation. Mathematically, the structure is expressed through a weighted adjacency matrix:  $A_{ij} = s_{ij}w_{ij}$ , where  $A_{ij} > 0$  implies a positive (reinforcing) effect and  $A_{ij} < 0$  a negative (balancing) one. The SOC system contains several interconnected feedback subsystems:

1. a **regulatory social-control** loop linking incident occurrence, media attention, and regulatory pressure (balancing BL<sub>1</sub>);
2. a **social-impact and acceptance** loop connecting incidents, social perception, and stakeholder attitudes (balancing BL<sub>2</sub>);
3. a **community-resilience and acceptance** loop (reinforcing RL<sub>1</sub>) coupling resilience, satisfaction, and public acceptance; and
4. a **trust-participation reinforcement** loop (reinforcing RL<sub>2</sub>) where trust, participation, and safety culture mutually strengthen each other.

Encoding the SOC CLD in this form allows the computation of standard network metrics—betweenness, eigenvector, PageRank, and harmonic closeness centralities—as well as HITS hubs and authorities, following the methodology in 5.7.4. These measures quantify the relative influence and dependency of each social variable, enabling identification of key leverage points in transparency, participation, and legitimacy.

**Table 6.15 — Structural relationships and causal parameters of the Social (SOC) network**

| From (source) | To (target) | Sign | Delay | Weight | Interpretation                                                   | References                             |
|---------------|-------------|------|-------|--------|------------------------------------------------------------------|----------------------------------------|
| ISI           | Media       | +    | 0     | 2      | Incident impact stimulates media attention and public discourse. | Kasperson et al. (1988); Slovic (2016) |



| From (source)                                                                                                                                                                                            | To (target) | Sign | Delay | Weight | Interpretation                                                                   | References                                   |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|------|-------|--------|----------------------------------------------------------------------------------|----------------------------------------------|
| Media                                                                                                                                                                                                    | RP          | +    | 1     | 2      | Media scrutiny heightens regulatory pressure with a short lag.                   | Renn (2008); Boholm (2010)                   |
| RP                                                                                                                                                                                                       | IF          | –    | 1     | 2      | Regulatory oversight constrains operational incidents.                           | Reniers & Cozzani (2013)                     |
| IF                                                                                                                                                                                                       | ISI         | +    | 1     | 2      | Frequent incidents increase perceived social impact.                             | Kasperson et al. (1988)                      |
| ISI                                                                                                                                                                                                      | PAL         | –    | 1     | 2      | Higher social impact diminishes public acceptance.                               | Slovic (2016); Renn (2008)                   |
| ISI                                                                                                                                                                                                      | SS          | –    | 1     | 2      | Negative social impact erodes stakeholder satisfaction.                          | Earle (2010)                                 |
| PAL                                                                                                                                                                                                      | RP          | –    | 1     | 2      | Improved public acceptance alleviates regulatory pressure.                       | Renn (2008)                                  |
| SS                                                                                                                                                                                                       | TCM         | +    | 1     | 1      | Satisfied stakeholders reinforce trust in management.                            | Earle (2010)                                 |
| CR                                                                                                                                                                                                       | SS          | +    | 1     | 2      | Resilient communities foster stakeholder satisfaction.                           | Ferran-Alcázar et al. (2020)                 |
| ERE                                                                                                                                                                                                      | CR          | +    | 0     | 1      | Effective emergency response strengthens community resilience.                   | Le Coze (2019); Ferran-Alcázar et al. (2020) |
| CR                                                                                                                                                                                                       | PAL         | +    | 0     | 2      | Greater community resilience improves public acceptance.                         | Earle (2010); Renn (2008)                    |
| IF                                                                                                                                                                                                       | RP          | +    | 1     | 2      | Higher incident frequency triggers regulatory action.                            | Renn (2008); Reniers & Cozzani (2013)        |
| ERE                                                                                                                                                                                                      | PAL         | +    | 1     | 1      | Visible emergency effectiveness enhances public acceptance.                      | Earle (2010); Le Coze (2019)                 |
| RP                                                                                                                                                                                                       | ERE         | +    | 0     | 1      | Regulatory demand promotes improved response preparedness.                       | Renn (2008)                                  |
| TCM                                                                                                                                                                                                      | ERE         | +    | 0     | 2      | Managerial trust boosts response coordination efficiency.                        | Hollnagel (2014)                             |
| TCM                                                                                                                                                                                                      | EPS         | +    | 1     | 2      | Trust motivates employee participation in safety programs.                       | Hollnagel (2014); Earle (2010)               |
| EPS                                                                                                                                                                                                      | SCL         | +    | 1     | 2      | Participation strengthens safety culture over time.                              | Hollnagel (2014); Le Coze (2019)             |
| SCL                                                                                                                                                                                                      | WSL         | +    | 1     | 2      | Strong safety culture enhances workforce safety behaviors.                       | Hollnagel (2014)                             |
| WSL                                                                                                                                                                                                      | TCM         | +    | 1     | 2      | Improved safety performance reinforces public trust in management.               | Earle (2010); Ferran-Alcázar et al. (2020)   |
| TCM                                                                                                                                                                                                      | PAL         | +    | 0     | 1      | Transparent and trusted management increases public acceptance.                  | Earle (2010); Renn (2008)                    |
| PAL                                                                                                                                                                                                      | SS          | +    | 1     | 1      | Social approval strengthens stakeholder satisfaction, closing the feedback loop. | Earle (2010); Renn (2008)                    |
| Acronyms: ISI – Incident-related Social Impact; Media – Media Attention; RP – Regulatory Pressure; IF – Incident Frequency; PAL – Public Acceptance Level; SS – Stakeholder Satisfaction; CR – Community |             |      |       |        |                                                                                  |                                              |

| From<br>(source)                                                                                                                                                                         | To<br>(target) | Sign | Delay | Weight | Interpretation | References |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|------|-------|--------|----------------|------------|
| Resilience; ERE – Emergency Response Effectiveness; TCM – Trust in Company Management; EPS – Employee Participation in Safety; SCL – Safety Culture Level; WSL – Workforce Safety Level. |                |      |       |        |                |            |

This network representation captures both short-term reactionary processes (media amplification and regulatory intervention) and slower, trust-based reinforcement mechanisms (participation, culture, and resilience). By converting these qualitative relationships into a weighted graph, the SOC subsystem can be quantitatively assessed within the FRISE analytical chain, providing a coherent view of how social dynamics influence—and are influenced by—technical and managerial performance. Numerical results and centrality analysis derived from this formulation are interpreted in the following section (§ 6.5.4).

#### 6.5.4- Graph Analysis and Results Interpretation

The network analysis of the Social (SOC) module reveals a strongly interconnected topology characterized by multiple mediating nodes linking public perception, organizational trust, and regulatory response. The distribution of centrality indices (Figure 6.12) illustrates how influence and dependency are dynamically allocated across the social subsystem, identifying the main actors that mediate information, legitimacy, and collective response.

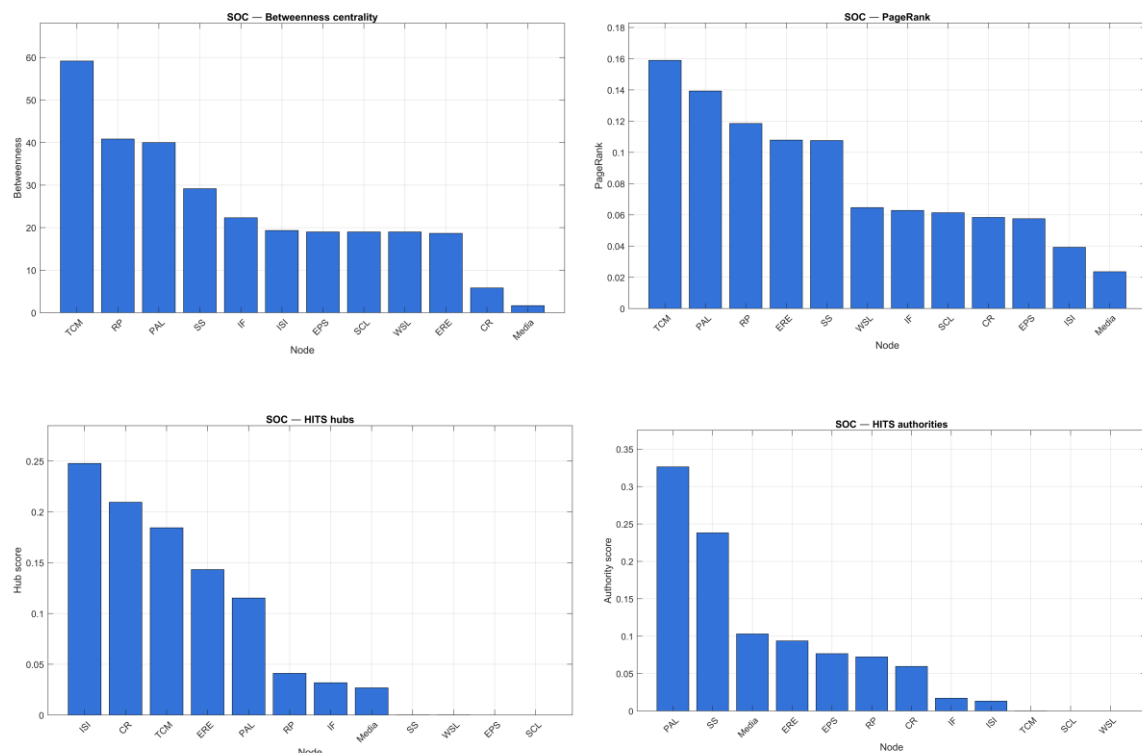


Fig. 6.12- Graph Theory results for the SOC module

### ***Network centrality structure***

The Trust in Company Management (TCM) variable exhibits the highest betweenness centrality ( $\approx 59.2$ ) and the highest PageRank value (0.159), confirming its systemic role as a key broker of social stability. TCM connects internal organizational dynamics ( $\text{EPS} \rightarrow \text{SCL} \rightarrow \text{WSL} \rightarrow \text{TCM}$ ) with external acceptance mechanisms ( $\text{TCM} \rightarrow \text{ERE} \rightarrow \text{PAL}$ ), allowing trust to propagate through both behavioral and communicative pathways. Its high betweenness indicates that many of the shortest influence chains traverse TCM, meaning that fluctuations in public or workforce trust can reconfigure the overall perception of safety performance. This aligns with Earle (2010) and Hollnagel (2014), who emphasize trust as a fundamental mediator in risk communication and safety management systems.

Public Acceptance Level (PAL) also emerges as a dominant influencer, presenting both high betweenness (40) and elevated eigenvector centrality (1.00). This indicates that PAL operates as a convergence point for multiple causal chains: it is affected by incident-related perception (ISI), resilience (CR, ERE), and trust (TCM), while simultaneously feeding back into satisfaction (SS) and regulatory pressure (RP). PAL's high harmonic closeness (0.333) underscores its accessibility from other nodes—public acceptance reacts swiftly to upstream variations, making it a sensitive indicator of socio-political balance.

A third central node is Regulatory Pressure (RP), with comparable betweenness ( $\approx 40.8$ ) and strong eigenvector value (0.848). RP acts as an institutional amplifier: it absorbs signals from social impact (ISI) and public sentiment (PAL) and redistributes them through compliance and governance mechanisms toward operational safety ( $\text{RP} \rightarrow \text{IF}, \text{ERE}$ ). Its dual role—as both a receiver and broadcaster—mirrors findings in regulatory feedback studies (Renn, 2008; Reniers & Cozzani, 2013), where reactive oversight functions as a stabilizing counterforce to social perturbations.

### ***Peripheral but influential clusters***

While Stakeholder Satisfaction (SS) ranks lower in out-degree, it still achieves a notable betweenness (29.2) and high eigenvector (0.874), acting as a terminal consolidator of perception and performance. SS integrates cultural and trust dynamics (TCM, PAL, CR) into a measure of collective legitimacy. In contrast, Emergency Response Effectiveness (ERE) exhibits moderate betweenness (18.7) but the highest harmonic closeness (0.370), indicating its proximity to all other variables. This suggests that rapid improvements or failures in

emergency preparedness propagate efficiently across the social subsystem—a finding consistent with resilience literature (Le Coze, 2019; Ferran-Alcázar et al., 2020).

The Incident-related Social Impact (ISI) node also exhibits relatively high betweenness (19.3) but low authority (0.013), implying that while it triggers many responses (Media → RP, PAL, SS), it exerts influence without accumulating feedback—typical of reactive drivers in risk perception models (Kasperson et al., 1988; Slovic 2016). Incident Frequency (IF) shows similar behavior: modest PageRank (0.063) but non-negligible betweenness (22.3), linking operational events to public discourse and policy pressure.

### ***HITS analysis and influence asymmetry***

HITS analysis reinforces the brokerage role of TCM and PAL. TCM is among the top hubs (0.184)—a strong initiator of positive trust-based feedback—while PAL and SS exhibit the highest authority scores (0.326 and 0.238), denoting their role as key endpoints for collective opinion and satisfaction. Media and ERE also demonstrate moderate authority values (~ 0.09–0.10), indicating their function as perception channels.

This asymmetry between trust (hub) and acceptance (authority) reflects a natural division between organizational influence and social response: management and workforce behaviors radiate trust outward, while acceptance and satisfaction aggregate the external perception. This finding corresponds with Earle (2010) and Boholm (2010), who describe trust as an “initiator variable” and acceptance as a “terminal variable” within the social amplification of risk framework.

### ***Systemic interpretation and implications***

The pattern of high betweenness in TCM, PAL, and RP, combined with their elevated PageRank values, indicates that the SOC module operates as a triadic regulatory system balancing organizational credibility, public tolerance, and institutional oversight. These nodes represent leverage points where soft variables—trust, transparency, and communication—translate into hard system stability.

Harmonic closeness (Figure 6.13) further clarifies the diffusion dynamics: ERE and RP display the highest values (~ 0.37 and 0.35), implying that they mediate fast, system-wide propagation of changes in perception or performance. Conversely, peripheral nodes such as Media, EPS, and SCL show low closeness (< 0.20), reflecting their localized, slow-moving influence—typical of gradual cultural processes.

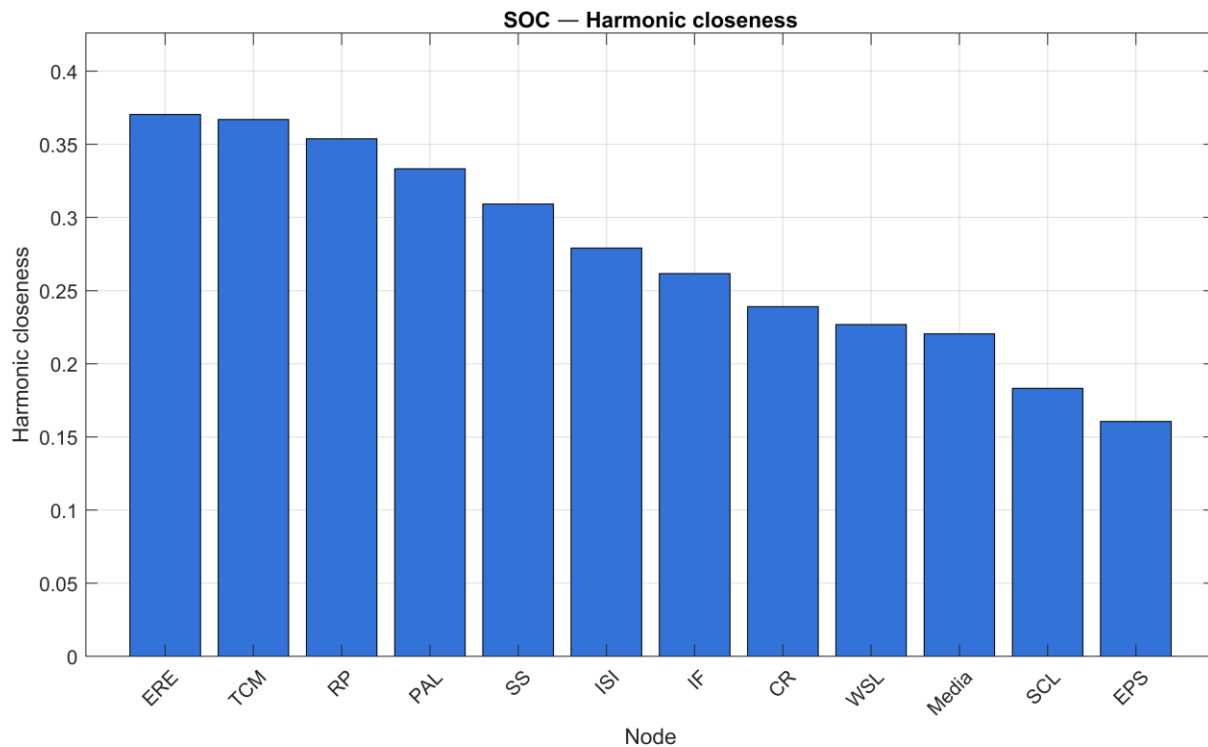


**Fig. 6.13- Harmonic closeness for the SOC module**

In systemic terms, the SOC network combines short-term, media-driven corrective loops with slower, cultural reinforcement processes, achieving adaptive equilibrium through the trust–participation–acceptance triad. These findings substantiate the role of the SOC module within the FRISE framework as the social resilience layer—the domain that transforms incident experience and managerial behavior into legitimacy, cooperation, and ultimately sustainability.

## 6.6- Comparative Synthesis of the FRISE Core Modules

The development and quantitative analysis of the five FRISE core modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—provide a multi-layered representation of system resilience where technical reliability, managerial adaptation, financial viability, ecological stability, and societal legitimacy interact through coupled feedbacks.

Although each module exhibits distinct variables and temporal scales, their graph-theoretical fingerprints reveal a consistent systemic logic: a small number of highly central nodes dominate influence propagation, while a larger ensemble of local stabilizers absorb perturbations. This structural asymmetry reproduces the behavior of real socio-technical systems, where resilience emerges from the interplay between reinforcing growth mechanisms and balancing regulatory processes (Rasmussen 1997; Leveson 2011; Zio 2016).

### 6.6.1- Structural and Functional Comparison

Table 6.16 summarizes the principal structural properties of the five modules, based on the number of variables, feedback composition, and dominant nodes identified through graph-theoretical analysis.

**Table 6.16 — Comparative structural characteristics of the FRISE core modules**

| Module                 | No. of Variables | Dominant Loops              | Core Drivers / Integrators | Principal Balancing Nodes  | Primary Function                                                           | Systemic                    |
|------------------------|------------------|-----------------------------|----------------------------|----------------------------|----------------------------------------------------------------------------|-----------------------------|
| RA – Risk Assessment   | 12               | 3 reinforcing + 4 balancing | ICM, REL, IF               | PBE–IDRE (barriers)        | Technical quantifies escalation and control.                               | nucleus: hazard and barrier |
| SM – Safety Management | 12               | 2 reinforcing + 3 balancing | SME, CL, IF                | AFR, IC (budget balancers) | Managerial and cultural regulator investment, trust, and compliance.       | linking                     |
| ECO – Economic         | 8                | 2 reinforcing + 1 balancing | SIL, P, AFR                | IC, OpC                    | Financial translates performance into profitability and reinvestment.      | engine: safety and          |
| ENV – Environmental    | 8                | 1 reinforcing + 2 balancing | EDL, RP                    | ECL, ERR                   | Ecological feedback layer linking industrial activity with sustainability. |                             |
| SOC – Social           | 12               | 2 reinforcing + 3 balancing | TCM, PAL, RP               | SS, ERE                    | Societal mediates trust, acceptance, and regulatory legitimacy.            | interface:                  |

Across all layers, the number of variables and feedbacks follows a similar order of complexity, ensuring modular balance. Reinforcing loops dominate the RA, SM, and ECO modules, reflecting the growth and adaptation tendencies of technical, organizational, and economic processes. The ENV and SOC layers exhibit stronger balancing influence, consistent with their stabilizing and legitimizing functions within the overall system.

### 6.6.2- Graph-Theoretical Convergence

The comparative examination of network metrics highlights recurrent structural motifs:

- **Central Integrators:** Each module exhibits a single dominant integrator variable: ICM (RA), SME (SM), SIL/P (ECO), EDL (ENV), and TCM/PAL (SOC). These nodes possess the highest betweenness and eigenvector scores, confirming that system behavior concentrates around a few mediating hubs that link local subsystems to the global feedback network. Their stabilizing role underlines the universality of “central brokers” in complex adaptive systems (Hollnagel 2014; Zio 2016).

- **Flow Direction and Accumulation:** HITS analysis reveals a consistent pattern of asymmetry: degradation or stress drivers (Aging, CL, IC, OI, ISI) act as hubs, while consequence or legitimacy variables (IV, SME, AFR, ERR, PAL) behave as authorities. This directional gradient ensures that influence flows from operational stressors toward absorptive sinks, maintaining bounded oscillation.
- **Temporal Stratification:** The inclusion of delays produces two temporal layers in every module: (i) fast feedbacks governing operational correction (RA: barrier response; SM: compliance; ECO: cost control; ENV: regulatory enforcement; SOC: media reaction) and (ii) slow feedbacks driving adaptation and learning (aging, culture, reputation, ecosystem recovery, trust). The coexistence of these timescales confers dynamic resilience—rapid responsiveness combined with long-term stability (Holling 2001; Ferran-Alcázar et al. 2020).
- **Harmonic Closeness and Connectivity:** Despite differences in size and weighting, all modules present moderate harmonic-closeness averages ( $\approx 0.25\text{--}0.35$ ), indicating efficient internal communication without excessive density. The ECO and SOC layers show slightly higher closeness due to their dense financial and social interlinkages, whereas RA and ENV networks maintain sparser, hierarchical topologies.

### 6.6.3- Comparative Functional Insights

A synthetic comparison of the five modules (Table 6.17) illustrates how each fulfills a complementary systemic function within the FRISE framework.

The comparative analysis underscores that resilience in FRISE is distributed across heterogeneous but interoperable mechanisms:

- RA provides reactivity (fast technical containment);
- SM ensures adaptivity (organizational learning and compliance);
- ECO guarantees sustainability (financial continuity);
- ENV secures stability (ecological recovery and regulatory feedback); and
- SOC confers legitimacy (trust-based social coherence).

Their interdependence forms a hierarchical yet mutually adaptive architecture in which disturbances in one domain can be absorbed or compensated by adjustments in others.

**Table 6.17 — Cross-module functional comparison and dominant leverage points**

| <b>Domain (Module)</b> | <b>Principal Leverage Variables</b> | <b>Dominant Feedback Mechanism</b>                  | <b>Primary Timescale</b> | <b>Cross-Coupling Links</b>                      | <b>Strategic Interpretation</b>                                                  |
|------------------------|-------------------------------------|-----------------------------------------------------|--------------------------|--------------------------------------------------|----------------------------------------------------------------------------------|
| RA (Technical)         | ICM, IF, REL                        | Reinforcing escalation vs balancing barrier control | Short operational –      | SM (compliance), ECO (costs), ENV (emissions)    | Controls physical risk propagation and defines system hazard boundary.           |
| SM (Managerial)        | SME, CL, TCM                        | Reinvestment–culture reinforcement                  | Medium – organizational  | ECO (budget), SOC (trust), RA (performance)      | Converts management and learning into sustained safety performance.              |
| ECO (Financial)        | SIL, P, AFR                         | Profit reinvestment vs cost erosion                 | Medium – economic cycle  | RA (IC), SM (SIL), SOC (MRS)                     | Transforms safety performance into economic resilience and resource flow.        |
| ENV (Environmental)    | EDL, RP, ECL                        | Degradation vs regulatory/recovery control          | Long – ecological        | SM (RP), SOC (sustainability awareness)          | Regulates ecological feedback and institutional response to industrial pressure. |
| SOC (Societal)         | TCM, PAL, RP                        | Trust and participation reinforcement               | Long – socio-cultural    | SM (culture), ECO (reputation), ENV (legitimacy) | Transforms risk communication into social acceptance and legitimacy.             |

#### 6.6.4- Methodological Coherence and Future Coupling

The modular comparison confirms the internal consistency of the FRISE methodological framework: each subsystem was modeled using an identical causal-loop-to-graph-network procedure, preserving polarity, delay, and relative weight. This uniform representation enables quantitative interoperability and facilitates the forthcoming cross-modular integration to be developed in Chapter 9 after considering the applications.

That cross-modular integration will address:

- Bidirectional coupling between modules via boundary variables (e.g., IF, IC, AFR, RP, TCM, ESI),
- Propagation of perturbations across technical, managerial, economic, environmental, and social layers, and
- System-level metrics of holistic resilience and sustainability.

These couplings will operationalize the Systemic Glue Layer introduced in Chapter 5, allowing simulation of multi-domain feedbacks and validation of emergent behavior through integrated graph-dynamics analysis.



### 6.6.5- Concluding Remarks

The comparative synthesis demonstrates that the five core modules collectively reproduce the essential features of complex industrial resilience systems: feedback dominance, non-linearity, and adaptive coupling across heterogeneous domains. Each module contributes a specific dimension—technical, organizational, financial, environmental, or social—to the global system’s stability.

While the present chapter isolates these components for clarity, their true significance lies in interaction. The forthcoming Cross-Modular Integration (Chapter 9) will merge these layers into a unified dynamic model, quantifying how information, resources, and legitimacy circulate across FRISE’s architecture. This step will complete the methodological cycle of the framework—transforming modular understanding into systemic foresight capable of supporting resilient and sustainable industrial decision-making (Hollnagel 2014; Renn 2008; Zio 2016).

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## **Chapter 7 – Application I: Hydrogen Safety and Sustainability**

This chapter introduces the operational implementation of the FRISE framework through three progressively integrated case studies that capture the dynamic interplay between safety, sustainability, and socio-technical adaptation in hydrogen systems. Building on the conceptual and methodological foundation of Chapters 5 and 6, this chapter translates the framework into an executable modelling environment combining Causal Loop Diagrams (CLDs), System Dynamics (SD), and Graph-Theoretic (GT) analysis. The purpose is twofold: (i) to demonstrate how FRISE can represent feedback-dominated behaviors such as degradation, learning, and policy adaptation, and (ii) to validate its scientific and practical robustness across diverse hydrogen-related domains—from risk escalation and explosion management to storage safety and technology adoption. Through these applications, the chapter provides empirical evidence that FRISE constitutes a reliable, adaptive, and integrative tool for managing safety–sustainability trade-offs in complex energy transition systems.

### **7.1- Introduction**

The transition toward a hydrogen-based economy is increasingly regarded as a cornerstone of the global strategy to achieve net-zero emissions and long-term energy sustainability. Hydrogen offers a high gravimetric energy density, can be generated from renewable sources, and presents a pathway for decarbonizing energy-intensive industries, transportation, and domestic sectors. However, its implementation at large scale introduces new layers of technological and systemic complexity, especially concerning safety, storage, and sustainability interactions. These challenges arise from the physical properties of hydrogen—such as its small molecular size, wide flammability range, and high diffusivity—as well as from the interconnected economic, environmental, and social systems within which hydrogen technologies operate (Rivkin et al., 2015; Dawood et al., 2020; Moradi and Groth, 2019).

Within this context, the present chapter introduces the first practical application of the FRISE Framework, previously developed in Chapters 5 and 6, to a real-world, socio-technical energy system. Entitled Application I: Hydrogen Safety and Sustainability, this chapter demonstrates how the FRISE framework can be used to analyse the dynamic interplay between safety performance, sustainability indicators, and management decisions in hydrogen technologies. In particular, it focuses on three complementary domains: (i) the dynamic risk assessment of hydrogen systems, (ii) the management of explosion safety during hydrogen enrichment, and (iii) the comparative sustainability and safety assessment of different hydrogen storage

pathways. Collectively, these studies exemplify how the FRISE framework integrates systemic analysis and feedback-driven modelling to evaluate emerging technologies under uncertainty.

Hydrogen systems are characterized by their inherently complex, adaptive, and feedback-rich nature. Their performance is influenced by nonlinear interactions among technical degradation, safety barriers, regulatory mechanisms, public perception, and financial investment (Dueñas Santana et al., 2025). Traditional risk assessment methods, which typically rely on static probabilities or linear cause–effect chains, are unable to capture these evolving relationships over time (Sterman, 2002). Consequently, a dynamic approach becomes essential—one that accounts for feedback delays, policy resistance, and cross-sectoral linkages between energy efficiency, safety management, and environmental performance. The FRISE framework offers such an integrative structure, combining Systems Thinking, Complexity Theory, and Sustainability Science into a unified methodological paradigm (Dueñas Santana et al., 2024; Salzano et al., 2014).

In this first application, the FRISE framework is employed to model the dynamic interactions among the five foundational modules developed in Chapter 6—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—all connected through the Systemic Glue Layer. Each module contributes to the analysis of hydrogen safety and sustainability from a distinct perspective: the RA and SM modules capture the evolution of barrier degradation, incident frequency, and organizational learning; the ECO and ENV modules quantify the interdependencies between investment, emissions, and ecological resilience; and the SOC module reflects cultural, regulatory, and trust-related dimensions. When integrated, these modules provide a comprehensive systemic representation of hydrogen technologies as socio-technical systems operating within feedback-dominated environments.

The application presented herein follows a dual modelling logic. First, Causal Loop Diagrams (CLDs) are used to map the qualitative feedback structures governing hydrogen safety and sustainability. These diagrams reveal the reinforcing and balancing mechanisms that shape system behavior, such as safety investment feedbacks, environmental recovery cycles, and trust–performance loops. Second, System Dynamics (SD) models are employed to quantify these relationships, simulate temporal trajectories, and evaluate the sensitivity of outcomes to different policy or investment scenarios. The combined CLD–SD approach enables both structural and behavioral understanding of the system—an approach consistent with the

Systems Thinking paradigm originally introduced by Forrester (1961) and expanded by Meadows (1999) and Sterman (2002).

Beyond modeling, the analysis also integrates Graph Theory (GT) metrics, which were introduced in Chapter 6 as a complementary quantitative method for characterizing systemic structure. GT analysis identifies the most influential variables (hubs, authorities, and bridges) in each hydrogen application and supports the detection of leverage points where targeted interventions can yield the highest systemic benefit. Although System Dynamics captures temporal evolution, GT metrics provide a snapshot of the network's structural hierarchy, thereby strengthening the explanatory power of the FRISE framework through a dual perspective of structure + behavior (Dueñas Santana et al., 2025).

Ultimately, this chapter demonstrates that the FRISE framework is not limited to theoretical or modular construction but can be effectively applied to real and complex technological systems. The hydrogen case studies illustrate how the integration of dynamic feedback modeling, safety management principles, and sustainability assessment can lead to more robust and adaptive decision-making strategies. The outcomes also highlight the capacity of the framework to bridge disciplinary boundaries, connecting engineering safety analysis with economic, environmental, and societal dimensions—an essential step for achieving sustainable, safe, and socially accepted energy transitions.

## **7.2- Contextual Background: Hydrogen Safety within the Energy Transition**

The selection of hydrogen safety and sustainability as the first application of the FRISE framework is driven by both conceptual and methodological motivations. As established in Chapter 4, hydrogen represents a paradigmatic case within the broader field of complex energy systems: it is a rapidly evolving technology situated at the intersection of risk assessment, safety management, and sustainability policy. The hydrogen economy integrates multiple feedbacks among technical reliability, safety culture, regulatory frameworks, environmental performance, and public perception—making it an ideal domain for testing the integrative and feedback-oriented nature of the FRISE framework.

Unlike mature industrial sectors such as petrochemical or conventional energy systems, hydrogen infrastructures are still in the process of technological, regulatory, and social consolidation. This transitional state amplifies uncertainty and dynamic interdependencies, as technological advances, policy incentives, and societal acceptance evolve concurrently. As discussed in previous chapters, such evolving conditions are best represented through Systems

Thinking and System Dynamics (SD) modeling, which can capture feedback mechanisms, time delays, and adaptive responses (Sterman, 2002; Salzano et al., 2014). In this regard, hydrogen systems provide a unique opportunity to operationalize the FRISE architecture in a domain where complexity is not only technical but also socio-political.

The FRISE framework was designed to integrate five interconnected modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—through a Systemic Glue Layer that enables cross-domain feedbacks. Hydrogen technologies naturally activate all these modules simultaneously. Risk assessment is essential for addressing explosion and embrittlement hazards; safety management governs the allocation of resources and learning mechanisms; economic considerations influence investment decisions and technology diffusion; environmental concerns relate to emissions, energy efficiency, and circularity; and social factors determine acceptance and trust in hydrogen adoption. Few technological domains encapsulate these interactions as tightly as hydrogen systems do.

Methodologically, applying FRISE to hydrogen enables the validation of its feedback-based analytical structure across multiple scales—from component-level failure dynamics to system-wide sustainability trade-offs. The framework can thus demonstrate its ability to model the temporal evolution of safety and sustainability performance under varying policy, investment, and technological scenarios. Moreover, this application allows the integration of complementary analytical methods—such as Graph Theory (GT) metrics—to identify leverage variables within the hydrogen system’s causal architecture. The combination of GT and SD modeling provides both structural and dynamic perspectives, strengthening the robustness of the analysis.

From a strategic standpoint, the hydrogen case also serves as a methodological testbed for the cross-sectoral generalization of the FRISE framework. Lessons derived from hydrogen—where systemic coupling between energy policy, technology, and safety governance is strong—can inform future applications in other sectors, such as fire safety engineering or chemical process industries. Thus, the present chapter does not aim to re-examine the technical literature on hydrogen production and safety, which has already been extensively reviewed in Chapter 4, but to apply the conceptual and methodological architecture of FRISE to an emerging, feedback-dominated domain.

In summary, hydrogen is chosen as the first application because it simultaneously exhibits (i) high systemic complexity, (ii) strong sustainability and safety interdependencies, and (iii) a need for integrated modeling approaches that go beyond reductionist methodologies. The subsequent sections operationalize this rationale by applying the FRISE framework to three interconnected case studies—dynamic hydrogen risk assessment, explosion safety management during hydrogen enrichment, and comparative analysis of hydrogen storage technologies—demonstrating how feedback-based modeling can support safer and more sustainable transitions within the hydrogen economy.

### **7.3- Methodological Setup: Applying the FRISE Framework**

The methodological structure adopted in this chapter follows directly from the theoretical and modular architecture of the FRISE framework, developed in Chapters 5 and 6. The application to hydrogen safety and sustainability aims to operationalize the framework’s integrative capacity—namely, its ability to represent interdependencies among technical, managerial, environmental, and socio-economic dimensions through feedback-based modeling. This section describes how the five core modules of FRISE are implemented in the context of hydrogen systems, the analytical workflow connecting qualitative and quantitative modeling, and the complementary use of Graph Theory (GT) metrics for structural analysis.

#### **7.3.1- Overview of the FRISE architecture**

The Feedback-based Risk Integration for Safety and Sustainability in Engineering (FRISE) framework was designed as a modular, dynamic, and transferable system capable of capturing the feedback-rich nature of modern socio-technical infrastructures. Each of its five core modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—represents a functional domain of the system, while the Systemic Glue Layer (SGL) ensures information exchange and feedback coupling across modules.

In the present application, these modules are instantiated for hydrogen technologies as follows:

- RA module: models the evolution of technical risk, including hydrogen leakage, material degradation, explosion probability, and domino effects.
- SM module: simulates the management feedback loops linking investment, maintenance, and safety culture to overall system reliability.
- ECO module: quantifies the economic dynamics associated with preventive investment, operational cost, and insurance or penalty mechanisms.



- ENV module: represents environmental impact metrics (e.g., emissions, energy efficiency, ecological damage, and recovery) influenced by system performance.
- SOC module: captures societal and regulatory dimensions, including risk perception, trust, compliance, and policy responsiveness.

The methodological innovation of FRISE lies in the explicit feedback coupling between modules. For example, an increase in safety investment (SM) reduces technical risk (RA) but simultaneously affects financial resources (ECO), which can influence regulatory confidence and public trust (SOC). Similarly, environmental degradation (ENV) may feedback into societal pressure (SOC) and policy stringency, altering management decisions (SM). These multidirectional interactions generate dynamic behavior that can only be captured through a systemic modeling approach.

### **7.3.2- Analytical workflow and modeling sequence**

The application of FRISE to hydrogen safety and sustainability follows a multi-stage workflow that connects qualitative system conceptualization with quantitative simulation and structural validation (Figure 7.1).

#### ***System boundary definition and variable identification***

The first step involves delineating the boundaries of the hydrogen subsystem to be analyzed—ranging from individual storage or enrichment processes to broader organizational and policy structures. Variables are selected based on literature evidence, expert input, and their relevance to at least one FRISE module. This ensures both domain fidelity and systemic completeness.

#### ***Causal Loop Diagram (CLD) development***

CLDs are used to map causal relationships and identify feedback structures that drive system behavior. Each causal link is characterized by its polarity (positive or negative) and its feedback classification (reinforcing or balancing). CLDs are developed using Vensim PLE and later validated through cross-consistency checks across modules.

#### ***Integration of modular subsystems***

Module-specific CLDs (e.g., RA, SM, ECO, ENV, SOC) are merged through the Systemic Glue Layer to form a single cross-modular CLD. This step allows the identification of high-level feedback loops, such as investment–risk–trust, emission–policy–compliance, or profit–safety–environmental integrity.

### ***System Dynamics (SD) model formulation***

Each CLD is translated into a quantitative SD model consisting of stocks, flows, auxiliary variables, and delays. The equations governing these elements are derived from empirical data (e.g., accident frequencies, economic indices), normalized values, or literature-based parameterizations (Dueñas Santana et al., 2025; Salzano et al., 2014). The SD models are simulated under different scenarios using Vensim DSS to assess time-dependent evolution of key indicators.

### ***Scenario definition and sensitivity analysis***

Multiple scenarios are developed to test the influence of policies or management decisions. Typical scenarios include variations in safety investment, hydrogen blending ratios, maintenance frequency, or emission constraints. Sensitivity analysis is performed to identify the most influential parameters on systemic performance.

### ***Graph Theory (GT) analysis and structural validation***

The structural configuration of the hydrogen system—derived from the CLD adjacency matrix—is analyzed through GT metrics using MATLAB. Metrics such as degree centrality, betweenness, eigenvector, and PageRank are calculated to identify key nodes (variables) acting as systemic leverage points or control hubs. The GT layer provides a structural validation of the qualitative and dynamic models, ensuring that feedback dominance corresponds with topological influence (Dueñas Santana et al., 2024).

### ***Cross-module integration and policy synthesis***

Finally, results from SD simulations and GT metrics are integrated to construct a composite picture of the hydrogen safety–sustainability system. Policy insights are derived by examining leverage variables and dominant loops—i.e., where small interventions can produce systemic improvements across safety, sustainability, and economic performance.

This workflow reflects the iterative and multi-scale logic of the FRISE framework: from conceptualization (CLD) → quantification (SD) → validation (GT) → policy synthesis. It ensures that both the structure and behavior of the hydrogen system are systematically assessed and that the dynamic outcomes can be interpreted through the lens of feedback interdependence.

### 7.3.3- Data structure and parameterization

The parameterization of the models integrates three complementary data sources:

- Empirical data and published studies, including hydrogen incident databases, explosion tests, and cost analyses (Rivkin et al., 2015; Dueñas Santana et al., 2025).
- Simulated outputs from prior SD-based models of hydrogen risk and explosion management (Dueñas Santana et al., 2024; 2025).
- Expert-informed assumptions for qualitative variables such as safety culture strength or trust elasticity, calibrated through sensitivity testing.

Where data uncertainty is significant, normalized scales (0–1) are used to capture relative dynamics rather than absolute values. Time constants and delays are set based on empirical or literature benchmarks (e.g., maintenance cycles, policy reaction times, degradation rates). This ensures that the model remains analytically rigorous while adaptable to limited data contexts typical of emerging technologies.

### 7.3.4- Model integration and simulation environment

All models are implemented in *Vensim* and interfaced with MATLAB for GT computations and visualization of cross-modular interactions. The workflow allows the exchange of information between platforms through variable export/import in matrix form. Feedback loops are automatically mapped as adjacency matrices, facilitating their use in GT analysis.

The simulation horizon typically spans 10–30 years, reflecting the medium- to long-term dynamics of hydrogen infrastructure deployment and policy adaptation. Key output indicators include:

- Time evolution of failure probability and domino effect likelihood (RA–SM).
- Dynamic trajectories of safety investment and cost-efficiency (ECO–SM).
- Environmental impact index and emission reduction rate (ENV–ECO).
- Trust, acceptance, and policy responsiveness scores (SOC).

These outputs collectively measure the co-evolution of safety and sustainability performance, providing an integrated picture of system resilience.

### 7.3.5- Validation approach

Validation in this context is twofold:

- Structural validation, achieved through Graph Theory metrics and expert review of causal consistency; and

- Behavioral validation, achieved through comparison of SD outputs with known dynamic patterns (e.g., accident frequency decay, investment–performance delay, or policy oscillations).

Furthermore, the coherence of results across modules is tested by verifying that positive trends in one domain (e.g., safety improvement) do not unrealistically contradict constraints in others (e.g., cost escalation or emission rebound). This multi-domain consistency test serves as an internal validation of the integrative logic of the FRISE framework.

In summary, the methodological setup for this first application translates the FRISE framework into a functional modeling environment that combines qualitative systemic mapping, quantitative dynamic simulation, and network-based structural validation. The following sections apply this methodology to three case studies—dynamic hydrogen risk assessment, explosion safety management during hydrogen enrichment, and comparative analysis of hydrogen storage systems—illustrating how the framework captures the dynamic interplay between safety performance, sustainability objectives, and systemic policy feedbacks in emerging hydrogen technologies.

## **7.4- Case Study I – Dynamic Hydrogen Risk Assessment**

### **7.4.1- Purpose and relevance**

The first application of the FRISE framework focuses on the dynamic risk assessment of hydrogen systems. This case study aims to evaluate how time-dependent feedback mechanisms shape the probability of failure and escalation in hydrogen containment systems. It illustrates how the Risk Assessment (RA) and Safety Management (SM) modules of FRISE interact dynamically and how their coupling affects the overall sustainability and resilience of hydrogen infrastructures.

Unlike conventional quantitative risk assessment (QRA) methods that rely on static failure probabilities, the dynamic approach developed here incorporates the temporal evolution of system degradation, learning feedbacks, and policy or investment delays. In doing so, it enables the analysis of how safety performance changes over time rather than providing a single-point estimate of risk (Sterman, 2002; Salzano et al., 2014).

### **7.4.2- Model conceptualization**

The model structure is based on the Systems Thinking representation of causal relationships among hydrogen safety factors. Figure 7.1 shows the developed Causal Loop Diagram for Dynamic Hydrogen Risk Assessment.

The diagram identifies six principal groups of factors, corresponding to the RA and SM modules:

1. Core risk model (structural integrity and failure probability)
2. Hazardous hydrogen-related factors (pressure, temperature, embrittlement)
3. Investigation and learning feedback on safety management
4. Consequence analysis and domino potential
5. Policy and investment feedbacks
6. External societal and regulatory drivers

These causal relationships form several reinforcing (RL) and balancing (BL) loops that explain the system's non-linear dynamics. For example:

- RL1 – Barrier degradation loop: aging and material degradation increase failure probability, which reduces trust and investment, further amplifying risk.
- BL1 – Preventive investment loop: higher incident frequency triggers increased safety investment and learning, which reduces failure probability over time.
- BL2 – Regulatory control loop: policy tightening reduces tolerable risk but introduces delay in management response, producing oscillatory behavior.

The total number of identified feedback loops for the developed CLD is 446 starting from the *Cumulative risk*, 422 starting from the *Leakage hydrogen*, and 365 starting from the *Domino effect*, which means that this is a highly interdependent system. The model has potential practical applications in hydrogen infrastructure safety, enabling the identification of critical intervention points, the design of risk mitigation strategies, and compliance with safety regulations.

Hydrogen safety dynamics are governed by a complex interplay of reinforcing and balancing feedbacks across the physical, organizational, and cognitive layers of the system. The causal loop diagram (CLD) reveals that risk does not emerge linearly from technical failures alone but through feedback-driven propagation, regulation, and adaptation processes. Table 7.1 summarizes the dominant loops identified in the DHRA causal network.

**Table 7.1- Main Feedback Loops in the Dynamic Hydrogen Risk Assessment (DHRA) Model**

| Loop ID                            | Type                | Core Variables Involved                                                                                                 | Description and Systemic Effect                                                                                                                                                        |
|------------------------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| R1 – Hydrogen Degradation Loop     | Reinforcing         | Material stress, hydrogen pressure, exposure time, H <sub>2</sub> embrittlement inflow, failure rate                    | Progressive embrittlement under sustained stress and pressure increases hydrogen permeability and component degradation, amplifying the probability of failure and leakage.            |
| R2 – Domino Escalation Loop        | Reinforcing         | Failure rate, number of failures, escalation probability, domino effect, cumulative risk (R)                            | Interdependent vessel and unit failures propagate through escalation and domino mechanisms, producing a positive feedback that accelerates overall system risk accumulation.           |
| R3 – Thermo-Mechanical Stress Loop | Reinforcing         | Temperature, pressure, thermal stress, mechanical strength, mechanical explosion, overpressure                          | Temperature and pressure rises increase mechanical stress, which weakens vessel strength and elevates explosion likelihood, creating a self-intensifying degradation–stress cycle.     |
| R4 – Human-Perception Loop         | Reinforcing         | Perceived risk level, safety culture, human error, failure rate                                                         | Reduced perceived risk weakens safety culture and increases operational error, which in turn heightens failure probability and actual risk, further diverging perception from reality. |
| B1 – Safety Barrier Loop           | Balancing           | Domino effect, safety barrier effectiveness, safety barriers action                                                     | Activation of engineered safety barriers mitigates domino propagation by containing physical escalation, generating a short-term stabilizing effect on risk escalation.                |
| B2 – Safety Control Loop           | Balancing           | Cumulative risk (R), emergency response, safety control                                                                 | Rising cumulative risk triggers emergency and management responses that reduce immediate hazards and maintain the system near a controllable operating range.                          |
| B3 – Organizational Learning Loop  | Balancing (delayed) | Major accident, investigation rate, completed investigations, lessons learned, preventive measures, safety improvements | Accidents stimulate learning and procedural updates; over time, organizational adaptation strengthens preventive measures and reduces recurrence, forming a long-delay balancing loop. |
| B4 – Cognitive–Ergonomic Loop      | Balancing           | Good ergonomics, cognitive factors, human error                                                                         | Enhanced ergonomics and cognitive performance decrease human error rates and stabilize operational reliability, countering the reinforcing effect of perception biases.                |

The coexistence of reinforcing (R) and balancing (B) loops demonstrates that hydrogen safety systems behave as nonlinear adaptive structures. Reinforcing loops (R1–R4) drive escalation processes — material degradation, cascading failures, and perceptual drift — while balancing loops (B1–B4) introduce regulatory forces through engineering controls, emergency management, and organizational learning. The dominance of either class of loops determines the dynamic regime of the system:

- Under robust safety control, balancing loops maintain stable operation (risk containment).

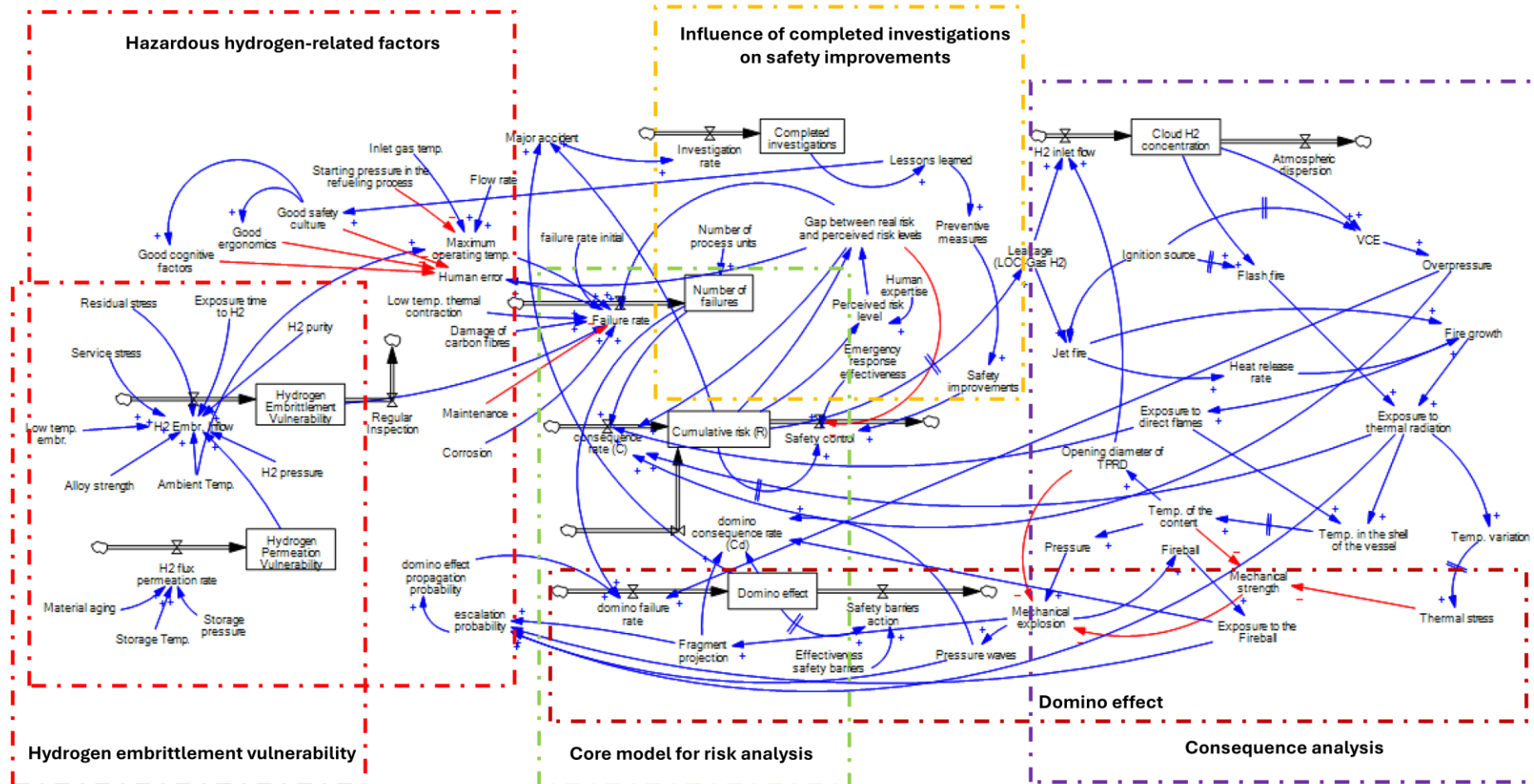


Fig. 7.1- Causal Loop Diagram (expressed in terms of SD environment) for dynamic hydrogen risk analysis

Note: a positive causality (blue color), a negative causality (red color).

- Under degraded barriers or complacency, reinforcing loops prevail, leading to exponential risk growth or cascading failures.

This interplay captures the dual nature of hydrogen safety within the FRISE framework — a co-evolution of technological reliability and human–organizational adaptation, where system resilience depends on the strength and responsiveness of feedback regulation.

#### 7.4.3- System Dynamics model development

The System Dynamics (SD) model developed for this study quantifies the temporal evolution of failure probabilities and cascading events between two interconnected hydrogen storage vessels (vessel 1 and vessel 2). The model structure is implemented in *Vensim* and follows the Systems Thinking approach introduced in previous sections, translating the conceptual feedback relationships into quantitative differential equations. Figure 7.2 presents the full SD model developed to evaluate the likelihood and consequences of cascading failures between the two vessels.

The numerical values adopted in the Dynamic Hydrogen Risk Assessment model reflect typical ranges reported in the hydrogen safety literature and engineering design guidelines. Parameters such as leakage rates, ignition probabilities, inspection delays, and mitigation efficiencies were selected to represent a generic but realistic reference scenario consistent with published studies and technical assessments. Where literature values varied across sources, mid-range or consensus estimates were used to preserve model generality.

#### *Dynamic failure rate formulation*

To represent the gradual degradation of vessels over their operational lifetime, the expected failure rate was modeled using a two-parameter Weibull distribution, as recommended by *Salzano et al. (2014)* and *Mannan (2014)*. This distribution allows the hazard rate to evolve dynamically rather than remain constant, thus providing a more realistic description of degradation processes such as hydrogen embrittlement, fatigue, or corrosion (Eq. 7.1).

$$f(t) = \frac{\beta}{\alpha} \left[ \frac{t}{\alpha} \right]^{\beta-1} e^{-\left( \frac{t}{\alpha} \right)^{\beta}} \quad (7.1)$$

Where:

- $\alpha$  = scale parameter (inverse of the initial failure rate, representing the characteristic life),



- $\beta$  = shape parameter (defining the hazard rate behavior).

For  $\beta < 1$ , the hazard rate decreases with time; for  $\beta = 1$ , it remains constant; and for  $\beta > 1$ , it increases—representing progressive deterioration. In this study,  $\beta = 1.5$  was adopted, corresponding to an increasing hazard rate typical of aging hydrogen containment systems.

The model also integrates stochastic inflows to simulate discrete failure or ignition events using the *RANDOM POISSON* function in *Vensim*, which generates random numbers following a Poisson distribution. This is suitable for modeling the number of events (e.g., ignitions or escalations) occurring within fixed simulation intervals. The mean of the Poisson distribution represents the expected number of events per time step, enabling probabilistic event generation within a deterministic SD environment.

The SD model consists of eight principal stocks representing vessel integrity, failure probabilities, and cumulative events. The inflows are governed by expected failure rates and ignition probabilities, while auxiliary variables define escalation likelihoods and event rates. Table 7.2 summarizes the quantitative inputs used for the SD simulations, corresponding to two comparative scenarios (S01 and S02). The parameters were selected based on values reported in Mannan (2014) and Salzano et al. (2014) for hydrogen systems.

**Table 7.2- Data for the SD modelling (quantitative input for the model)**

| Scenario | Initial failure rate ( $y^{-1}$ ) | $\beta$ parameter | Hydrogen release rate (kg/s) | Escalation probability v1–v2 | Escalation probability v2–v1 | Time scale (years) |
|----------|-----------------------------------|-------------------|------------------------------|------------------------------|------------------------------|--------------------|
| S01      | $4.3 \times 10^{-3}$              | 1.5               | 0.5                          | 0.25                         | 0.15                         | 50                 |
| S02      | $4.3 \times 10^{-3}$              | 1.5               | 0.5                          | 0.75                         | 0.65                         | 50                 |

The SD model begins with both vessels operating under normal conditions (probability = 1). As time progresses, degradation governed by the Weibull-based failure rate  $f(t)$  gradually increases the probability of failure for each vessel. A failure in one vessel can trigger direct or delayed ignition events and, depending on escalation probabilities, propagate to the neighboring vessel. Cumulative events—representing the total number of failures and escalations—are tracked over the full simulation period (50 years). The stochastic Poisson formulation captures the randomness of ignition and escalation events, while deterministic feedbacks ensure that the probability of failure dynamically evolves in response to operational degradation.

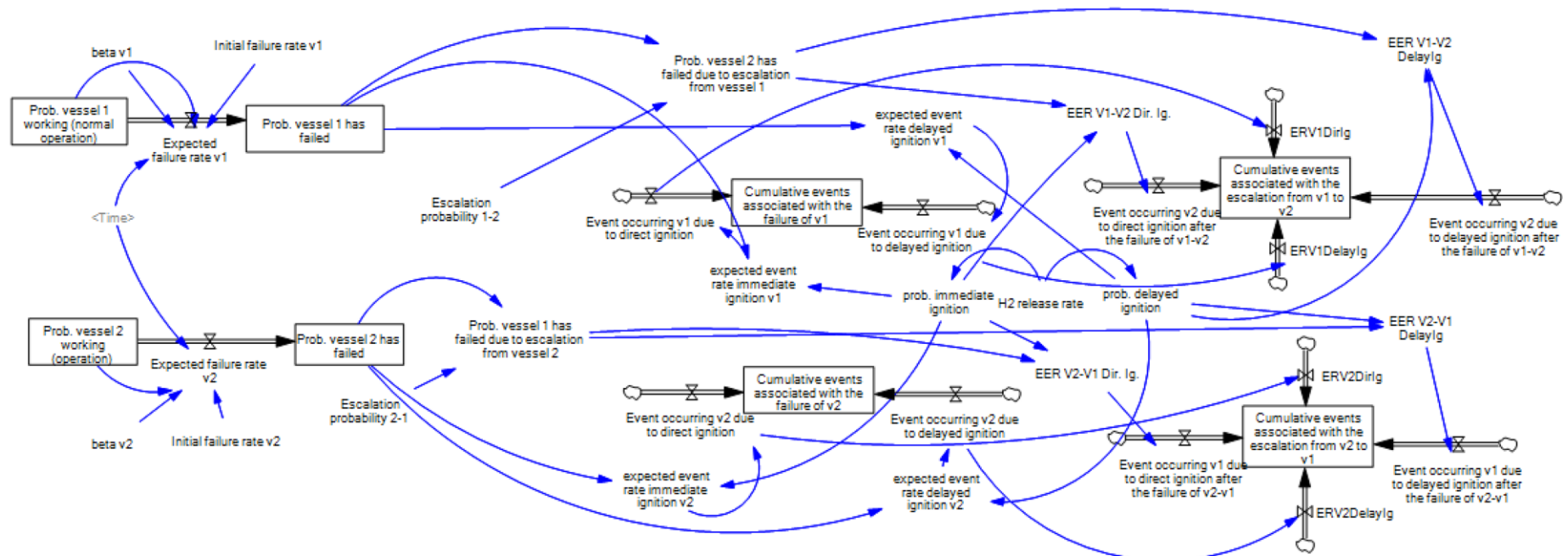


Fig. 7.2- System Dynamics model for dynamic hydrogen risk assessment

#### 7.4.4- Simulation Scenarios and Results

Each vessel's failure not only results in its own risk of hazardous material release but can also escalate to the failure of the other vessel, with escalation probabilities quantifying the likelihood of such interdependence. This escalation mechanism captures the cascading nature of failures which could happen in industrial systems. Upon failure, hazardous releases may lead to either direct ignition, which occurs immediately, or delayed ignition, which happens after some time has passed. Both ignition types are modeled with distinct probabilities and expected event rates, reflecting the dynamics of ignition scenarios and their contribution to overall system risk. Additionally, the model tracks cumulative events caused by failures, escalation, and ignition, presenting a clear picture of the system's vulnerability to repeated or compounding failures. Escalation event rates are defined for both direct and delayed ignition pathways, further highlighting the risks of failure propagation through interconnected systems. The inclusion of cumulative escalation events, event occurrence probabilities, and escalation rates between the vessels provides a realistic dynamic mechanism for assessing systemic reliability and identifying potential failure hotspots.

Figure 7.3 illustrates the cumulative events and associated probabilities over time for two vessels (denoted as vessel 1 and vessel 2) under a scenario labeled S01.

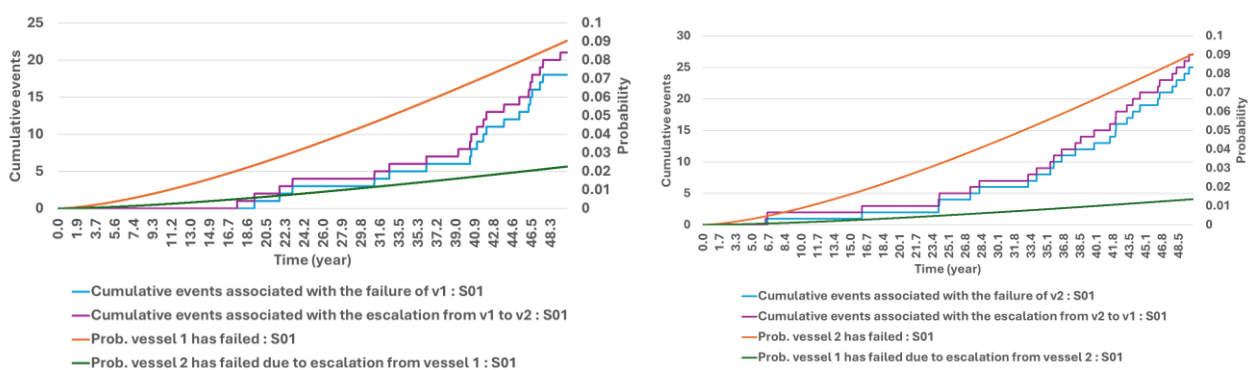


**Fig. 7.3- Results from performed simulations using the SD model for the scenario S01**

The probabilities and cumulative events grow over time, with distinct differences in their rates of increase. This visualization effectively combines temporal dynamics of failures and their cascading effects. The connection between the figures is clear: the rising failure probability in Figure 7.3a (left) directly drives the growth of cumulative events in Figure 7.3b (right), emphasizing the need for time-based risk management. Together, these insights recommend

regular inspections, preventive maintenance, and strengthened safety barriers to mitigate escalating risks, particularly after the 20-year mark. They also stress monitoring early signs of material vulnerabilities to prevent failures from propagating through interconnected systems, ensuring safer operations across the lifecycle of hydrogen infrastructure. Figure 7.4 analyzes the cumulative escalation events between two vessels (v1 and v2) under two scenarios, S01 (blue lines) and S02 (red lines), over a 50-year period. S02 refers to the scenario with higher escalation probability associated (Table 2).

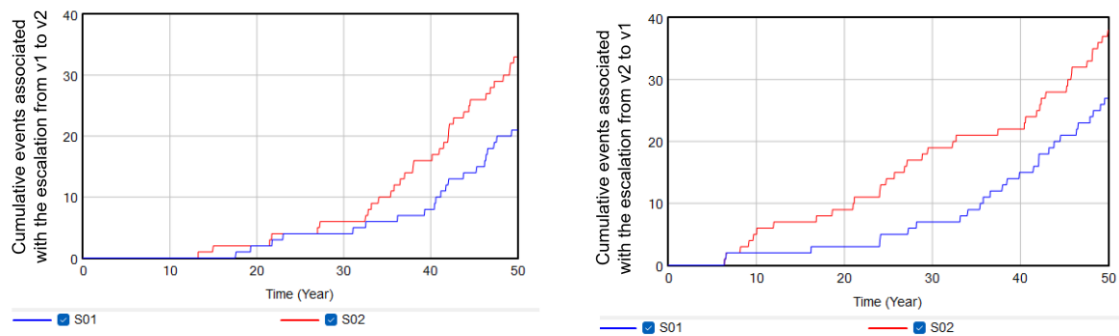


**Fig. 7.4- Results from performed simulations using the SD model for comparing scenarios S01 and S02**

The stepped curves in each plot reflect discrete escalation events occurring at specific times, with differences in the frequency and timing of these events between the two scenarios. The steeper slopes of the red curves compared to the blue curves in both figures highlight that scenario S02 has a higher escalation probability. The divergence between the scenarios becomes more pronounced after the midpoint of the time horizon, suggesting that the risk of escalation accumulates and accelerates with time under S02. Together, these figures underscore how different scenarios impact the dynamics of failure escalation, with S02 being more severe than S01 in terms of both frequency and magnitude of cumulative escalations between the vessels, highlighting the relevance of the effectiveness of safety barriers for reducing the escalation probability.

The simulation outcomes demonstrate the dynamic character of hydrogen safety, where risk accumulation is governed by the combined effects of degradation, feedback delays, and probabilistic ignition. The Weibull-based approach allows realistic representation of aging behavior, while the stochastic Poisson process introduces randomness consistent with observed industrial incident data.

The results highlight the critical importance of feedback-driven safety management: proactive interventions in the early stages of operation can prevent the nonlinear escalation observed in later years. Consequently, maintenance scheduling, inspection frequency, and policy adjustments should be optimized as time-dependent functions, rather than fixed intervals, to sustain acceptable safety levels over the infrastructure lifetime.

#### **7.4.5- Graph-theoretic analysis of the DHRA causal network**

The graph-theoretic (GT) results (Figure 7.5) quantify the structural roles of variables in the Dynamic Hydrogen Risk Assessment (DHRA) causal network and clarify where feedback regulation or escalation is most effectively leveraged. Across centrality measures, the domino chain emerges as the backbone of systemic risk propagation: Domino effect has the highest PageRank ( $\approx 0.097$ ) and the largest betweenness ( $\approx 688$ ), while domino failure rate ranks second in PageRank ( $\approx 0.078$ ) and similarly high in betweenness ( $\approx 679$ ). Together with Failure rate (PageRank  $\approx 0.066$ ; betweenness  $\approx 437$ ) and Number of failures (PageRank  $\approx 0.061$ ; betweenness  $\approx 428$ ), these nodes form a high-centrality corridor that connects local degradations to plant-level escalation. Their high betweenness indicates that most causal paths from material, thermal, and human precursors to system-level loss traverse this corridor; interventions that cut flow through any of these interfaces will disproportionately reduce global connectivity and, therefore, systemic risk.

The risk-aggregation layer is structurally influential but less bridging. Cumulative risk (R) holds a high PageRank ( $\approx 0.053$ ) but a lower betweenness than the domino corridor ( $\approx 324$ ), indicating that it concentrates incoming influence rather than redistributing it. This matches the model semantics: risk accumulates as an endpoint of multiple chains, while escalation variables mediate inter-subsystem transfer. Notably, domino consequence rate (Cd) also carries non-negligible centrality (PageRank  $\approx 0.030$ ; betweenness  $\approx 168$ ), reinforcing that consequence-generating pathways remain active even when ignition is delayed, and underscoring the need for consequence-mitigation barriers alongside frequency-reduction measures.

The human–organizational layer is not peripheral. Human error exhibits PageRank comparable to Cumulative risk (R) ( $\approx 0.055$ ) and high betweenness ( $\approx 326$ ), meaning it both receives substantial upstream influence (e.g., risk perception gaps, culture, ergonomics) and brokers many paths toward technical failure. Perceived risk level (PageRank  $\approx 0.048$ ; betweenness  $\approx 295$ ) and Gap between real and perceived risk (PageRank  $\approx 0.044$ ; betweenness  $\approx 266$ ) sit

centrally within the socio-cognitive loops, confirming that miscalibration of risk perception can amplify failure-producing behaviors across the network. Good safety culture shows moderate PageRank ( $\approx 0.014$ ) and betweenness ( $\approx 128$ ), but—importantly—feeds into both ergonomics and cognitive performance, thus exerting second-order control on Human error. On the learning side, Major accident (PageRank  $\approx 0.030$ ; betweenness  $\approx 396$ ), Investigation rate ( $\approx 0.029$ ;  $\approx 367$ ), Completed investigations ( $\approx 0.027$ ;  $\approx 338$ ), and Lessons learned ( $\approx 0.026$ ;  $\approx 309$ ) form a high-betweenness, delayed balancing loop. Their structural positions explain why learning-and-improvement effects often appear after escalation has already occurred: these nodes are central brokers, but their influence acts with delays by design.

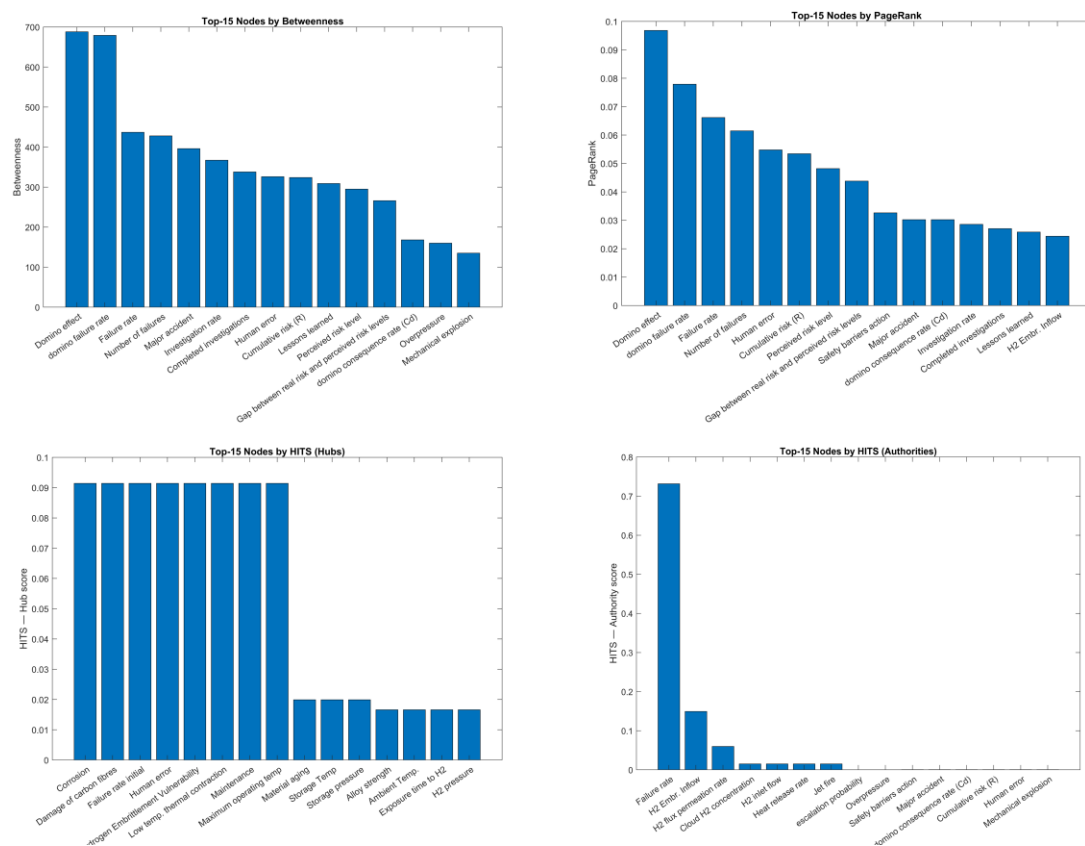


**Fig. 7.5- GT metrics for the dynamic hydrogen risk assessment CLD**

The thermo-mechanical pathway functions as a feeder into escalation rather than a terminal sink. Mechanical explosion holds moderate PageRank ( $\approx 0.014$ ) with high betweenness ( $\approx 135$ ), while Pressure waves (PageRank  $\approx 0.0068$ ; betweenness  $\approx 132$ ) and Overpressure (PageRank  $\approx 0.0081$ ; betweenness  $\approx 160$ ) bridge mechanical failure to escalation probability and domino propagation. These results align with the causal diagram where thermal stress, pressure, and strength degradation are upstream of explosion phenomena and, in turn, violent loads broker transitions to the domino layer.

HITS scores provide a complementary interpretation. Authorities identify nodes pointed to by strong broadcasters: Failure rate dominates the authority ranking ( $\approx 0.73$ ), coherently reflecting that many independent precursors (corrosion, initial failure rate, embrittlement vulnerability, maintenance quality, thermal contraction, human error) converge into this single integrator of reliability. Hubs capture how strongly a node points to authoritative targets; as expected for a largely feed-forward technical layer, exogenous degraders such as Corrosion, Damage of carbon fibres, and Failure rate initial have the largest hub scores ( $\approx 0.091$ ), whereas socio-technical broadcasters (e.g., Exposure to the Fireball) score lower because they feed into a smaller set of authoritative targets. The hub–authority pattern therefore validates the model’s structure: dispersed physical and human precursors broadcast toward a small set of authoritative integrators (notably Failure rate), which then channel influence into the domino corridor where PageRank and betweenness peak.

The barrier and response layer shows targeted influence. Safety barriers action has modest PageRank ( $\approx 0.033$ ) and low betweenness ( $\approx 19$ ), consistent with its role as a local balancing counterflow on the domino chain rather than a global broker. Safety control (PageRank  $\approx 0.018$ ; betweenness  $\approx 66$ ) and Safety improvements (PageRank  $\approx 0.015$ ; betweenness  $\approx 75$ ) operate downstream of perception, learning, and emergency response; their positions suggest that investment timing and persistence (e.g., ensuring learning translates into durable improvements) are critical for shifting long-run centrality away from the domino corridor.

Taken together, the GT results recommend a prioritized intervention strategy consistent with the CLD: (i) concentrate effort on cutting the domino corridor by lowering escalation probability and domino failure rate (engineering segregation, passive fire protection, emergency depressurization); (ii) lower the authority of *Failure rate* by acting on its diversified hub set (embrittlement management, maintenance quality, thermal-mechanical stress control, human reliability programs); and (iii) stabilize socio-cognitive regulation by shrinking the perception gap and strengthening safety culture, thereby reducing *Human error*—a high-centrality broker coupling the social and technical layers. Because centrality in directed causal networks correlates with both the frequency and the reach of influence, shifting resources toward these leverage points should produce the largest reduction in the volume and connectivity of risk-bearing paths, which the PageRank and betweenness profiles quantify.

#### **7.4.6- Discussion: Dynamic behavior, delay effects, and adaptive policy responses within the FRISE framework**

The analysis of the Dynamic Hydrogen Risk Assessment (DHRA) model within the FRISE framework demonstrates the capacity of the approach to capture the nonlinear, feedback-driven, and adaptive nature of hydrogen safety and sustainability systems. The FRISE structure integrates physical, organizational, and cognitive subsystems into a single dynamic environment, where feedback loops and causal interdependencies evolve over time rather than remaining static. In contrast to traditional probabilistic risk assessment or fault-tree techniques that rely on fixed event probabilities (Mannan, 2014; Salzano et al., 2014), FRISE explicitly models time-dependent failure rates, learning delays, and management responses as endogenous variables.

##### ***Dynamic feedback behavior***

The graph-theoretic analysis confirms that reinforcing and balancing feedbacks coexist and interact dynamically within the DHRA network. Reinforcing loops (e.g., R1 – Hydrogen degradation and R2 – Domino escalation) amplify risk through positive coupling between degradation, failures, and overpressure, while balancing loops (B1–B3) exert stabilizing influences via barrier activation, safety control, and organizational learning. These feedbacks generate oscillatory or S-shaped trajectories typical of complex socio-technical systems (Sterman, 2000; Leveson, 2011). For example, the accumulation of Cumulative risk (R) in the model is not instantaneous but follows a logistic pattern: rapid growth during escalation, deceleration when balancing loops dominate, and renewed growth if learning effects erode or resource investment declines. Such dynamics correspond to real-world hydrogen infrastructures, where operational reliability and accident frequency fluctuate with maintenance cycles, organizational vigilance, and regulatory pressure (CCPS, 2023; Sala et al., 2025).

##### ***Delay effects and learning dynamics***

A distinctive feature of the FRISE implementation is the explicit representation of temporal delays between events, decisions, and outcomes. The organizational learning loop (B3) introduces time-lags between Major accident → Investigation → Lessons learned → Preventive measures → Safety improvements. These long-delayed balancing effects are visible in the GT metrics as nodes with high betweenness but moderate PageRank (e.g., Lessons



learned, Investigation rate), confirming that they mediate information flow across the network but with slower response times. Delay functions such as DELAY FIXED and INTEG within the system-dynamics formulation reproduce the accumulation and dissipation of management knowledge, inspection data, and regulatory adaptation. Similar lag structures have been reported in systemic accident models such as STAMP (Leveson, 2011) and in dynamic safety management frameworks for process industries (Ge et al., 2022; Khakzad et al., 2013).

### ***Adaptive policy responses***

FRISE also embeds adaptive policy feedback, allowing safety investment, inspection frequency, and emergency preparedness to evolve according to observed risk levels. As Cumulative risk (R) rises, Safety control and Emergency response effectiveness are activated, representing short-term policy adaptation; over longer horizons, Safety improvements and Safety culture evolve through learning and reinforcement. This adaptive structure enables the framework to simulate scenarios where risk reduction measures themselves change system behavior, a capability absent in static probabilistic models. The GT metrics corroborate this adaptivity: high in-degree but low out-degree of nodes such as Safety control and Safety improvements indicates that they function as response sinks that integrate multiple drivers rather than as simple modifiers of isolated events. These systemic properties make FRISE a useful policy laboratory for assessing how different investment or inspection strategies affect overall resilience (Nazir et al., 2019; Blokland & Reniers, 2020).

### ***Validation of model behavior***

Validation of the DHRA application has been pursued through three complementary strategies:

- Structural validation – the topology extracted from the model (Section 7.4.5) was consistent with theoretical and empirical studies of domino and escalation phenomena in process plants (Salzano et al., 2014), confirming that the causal pathways reproduce known accident-propagation mechanisms.
- Behavioral validation – dynamic simulations (Section 7.4.3) generated realistic temporal patterns of failure accumulation and escalation probability over 50 years, comparable to historical failure data and reliability studies for pressurized hydrogen systems (CCPS, 2023; Mannan, 2014).

The dynamic patterns observed in this case study are strongly influenced by the presence of delays in detection, maintenance, and managerial response. These delays allow risk to accumulate before corrective actions become effective, reinforcing the impact of the dominant feedback loops identified in the CLDs. As a result, even moderate increases in response time can shift the system's trajectory significantly, illustrating how delay structures act as leverage points in hydrogen safety management.

Overall, the FRISE framework succeeded in reproducing dynamic and adaptive behaviors that conventional linear models cannot capture. The feedback architecture explains why risk mitigation policies may exhibit transient paradoxes—initial improvement followed by stagnation or rebound—and provides a quantitative foundation for testing adaptive strategies. The validated correspondence between simulated and theoretical dynamics supports the framework's use as a decision-support tool for sustainable and safe hydrogen infrastructures.

## **7.5- Case Study II – Explosion Safety Management during Hydrogen Enrichment**

### **7.5.1- Purpose and Relevance**

The second application of the FRISE framework focuses on explosion safety management during hydrogen enrichment, addressing one of the most critical operational challenges in the transition toward hydrogen-based energy systems. Hydrogen enrichment—defined as the controlled substitution or blending of hydrogen into existing gas networks or combustion systems—offers a pathway to decarbonization but simultaneously introduces significant explosion and fire hazards due to hydrogen's physicochemical characteristics: low ignition energy, high diffusivity, and broad flammability limits (Duan et al., 2020).

In the context of process industries and energy infrastructures, explosion safety encompasses both preventive and mitigative layers that act before and after an ignition occurs. The safety performance of these systems depends not only on engineering design (venting, segregation, barrier systems) but also on management practices, operational discipline, and learning feedbacks that adapt to changing risk conditions (Mannan, 2014; CCPS, 2023). As such, hydrogen enrichment provides an ideal testbed for the FRISE framework, which aims to capture dynamic interactions between physical degradation, risk control measures, and organizational adaptation.

While the first case study (Section 7.4) demonstrated how FRISE can model cascading and domino effects in hydrogen storage systems, this second application focuses on explosion dynamics, ignition probability, and management resilience in operational environments. The model addresses how deviations in enrichment concentration, system pressure, or barrier effectiveness influence the probability and consequence of explosions over time. Furthermore, it explores how adaptive safety policies, such as maintenance scheduling, safety training, or investment in monitoring technologies, influence overall system behavior and stability.

The relevance of this case study is twofold. Scientifically, it extends the FRISE framework to transient phenomena characterized by high-frequency feedbacks and delay effects in ignition control and emergency response. Practically, it supports the design of risk-informed management strategies for hydrogen blending and combustion facilities, where process safety and sustainability objectives must be co-optimized. By integrating system dynamics, graph-theoretical topology, and safety management principles, this case contributes to bridging the gap between accident causation modeling and adaptive risk governance in hydrogen technologies (Khakzad et al., 2013; Blokland & Reniers, 2020).

### 7.5.2- Model Conceptualization and CLD development

Hydrogen enrichment implementation brings several advantages to the hydrogen economy (Makaryan et al., 2022). Notwithstanding, it triggers some negative effects, especially for the increased explosion risk and therefore less public acceptance (Groth and Al-Douri, 2023). Table 7.3 shows some of the most relevant advantages and disadvantages of the HE practice according to the reports in the literature (De Santoli et al., 2017; Judd and Pinchbeck, 2015; Middha et al., 2011; Middha, 2016).

**Table 7.3- Advantages and disadvantages of the hydrogen enrichment**

| Factor                | Advantages                                                                                                                                          | Disadvantages                                                                                 |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Economic impact.      | Increase in the efficiency of the hydrogen economy.                                                                                                 | Capital investments and new infrastructures (especially with higher hydrogen concentrations). |
| Environmental impact. | Decrease the emissions of carbon dioxide, carbon monoxide, and methane. In general, it brings much more environmental benefits compared to methane. | It could increase the emissions of nitrogen oxides.                                           |
| Societal impact.      | Works on public acceptance should be implemented by investing in safety.                                                                            | Public acceptance could be decreased if an explosion occurs.                                  |
| Safety management.    | Stricter safety regulations are needed triggering more efficient safety management procedures.                                                      | Increased explosion risk.                                                                     |

The CLD helps to visualize the complex interdependencies among the following variables: (1) adoption rate for using hydrogen/methane mixtures, (2) hydrogen enrichment practice, (3) technology efficiency, (4) environmental benefits, (5) efficiency of the hydrogen economy, (6) public acceptance, (7) failure probability, (8) explosion risk, (9) RE production and integration, (10) investment in safety, (11) explosion event, (12) domino effect propagation, and (13) major explosion consequences. These variables are linked by analysing the feedback loops which include them. Additionally, the role of effective safety management procedures, the gap between the actual and the perceived risk level, the human expertise, the innovation and development advancements, and the inherent safety are linked to the explosion risk by developing a system dynamics-based model.

Table 7.4 shows the six feedback loops that are taken as the starting point for building the CLD in this research framework. These loops consider (1) H<sub>2</sub> enrichment (HE) reinforced by technology efficiency; (2) HE reinforced by environmental benefits; (3) HE linked to renewable energy (RE) production and integration, and the hydrogen economy; (4) HE practices linked to the explosion risk and the public acceptance; (5) efficiency of H<sub>2</sub> economy linked to the explosion safety management Public acceptance of the HE practice. These feedback loops were built from a deep review of the current state of the art of the hydrogen enrichment practice and expert consultation.

Figure 7.6 shows the interrelations among the adoption rate for using HE practice, the efficiency of the hydrogen economy, the technology efficiency, and the integration with renewable energy production. The adoption of the HE practice has led to several technological advancements such as an increase in the ignition limits, the combustion rate, the thermal efficiency, the flame stability, the velocity of flame propagation, and a reduction in fuel consumption. The increased level of the technology efficiency increases the efficiency of the hydrogen economy, and therefore, the adoption rate of the HE practice, closing this reinforcing loop. At the same time, the increased HE practice will lead to a connection with RE pathways, allowing improved RE production (with certain delay) and integration with the hydrogen economy. After that, a more efficient economy provokes more adoption of this HE practice closing another reinforcing loop. Also, it is important to take into account that the HE needs some capital investments which can decrease the level of the economic profitability and balance the system.

**Table 7.4- Integrated feedback loops (FL) in the CLD for analyzing the adoption of hydrogen enrichment to methane fuel gas**

| No. | Feedback loop                                                                               | Loop description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-----|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 01  | H <sub>2</sub> enrichment (HE) reinforced by technology efficiency.                         | The HE practice has several advantages from a technological point of view such as (1) a decrease in fuel consumption, (2) an increase in ignition limits, (3) a higher combustion rate, (4) higher thermal efficiency, (5) better flame stability, (6) an increase in the velocity of the flame propagation. These characteristics linked to the addition of H <sub>2</sub> to methane brings more efficient fuel combustion, leading to higher technology efficiency. In other words, this promotes a more efficient hydrogen economy, reinforcing the adoption of HE.                                                                                                                                                                                                                                                                                                                                                                                   |
| 02  | HE reinforced by environmental benefits.                                                    | The adoption of HE brings some positive impacts on the environment such as the reduction in CO <sub>2</sub> , CO, and CH <sub>4</sub> emissions. However, there are some studies which support the idea that the HE can lead to more NO <sub>x</sub> emissions. Despite this, in general, the HE reduces the pollutant gases, helping to meet the decarbonization objectives of the European Union. This positive environmental impact reinforces the public acceptance of the HE practice, and therefore the adoption of the HE itself.                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 03  | HE linked to renewable energy (RE) production and integration, and to the hydrogen economy. | If the hydrogen used for the HE practice is produced from RE sources, this reinforces the integration of RE production leading to more forces on the HE itself. At the same time, when more hydrogen is required, more pressure will be established on green and/or blue hydrogen, making more efficient the current hydrogen economy.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| 04  | HE practices linked to the explosion risk and the public acceptance.                        | HE can lead to a higher failure probability (due to the addition of H <sub>2</sub> phenomena such as hydrogen embrittlement). After a loss of containment, a flammable fuel-air cloud increases the explosion risk. This risk itself can decrease the public acceptance of HE usage. An explosion event can occur via a detonation (with direct ignition, but less probable) or deflagration phenomenon (with a delayed ignition, and much more probable). The major consequences came from a detonation rather than a deflagration. However, the hydrogen presence brings an additional complex issue in this regard, due to the deflagration-to-detonation transition (DDT), which can cause real severe damage. The high pressures due to a detonation can provoke structural damage, loss of life, and additional fires and/or BLEVEs. These major explosion consequences, decrease the public acceptance of the HE practice, balancing its adoption. |
| 05  | Efficiency of H <sub>2</sub> economy linked to the explosion safety management.             | The implementation of the HE can lead to a more efficient hydrogen economy, one of the most crucial challenges nowadays. Part of this profits must be used for investing in safety management. The investment in mitigation measures as well as in prevention procedures will reduce the explosion risk, reinforcing the HE implementation.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| 06  | Public acceptance of the HE practice.                                                       | The public acceptance of the HE implementation can be reinforced due to the environmental benefits and the efficiency of the hydrogen economy. On the other hand, public acceptance is balanced by the increased explosion risk and the possible major explosion consequences. Public acceptance itself can bring a certain delay to promote the adoption of the HE practice.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |

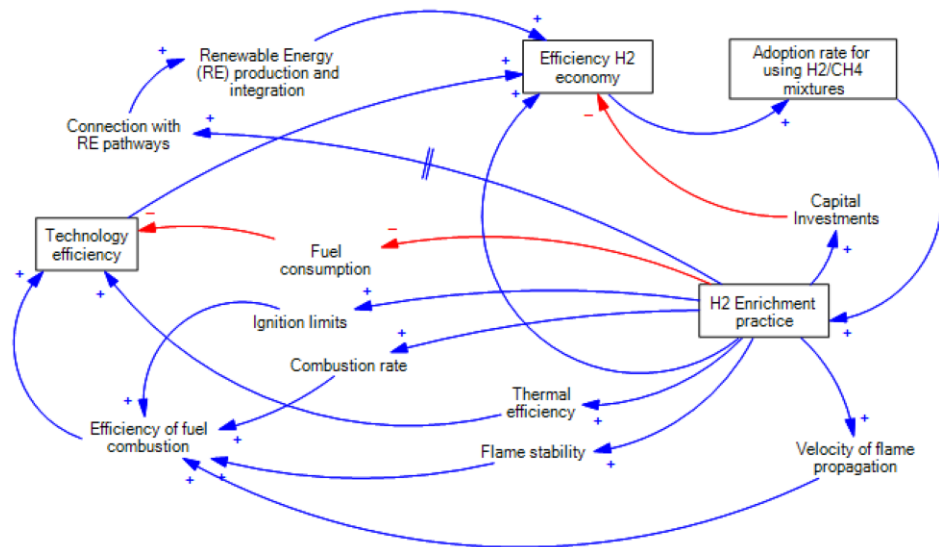


**Fig. 7.6- Interdependencies among the HE practice, the technology, and economic efficiency**

Figure 7.7 considers the previously explained feedback loops and additionally, the environmental benefits, increasing the complexity of the model. The HE practice leads to a decrease in almost all the pollutant gases such as carbon monoxide, carbon dioxide, and methane, triggering more environmental benefits; however, it can increase nitrogen oxide emissions. These environmental benefits have a positive impact on the adoption rate of HE, closing the reinforcing loops.

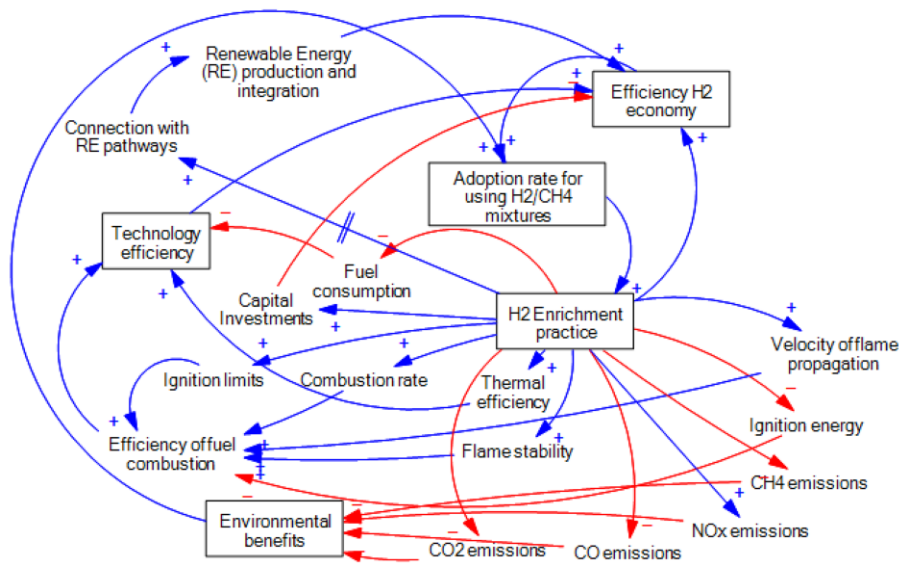


**Fig. 7.7- Interdependencies between the HE practice and the environmental benefits**

Figure 7.8 shows the concerns regarding the explosion risk that emerged due to the addition of hydrogen to the gas mixture. In the case of an explosion event, it is particularly important to

consider the Deflagration to Detonation Transition (DDT) due to the presence of hydrogen in the mixture. This phenomenon involves the transition of a subsonic flame (deflagration) into a supersonic detonation wave. In a typical combustion reaction involving methane and air, the reaction begins as a deflagration. In other words, it is a slow-burning flame where the reaction front propagates at subsonic speeds relative to the unburned gas ahead of it. With the hydrogen addition, the mixture becomes more reactive due to the hydrogen's lower activation energy and higher diffusivity. This increases the flame speed and shortens the induction times for reactions, making the initial flame propagation faster compared to pure methane combustion.

As the deflagration progresses, instabilities can develop in the flame front, especially if the flame is confined. The HE enhances these instabilities because hydrogen has a high diffusivity and reactivity, leading to more turbulent and vigorous flame behavior. Under certain conditions, the accelerating flame can trigger a transition from a deflagration to a detonation. This typically happens when the flame speed approaches the speed of sound in the unburned gas, and the compression waves ahead of the flame coalesce into a shock wave. The shock wave compresses and ignites the unburned mixture instantaneously, leading to a detonation, which is characterized by a supersonic shock wave coupled with a reaction front. Hydrogen-enriched methane mixtures can undergo DDT at lower pressures and temperatures compared to pure methane-air mixtures, making the transition to detonation more feasible in practical systems.

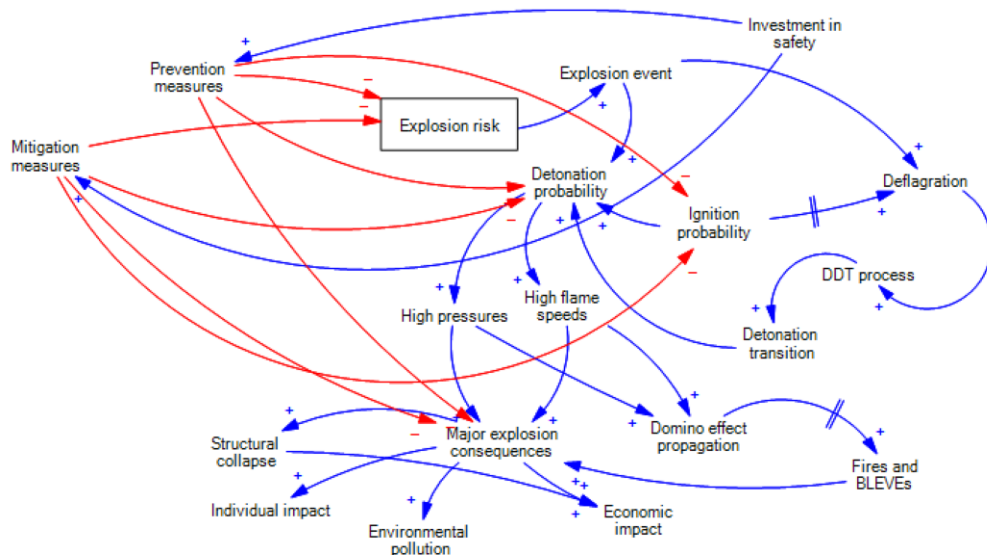


**Fig. 7.8- Interrelations considering the explosion risk for HE practice**

Therefore, after a detonation, major explosion consequences are expected (due to high pressures and high flame speeds). Moreover, the overpressure can lead to the escalation of the

primary event triggering a probable domino propagation which can cause (with certain delay) fires and BLEVEs depending on the specificities of the chemical site, the storage, and weather conditions. The major explosion consequences impact a probable structural collapse, individuals, environment pollution, and the economy. The feedback loops concerning these phenomena and chains are reinforcing loops.

The way to balance the system is by the implementation and effectiveness of prevention and mitigation measures. Prevention measures are designed to reduce the likelihood of an accident occurring, therefore they have a direct effect on reducing the ignition probability and the detonation probability. At the same time, the leak detection and maintenance programs reduce the major accident consequences. Mitigation measures are designed to reduce the impact or consequences of an incident should it occur. Therefore, they have a direct effect on reducing the major accident consequences but also on reducing the ignition and detonation probabilities (for instance in the case of automatic shutdown systems). A way to implement effective prevention and mitigation measures is by safety investments.

Figure 7.9 contains the previous feedback loops regarding the explosion risk interacting with the public acceptance and the adoption rate for using HE practice. There emerged some new balancing loops such as the decrease in the level of public acceptance due to the individual impact in the case of an explosion event and to the explosion risk itself (perceived by people). Furthermore, the prevention measures can reduce the ignition limits of the mixture. Public acceptance gradually will promote the adoption of HE practice.

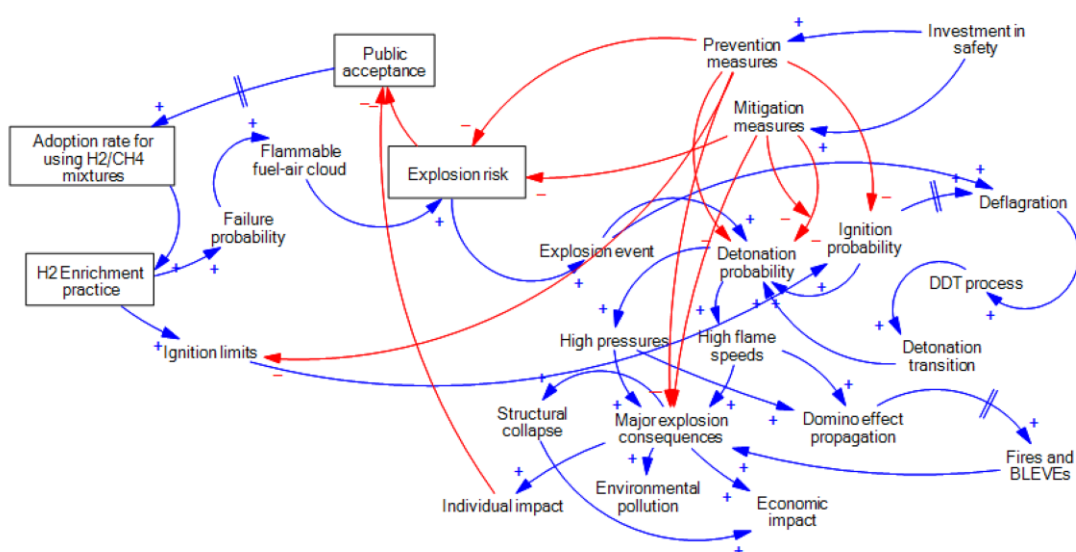


**Fig. 7.9- Interdependencies among the HE practice, the explosion risk, and the public acceptance**



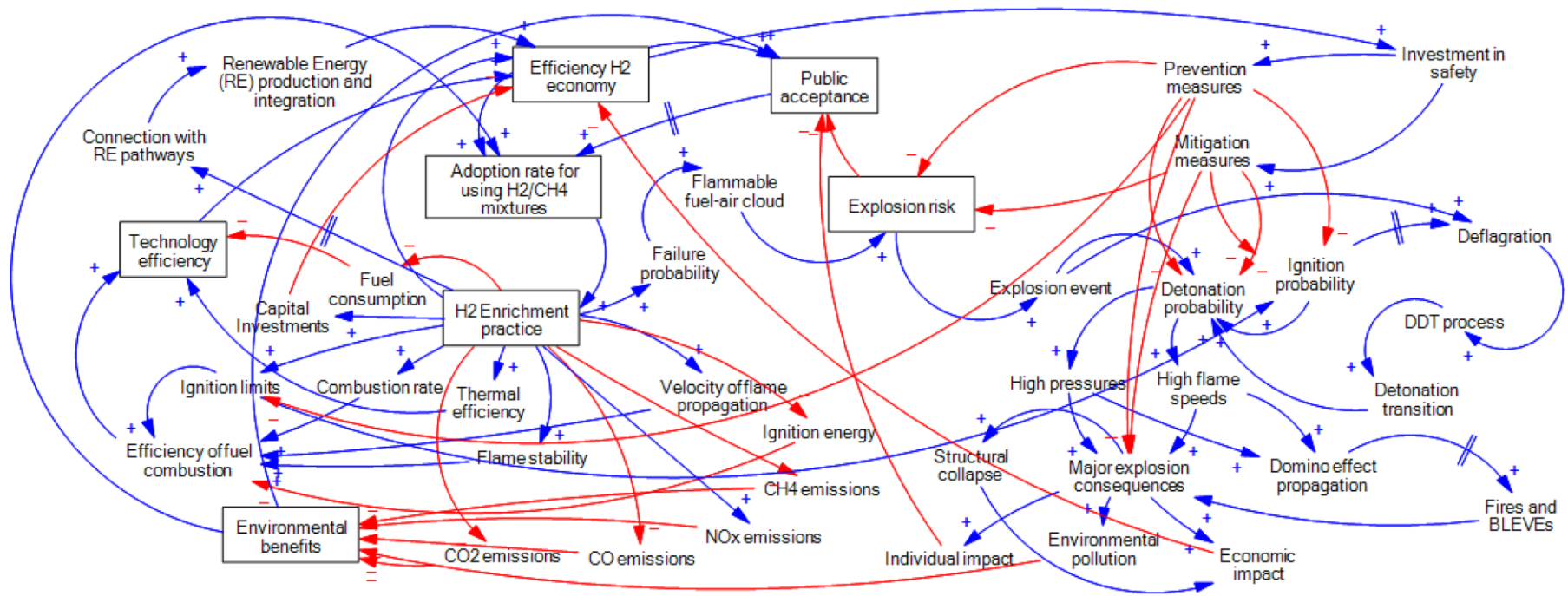


**Fig. 7.10- CLD for analyzing the hydrogen enrichment implementation**

These subsystems developed for considering the complex interactions for the adoption of HE practice are then integrated into the same model: a CLD for hydrogen enrichment.

Considering all the aforementioned feedback loops and interdependencies, a new conceptual model (CLD) is proposed for capturing the complexity related to the HE (Fig. 7.10).

This CLD was built starting with six main feedback loops (Table 7.4), considering the interdependencies among the model variables. Figures 7.11, 7.12, and 7.13 show the causal tracing for the variables: (1) adoption rate, (2) hydrogen enrichment practice, and (3) public acceptance. This analysis brings the remark that the hydrogen enrichment implementation is a high-interconnected complex system itself, where the main variables influence each other, triggering a huge number of new feedback loops.

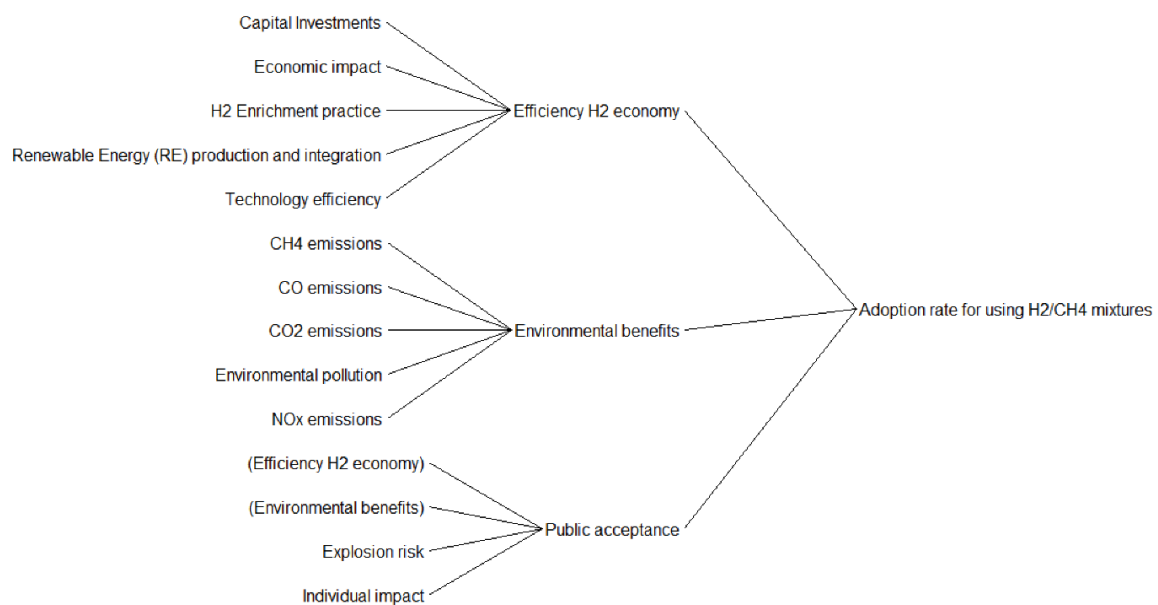


**Fig. 7.11- Causal tracing for the adoption rate for using H<sub>2</sub>/CH<sub>4</sub> mixtures**

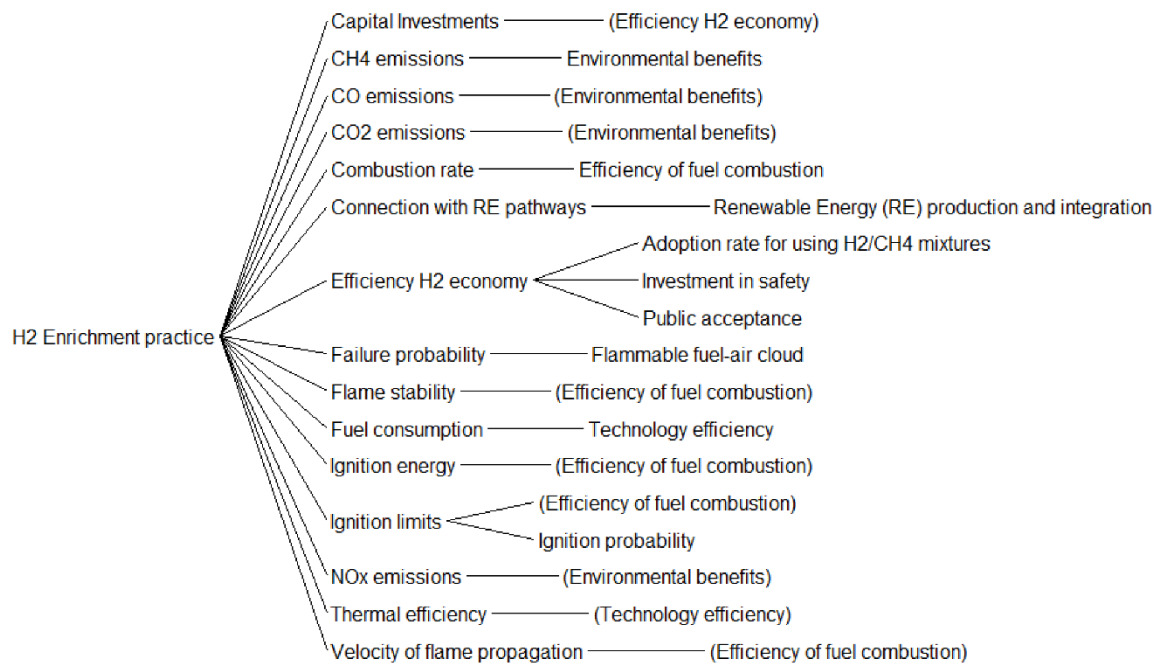


**Fig. 7.12- Consequences of the hydrogen enrichment practice**

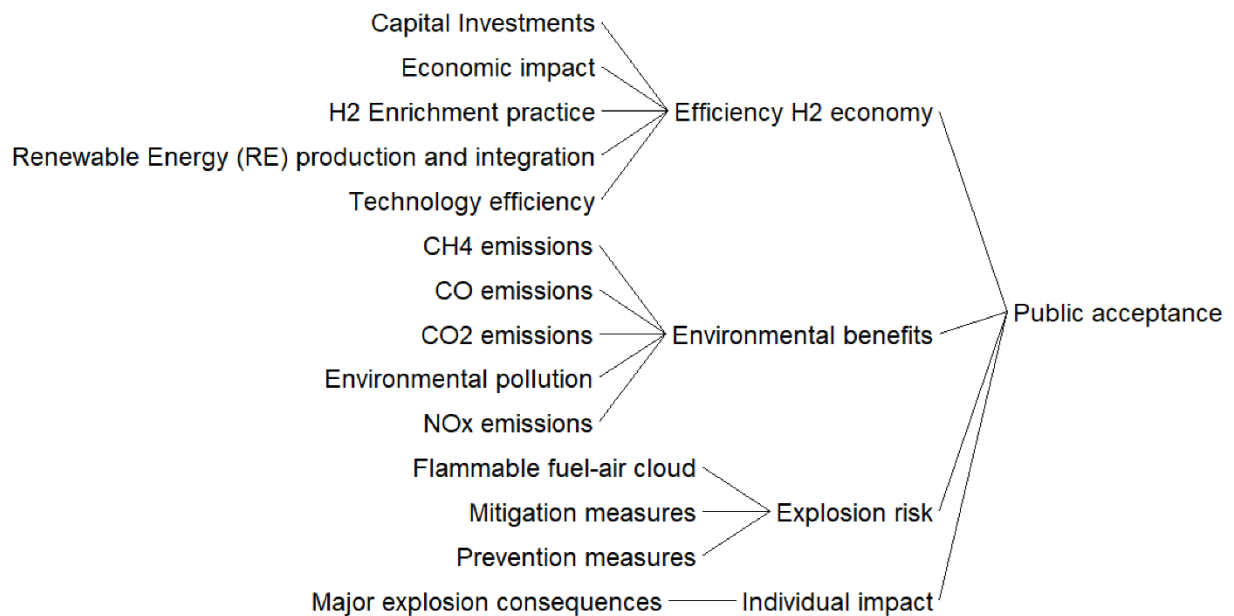


**Fig. 7.13- Causal tracing for the public acceptance of the hydrogen enrichment practice**

These huge number of new feedback loops appear as a consequence of the emerging complexity of the hydrogen enrichment implementation. Figure 7.14 shows the number of loops and the maximum observed loop length starting from the main model variables.

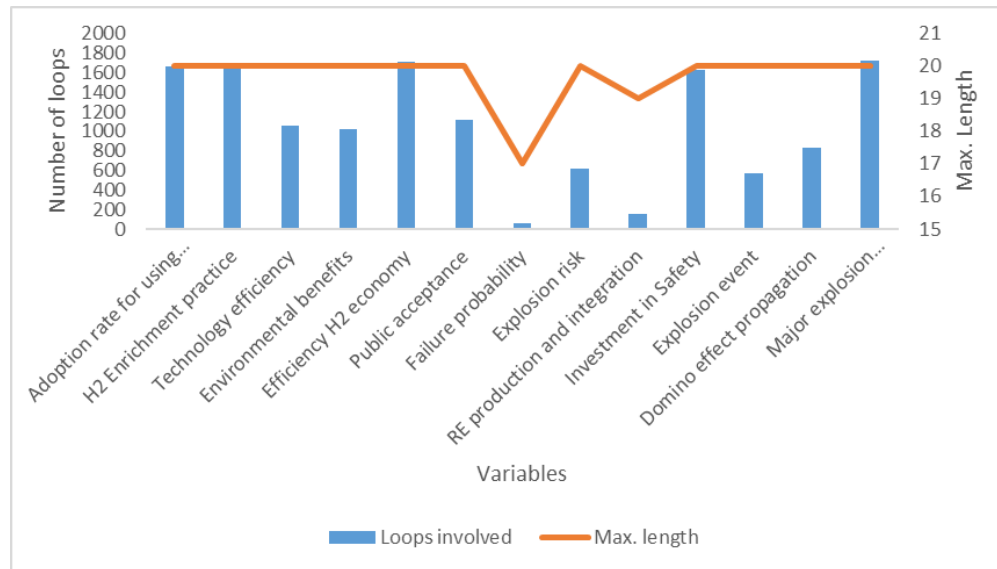


**Fig. 7.14- Loops involved and max. length for the main model variables**

The maximum number of feedback loops is observed starting from the variable “Major explosion consequences”, with 1720 loops, and the maximum length is 20, which means that 20 out of the 42 variables are involved at least in one of these loops (47.6%). This reinforces the idea that safety management plays a crucial role in the adoption of HE practice considering the economic, environmental, and societal implications. Hence, the explosion risk plays a crucial role in the hydrogen enrichment implementation which is additionally studied in the next section.

Following this, the second most interconnected variable is the “Efficiency hydrogen economy”, with 1713 loops and a maximum length of 20. Next, the adoption rate and H<sub>2</sub> enrichment practice, with 1669 loops (each one), and the maximum length is 20. After that, the fifth most interconnected variable is the “Investment in Safety” with 1629 loops and a maximum length of 20; followed by the “Public acceptance” with 1115 loops and a length of 20; “Technology efficiency” with 1055 loops and length of 20; and the “Environmental benefits” with 1024 loops and length of 20 as well.

### 7.5.3- An SD-based model for explosion risk related to hydrogen enrichment

This section focuses on developing a System Dynamics-based model (Fig. 7.14) for computing the explosion risk considering different percentages of hydrogen enrichment. This SD-based

model complements the previously developed CLD by adding the following variables: (1) explosion safety management, (2) innovation and technology development, (3) inherent safety, (4) optimal storage conditions, (5) gap between actual and perceived risk level, and (6) human expertise.

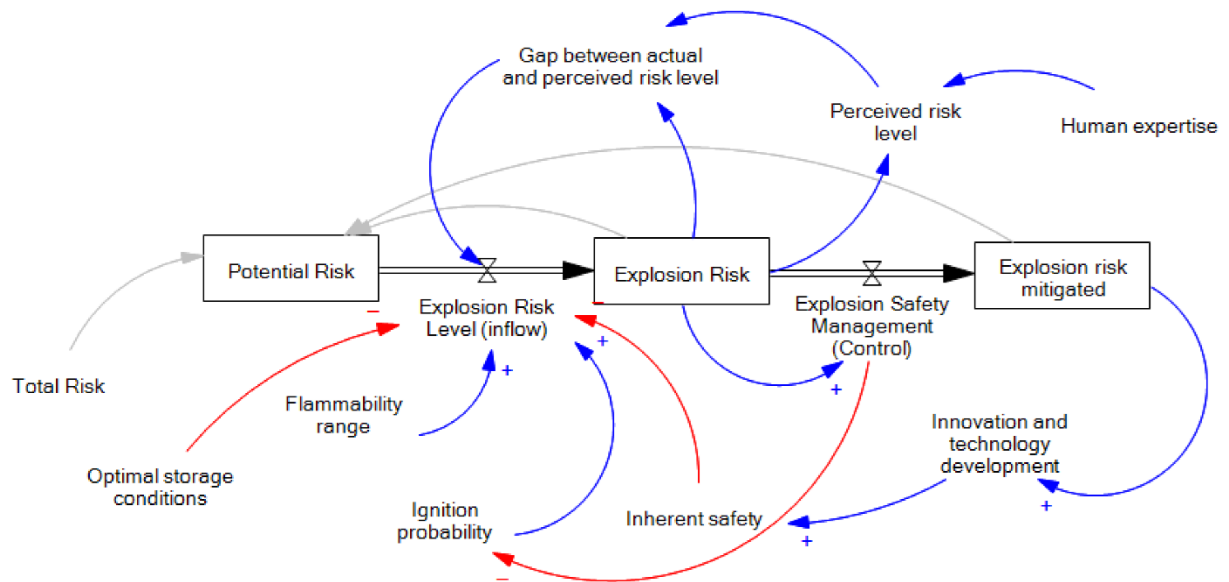


**Fig. 7.15- SD-based model for explosion risk linked to hydrogen enrichment**

For simulation purposes, the flammability in this model is taken as the difference between the flammability limits of different hydrogen compositions in the gas mixture according to Table 7.5 (adapted from the study of Atzori, 2023).

**Table 7.5-. Data for SD-based model simulations**

| Molar Hydrogen Percentage | Lower Flammability Limit (LFL) (% vol.) | Upper Flammability Limit (UFL) (% vol. ) | Flammability range (% vol.) |
|---------------------------|-----------------------------------------|------------------------------------------|-----------------------------|
| 0                         | 4.4                                     | 16.5                                     | 12.1                        |
| 20                        | 4.4                                     | 17.9                                     | 13.5                        |
| 30                        | 4.3                                     | 19.5                                     | 15.2                        |
| 40                        | 4.2                                     | 24.0                                     | 19.8                        |
| 100                       | 4.0                                     | 75.0                                     | 71.0                        |

Figure 7.16 shows the dynamic evolution of the explosion risk profiles considering different hydrogen compositions (Table 7.5).

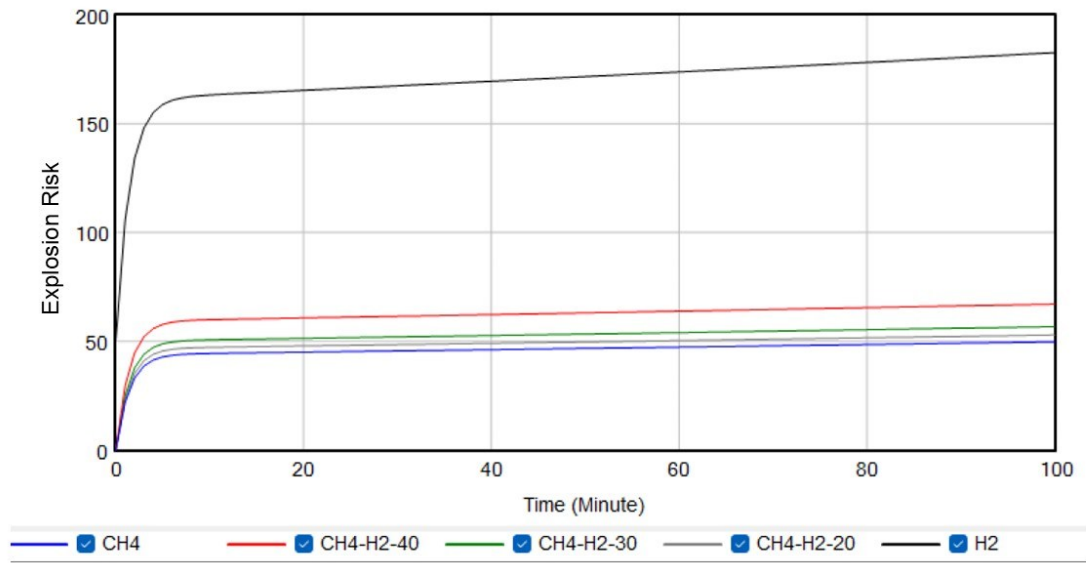


**Fig. 7.16- Dynamic evolution of the explosion risk profiles linked to the hydrogen enrichment**

In general, it is observed an exponential growth in the first 5 minutes after a gas release for all the fuel mixtures, after that a slow increment of the explosion risk is captured due to the effect of the safety control measures. Despite that, this increment tendency is much higher for pure hydrogen than for the mixtures with methane. Similar tendencies are obtained for hydrogen compositions of 20% and 30% with regard to pure methane, however, the explosion risk is slightly higher. For hydrogen composition, 40% higher differences are observed compared to pure methane, but the explosion risk is still much lower than that of pure hydrogen. Therefore, this reinforces the idea that hydrogen enrichment explosion risk, although not negligible, can be managed effectively in the same way that the methane explosion risk for hydrogen molar compositions below 30%. These results are similar to those reported in the literature (Messaoudani et al., 2016; Molnarne and Schroeder, 2019).

The numerical assumptions in the explosion safety model for hydrogen enrichment reflect representative conditions found in hydrogen blending and combustion studies, including typical enrichment fractions, ignition probabilities, and mitigation effectiveness. These values are intended to capture a plausible operational envelope for enrichment practices rather than to model a particular network. Qualitative testing showed that the main dynamic patterns, such as delayed reduction of explosion risk following policy changes, remain stable under reasonable

parameter variations, reinforcing that the insights arise from the feedback mechanisms embedded in the model.

#### 7.5.4- Graph-theoretic analysis of the hydrogen enrichment implementation CLD

The causal network analysis of the hydrogen enrichment implementation model within the FRISE framework provides a quantitative understanding of how structural connectivity and feedback dominance shape system dynamics in explosion safety and energy efficiency contexts. The obtained graph-theoretic (GT) results — summarized in Figure 7.17 — indicate that the hydrogen enrichment subsystem exhibits a hierarchically organized but strongly coupled topology, in which energy-efficiency drivers, explosion dynamics, and public acceptance processes are tightly interlinked through feedbacks at both technical and socio-organizational levels.

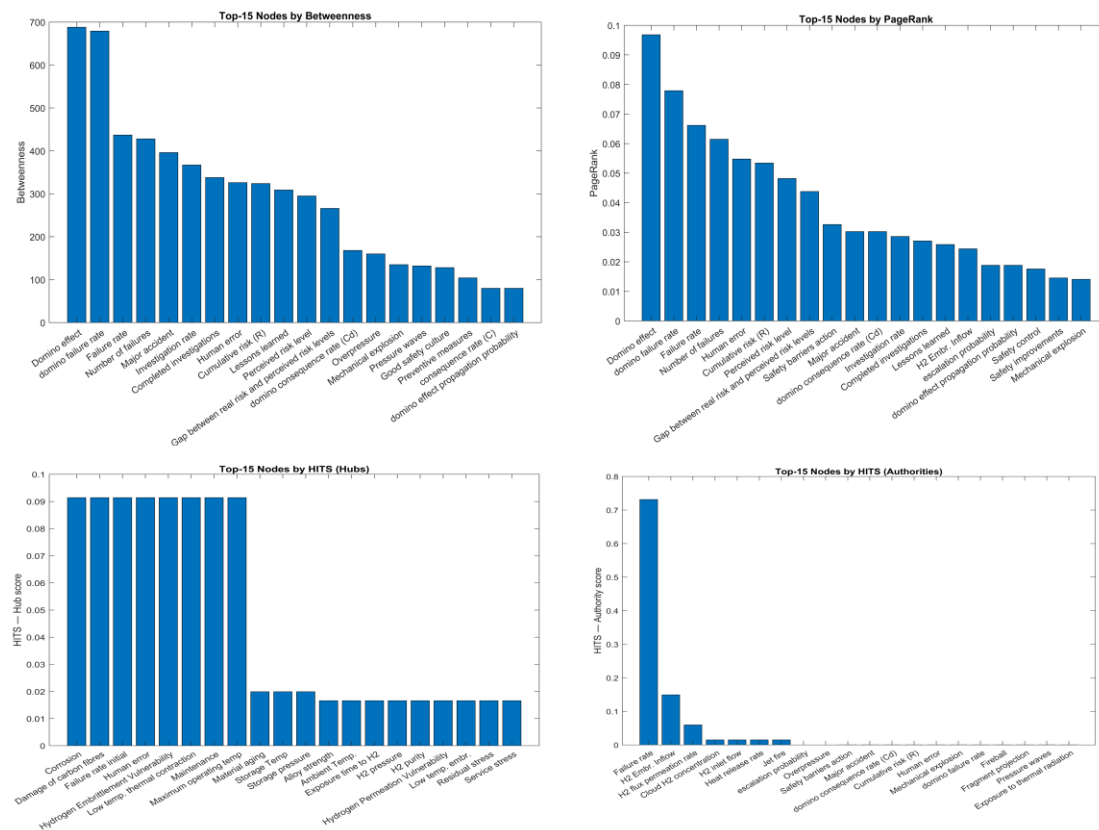


Fig. 7.17- GT metrics for the hydrogen enrichment of methane CLD

#### Centrality and network structure

The PageRank distribution highlights Efficiency H<sub>2</sub> economy, H<sub>2</sub> Enrichment practice, and Public acceptance as the three most influential nodes, with normalized scores of approximately 0.12, 0.086, and 0.066, respectively. This pattern reveals a system whose structural core is dominated by policy–technology interactions: enrichment practices drive technological

feedbacks and environmental outcomes, which in turn feed back through efficiency gains and socio-economic acceptance. These nodes act as integrative attractors, concentrating influence from both physical and managerial layers of the system. Similar behavior has been observed in sustainability-oriented energy transitions where efficiency and public trust reinforce adoption trajectories (Duan et al., 2020; Sala et al., 2025).

High betweenness centrality values (Figure 7.18) identify H<sub>2</sub> Enrichment practice ( $\approx 735$ ), Efficiency H<sub>2</sub> economy ( $\approx 366$ ), and Explosion risk ( $\approx 276$ ) as key information brokers that mediate flows between otherwise separated subsystems — namely, the technological efficiency domain, explosion safety subsystem, and social response domain. The dual high-betweenness of Explosion risk and Prevention/Mitigation measures ( $\approx 245$ – $158$ ) demonstrates the coupling between technical escalation and policy response, a hallmark of the FRISE systemic approach that models feedback-based regulation instead of static safety barriers (Khakzad et al., 2013; Blokland & Reniers, 2020).

Nodes such as Environmental benefits and Efficiency of fuel combustion also exhibit elevated PageRank ( $\approx 0.055$ – $0.036$ ) and betweenness ( $\approx 163$ – $132$ ), bridging the energy-efficiency and emission-reduction clusters. This suggests that environmental performance is not a passive outcome but an active mediator within the hydrogen economy feedback loops — a role consistent with sustainability-driven design frameworks incorporated in FRISE (see Chapter 5). Similarly, Technology efficiency (PageRank  $\approx 0.029$ ; Betweenness  $\approx 207$ ) occupies a transitional position connecting Fuel consumption and Renewable energy integration, reinforcing the notion that technical progress interacts dynamically with resource flows and capital investments.

### ***HITS hub–authority patterns***

The HITS analysis further clarifies directional influence within the network. The highest authority scores are found in Failure rate, H<sub>2</sub> Embr. Inflow, and Cumulative risk (R) ( $\approx 0.73$ – $0.07$ ), confirming that these nodes are major receivers of causal flow, i.e., they integrate the influence of many other processes. This is consistent with the FRISE interpretation of risk accumulators, where system states (e.g., failure probability, risk index) represent integrals of preceding physical and human factors. Conversely, hub scores peak for nodes such as Corrosion, Damage of carbon fibres, and Residual stress ( $\approx 0.09$  each), which act as source variables — initial excitations that broadcast influence through the technical degradation chain toward explosion or efficiency outcomes. This hub–authority polarity reflects the dual-layer



FRISE structure: source nodes represent exogenous drivers of degradation or innovation, while authority nodes represent endogenous accumulators regulating adaptive feedback and management response.

In the enrichment-specific context, H<sub>2</sub> Enrichment practice functions as a hybrid node with both hub and authority characteristics, mediating between upstream technological inputs and downstream socio-environmental consequences. Its central placement and dual nature confirm that hydrogen enrichment operates as a pivot variable in sustainable transition pathways, balancing efficiency gains with explosion risk and public perception.

### ***Systemic interpretation within FRISE***

From the FRISE perspective, the GT results underscore three major systemic behaviors:

- Coupled feedback dominance – The coexistence of high-centrality technical and social nodes indicates a tightly interwoven system where risk, efficiency, and acceptance evolve together. Reinforcing loops (e.g., “efficiency–adoption–investment”) coexist with balancing loops (“risk–prevention–mitigation”), resulting in emergent oscillations characteristic of adaptive safety management (Stermann, 2000; Leveson, 2011).
- Delay and adaptation effects – Nodes representing Prevention and Mitigation measures exhibit intermediate PageRank but high betweenness, signifying that management actions are delayed intermediaries between accidents and learning outcomes. This matches the FRISE framework’s capacity to represent temporal delays and adaptive corrections that differentiate it from static probabilistic approaches (Ge et al., 2022).
- Multi-domain resilience leverage – High interdependence between Efficiency H<sub>2</sub> economy, Explosion risk, and Public acceptance suggests that resilience must be co-designed across technical, environmental, and social domains. Policy strategies that improve safety can simultaneously strengthen adoption and efficiency — a cross-domain synergy quantified here through network metrics.

### ***Interpretation and implications***

The topological metrics reveal that hydrogen enrichment safety and sustainability form a scale-free network with concentrated influence around a few high-degree nodes. This structure implies that interventions focused on those nodes — particularly H<sub>2</sub> Enrichment practice, Explosion risk, and Efficiency H<sub>2</sub> economy — will yield disproportionate system-wide

benefits. Within the FRISE decision-support paradigm, these act as control levers for managing trade-offs between safety and sustainability objectives.

Furthermore, the network's dense connectivity across domains emphasizes that risk management policies cannot be isolated: engineering modifications (e.g., venting design, monitoring technologies) should be integrated with public communication and economic incentives to maintain long-term stability. The observed high betweenness of socio-technical nodes validates FRISE's Systemic Glue Layer, which explicitly models these cross-domain dependencies to inform holistic hydrogen safety governance.

#### **7.5.5- Discussion: Dynamic Behavior, Delay Effects, and Adaptive Policy Responses within the FRISE Framework for the hydrogen enrichment practice**

The second application of the FRISE framework—focused on hydrogen enrichment and explosion safety management—demonstrates how complex technical and socio-organizational interactions generate emergent, adaptive, and sometimes counterintuitive system behaviors. The dynamic and graph-theoretic analyses confirm that the FRISE framework effectively captures the multi-domain feedbacks, temporal delays, and adaptive responses that govern hydrogen safety and sustainability under conditions of technological transition.

##### ***Dynamic behavior and feedback dominance***

The hydrogen enrichment CLD exhibits intertwined reinforcing and balancing feedbacks that collectively drive non-linear system evolution. Reinforcing loops such as the Efficiency–Adoption–Investment cycle amplify the growth of hydrogen blending technologies and renewable integration, promoting long-term decarbonization benefits (Duan et al., 2020). However, as identified in the GT analysis (Section 7.5.4), nodes such as H<sub>2</sub> Enrichment practice, Explosion risk, and Public acceptance hold the highest centrality values, meaning that they mediate most dynamic interactions between subsystems. When enrichment levels rise rapidly, these loops strengthen one another, accelerating efficiency gains but also increasing system vulnerability through failure probability and ignition limits expansion (Mannan, 2014; CCPS, 2023).

The balancing loops—particularly those involving Prevention and Mitigation measures—introduce self-regulatory behavior by reducing Explosion risk and Detonation probability after an incident or risk increase. This dynamic resembles the adaptive control mechanisms observed in socio-technical systems where human and organizational factors respond to variations in system performance (Leveson, 2011; Blokland & Reniers, 2020). The coexistence of both loop

types reflects the systemic duality inherent to hydrogen transition: progress in technological efficiency is inseparable from the continuous management of emerging hazards.

### ***Delay effects and oscillatory patterns***

A key feature of the FRISE modeling environment is its ability to represent temporal delays—a property absent in conventional static safety analyses. Within the hydrogen enrichment system, these delays appear in several forms:

- Engineering response delays, associated with lag times in implementing new preventive technologies or maintenance upgrades after identifying performance degradation.
- Organizational learning delays, reflecting the time required for lessons from Explosion events to propagate through the Investigation–Learning–Improvement chain.
- Public perception delays, where Public acceptance adjusts slowly in response to visible incidents or improvements, affecting future adoption rates.

These delays can create oscillatory or S-shaped dynamic behavior. For example, an improvement in Efficiency H<sub>2</sub> economy may initially boost Adoption rate and H<sub>2</sub> Enrichment practice, increasing the potential for explosion events before safety investments and prevention policies catch up. Such lag-induced fluctuations are consistent with system-dynamics studies of safety management, which identify delays as fundamental drivers of accident recurrence and risk oscillation (Ge et al., 2022; Khakzad et al., 2013). In the FRISE context, these time-based effects are mathematically implemented through integration and delay functions (e.g., INTEG, DELAY FIXED), enabling the quantitative reproduction of real-world adaptation cycles.

### ***Adaptive policy responses and systemic learning***

The feedback structure of the enrichment model supports adaptive policy loops, in which risk signals dynamically trigger management responses and policy reinforcement. As Explosion risk increases, Investment in safety and Prevention measures are strengthened, reducing ignition probabilities and mitigating damage consequences. Over time, Environmental benefits and Efficiency H<sub>2</sub> economy feed back positively on Public acceptance, closing the socio-technical adaptation cycle.

This adaptive behavior is central to the FRISE philosophy, which emphasizes co-evolution between safety and sustainability subsystems rather than isolated optimization. FRISE models how management strategies—such as inspection frequency, innovation funding, and safety culture enhancement—alter systemic structure and feedback dominance over time. The strong

connectivity between Prevention measures, Mitigation measures, and Explosion risk observed in the GT analysis supports this conceptualization: these nodes function as regulatory hubs that mediate between physical hazards and organizational responses, forming the dynamic backbone of adaptive governance (Sterman, 2000; Nazir et al., 2019).

Moreover, the feedback between Public acceptance and Efficiency H<sub>2</sub> economy introduces a social adaptation layer. This loop translates perceived safety performance into socio-political legitimacy, affecting investment, innovation, and deployment rates—an essential component of sustainability transitions (Sala et al., 2025). Thus, adaptive policy within the FRISE framework extends beyond technical countermeasures to encompass cognitive and societal feedbacks, recognizing that resilience emerges from the collective adaptation of human, technical, and institutional elements.

### ***Validation of model behavior***

Model validation followed three complementary dimensions consistent with dynamic systems modeling best practices (Sterman, 2000):

- Structural validation confirmed that the causal and feedback architecture reproduces theoretical and empirical relations identified in hydrogen safety literature (Salzano et al., 2014; Duan et al., 2020).
- Behavioral validation was achieved by verifying that the model produces realistic dynamic patterns—such as delayed safety recovery and fluctuating risk levels—consistent with documented hydrogen blending and explosion scenarios (Koutsourakis et al., 2023; CCPS, 2023).
- Expert validation was performed through iterative discussions with domain specialists in hydrogen safety and process systems engineering, confirming the interpretability and logical coherence of the modeled mechanisms.

The behavior of the enrichment-related risk model reflects the combined influence of reinforcing loops associated with enrichment demand and balancing loops related to mitigation actions. Delays in implementing corrective measures or adjusting enrichment policies result in temporary overshoots in risk levels, highlighting how timing plays a central role in shaping explosion risk trajectories. This sensitivity to delay duration underscores the need for prompt policy adaptation when operational conditions change.

Together, these validation steps confirm that the FRISE-based enrichment model captures plausible dynamic behaviors grounded in both physical and managerial reality. By unifying feedback structures across technical, environmental, and social domains, FRISE demonstrates its value as a systemic decision-support tool for hydrogen transition governance.

### ***Concluding remarks***

The hydrogen enrichment case study highlights the role of FRISE as a framework capable of anticipating emergent risks and guiding adaptive management policies in evolving energy systems. By integrating systemic feedbacks, temporal delays, and multi-domain interdependencies, the framework enables a dynamic understanding of resilience and sustainability. The ability to quantify causal influence (via GT metrics) and simulate adaptive responses (via SD modeling) positions FRISE as a bridge between engineering reliability models and systemic sustainability analysis—a crucial methodological advance for future hydrogen safety research and risk-informed policy design.

## **7.6- Case Study III – Safe Storage Pathways: Comparing GH<sub>2</sub> and NH<sub>3</sub>**

### **7.6.1- Purpose and Relevance**

The third application of the FRISE framework addresses the safe storage of hydrogen and ammonia (NH<sub>3</sub>), two central vectors in the emerging hydrogen economy. While both substances enable large-scale hydrogen storage and transportation, they embody contrasting safety profiles and sustainability implications (Apostolou & Xydis, 2019; Valera-Medina et al., 2018).

This case study extends the previous analyses by applying the FRISE methodology to the comparative assessment of gaseous hydrogen (GH<sub>2</sub>) and ammonia-based storage pathways, focusing on how systemic feedbacks, degradation mechanisms, and management responses influence their safety performance and environmental sustainability.

Hydrogen and ammonia storage represent complementary technological options:

- GH<sub>2</sub> storage offers direct integration into fuel cell and transport applications, but its high diffusivity, low ignition energy, and embrittlement potential increase the probability of leaks, explosions, and cascading failures (Mannan, 2014; Salzano et al., 2014; Aziz, 2020).
- NH<sub>3</sub> storage provides higher volumetric energy density and more favorable thermodynamic stability, but poses toxicological and environmental hazards, including

potential ammonia slip, corrosion, and NO<sub>x</sub> formation during conversion (Valera-Medina et al., 2018).

The purpose of this case study is twofold. First, it evaluates how each storage pathway behaves dynamically when exposed to material degradation, operational stress, and management intervention delays. Second, it illustrates how the FRISE framework can integrate multi-hazard dynamics (flammability, toxicity, corrosion, and environmental release) within a unified systemic model. By comparing GH<sub>2</sub> and NH<sub>3</sub> storage, this case provides decision-support insights for technology selection and policy prioritization in hydrogen infrastructure planning.

From a broader perspective, this application demonstrates FRISE's capability to function as a comparative systems-analysis platform, where diverse technologies can be assessed not only in terms of quantitative safety indicators, but also through feedback-driven sustainability trade-offs. In line with the framework's principles, both physical degradation and organizational learning are modeled as interdependent feedback processes, highlighting that storage safety evolves dynamically over the operational life cycle rather than as a fixed property (Khakzad et al., 2013; Blokland & Reniers, 2020).

#### **7.6.2- Model Conceptualization and CLD development**

The Safe Storage Pathways (SSP) model is conceptualized as a comparative system-dynamics representation capturing the evolution of safety, degradation, and management effectiveness in GH<sub>2</sub> and NH<sub>3</sub> storage systems. The model boundary includes storage vessels, containment barriers, environmental conditions, and safety management subsystems, with particular attention to failure propagation, hazard interaction, and regulatory feedback.

Table 7.6 shows the integrated feedback loops for building the CLD (Figure 7.18). In Figure 7.18, an arrow with a positive sign (+) means that an increase in the first variable increases the second variable above what it would otherwise have been; and an arrow with a negative sign (-) means that an increase in the first variable decreases the second variable below what it otherwise would have been.

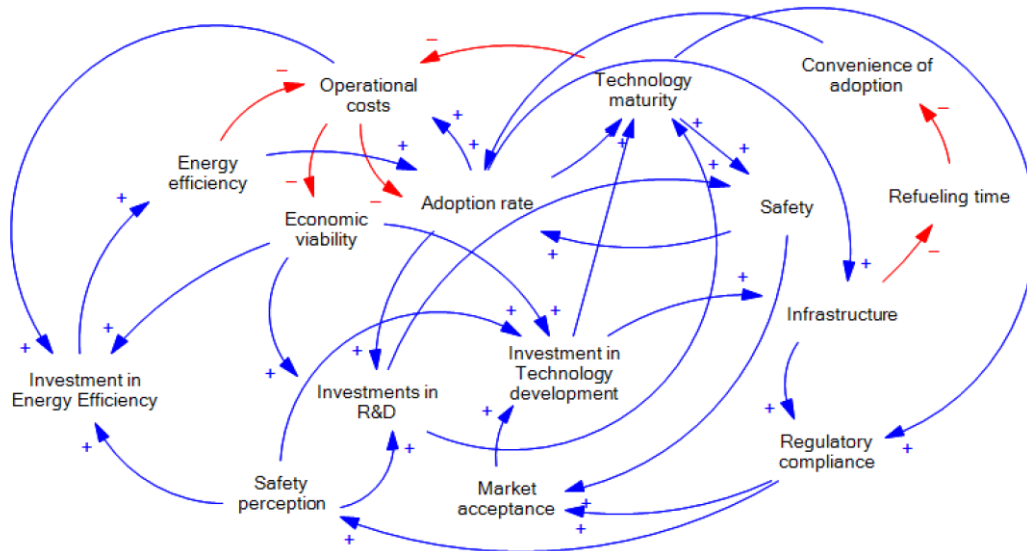


**Fig. 7.18- CLD for analyzing the adoption of hydrogen storage technologies**

After building the CLD for analyzing the adoption rate of hydrogen storage systems, it is possible to identify the causal relations of this variable and the main variables influenced as well (by causal tracing). Figure 7.19 shows the causal tracing for the adoption rate of hydrogen storage systems.

**Table 7.6- Feedback loops for building the CLD by analyzing the adoption of hydrogen storage technologies**

| No. | Feedback Loop                         | Loop Description                                                                                                                                                                                                                                                                                                                                                       |
|-----|---------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 01  | Cost-Driven Adoption Loop             | As the cost associated with hydrogen storage technologies decreases—due to technological progress or scale economies—the adoption rate of these technologies increases. Higher adoption levels, in turn, promote further cost reductions through learning-by-doing, increased production volumes, and innovation spillovers, creating a reinforcing economic feedback. |
| 02  | Technology Maturity and Safety Loop   | As hydrogen storage technologies mature, improved design, materials, and manufacturing processes enhance intrinsic safety. Greater safety raises consumer confidence and regulatory trust, which accelerates technology deployment and stimulates further research and development, reinforcing the maturity–safety cycle.                                             |
| 03  | Refueling Time and Convenience Loop   | Shorter refueling times increase convenience and user satisfaction, attracting more consumers and incentivizing infrastructure expansion (e.g., additional refueling stations). Expanded infrastructure further reduces refueling times, generating a reinforcing loop of convenience, adoption, and infrastructure development.                                       |
| 04  | Safety and Regulatory Compliance Loop | Compliance with safety and performance standards strengthens public confidence and market acceptance, encouraging investment in advanced technologies and infrastructure. Enhanced compliance simultaneously                                                                                                                                                           |

| No. | Feedback Loop                                     | Loop Description                                                                                                                                                                                                                                                                                            |
|-----|---------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     |                                                   | lowers accident probability, reinforcing positive perceptions of safety and regulatory integrity.                                                                                                                                                                                                           |
| 05  | Energy Efficiency and Cost-Reduction Loop         | Improvements in energy efficiency reduce operational costs associated with hydrogen and ammonia storage systems, making them more economically competitive. Lower costs stimulate further investment in efficiency-enhancing technologies, creating a virtuous cycle of performance and affordability.      |
| 06  | Technology Maturity and Standards-Compliance Loop | As storage technologies advance technologically, their likelihood of meeting or exceeding safety and performance standards increases. Greater conformity with standards boosts market legitimacy and user confidence, which accelerates further development and refinement of technology maturity.          |
| 07  | Safety and Market-Acceptance Loop                 | Safer storage and handling systems increase public and market acceptance, attracting additional investment into safety-oriented innovation. These improvements feed back to further enhance system safety, forming a reinforcing socio-technical feedback that strengthens resilience and reliability.      |
| 08  | Energy Efficiency and Adoption Loop               | Rising energy efficiency enhances attractiveness and adoption rates; however, expanded deployment raises operational demands, motivating additional investment in efficiency improvements. Over time, this balancing-cum-reinforcing loop drives continuous technological optimization and cost moderation. |

Therefore, the main identified variables linked with the increase in the adoption rate of hydrogen storage systems are the convenience of adoption, the energy efficiency, the operational costs, and the safety. From eight feedback loops, after considering the interconnections and loops, a huge amount of new feedback loops emerged, as a result of the complexity linked to this system. Figure 7.20 shows a complexity analysis considering the number of feedback loops linked to each variable and its maximum length.

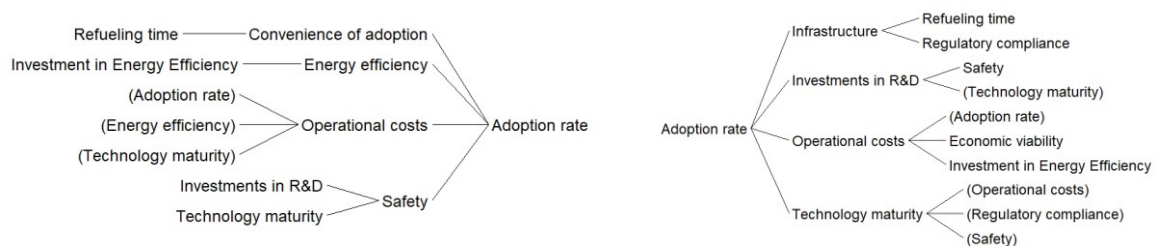


**Fig. 7.19- Causal tracing for the adoption of hydrogen storage technologies**



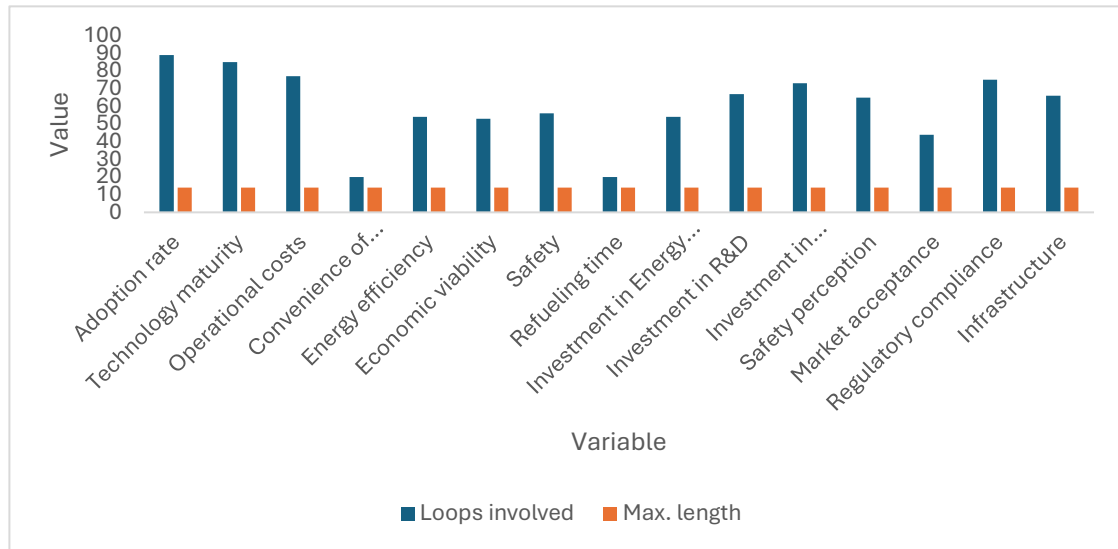


**Fig. 7.20- Complexity emerged from the developed CLD**

The maximum number of feedback loops is 89, linked precisely to the analyzed variable adoption rate, followed by technology maturity (85), and operational costs (75). Notice that the maximum length for each variable is 14, which means that this is a complex interdependent system.

### 7.6.3- System Dynamics-based model for hydrogen safe storage assessment

For developing the System Dynamics (SD)-based model for hydrogen safe storage assessment, and for comparing  $\text{GH}_2$  with  $\text{NH}_3$ , two main stocks are proposed (they represent accumulation): Fire and Explosion Risk, and Toxic and Environmental Risk. For each stock, there is an inflow rate (represented by the increased risk rate) and an outflow rate (represented by the safety management features). Moreover, the delay effects between the increased risk level and the activation of the contingency plans are considered. The other variables are auxiliary and represent the physical-chemical properties of each storage material, the scope of the possible

scenarios (such as jet fires, VCE), and toxic properties and their scope. Figure 7.21 shows the developed SD-based model.

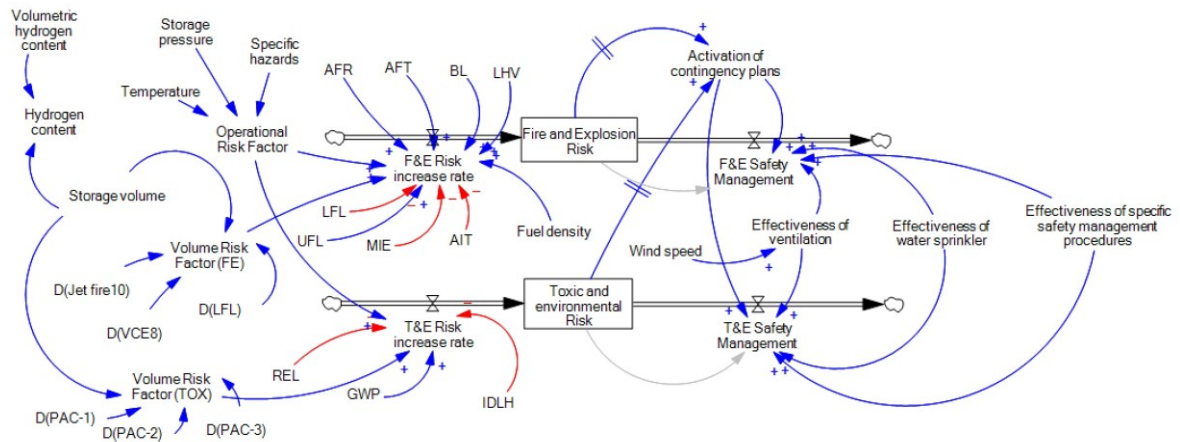


**Fig. 7.21- System Dynamics-based model for computing the risk associated with the hydrogen storage systems**

Additionally, it is considered that an increase in the risks will trigger the activation of the contingency plans (which certain delay), and this will lead to better safety management in order to reduce the detected increased risk.

Figure 7.22 and Figure 7.23 show the dynamic risk for fires and explosions, and for toxicity and environmental impact respectively, by comparing the  $\text{GH}_2$  and the  $\text{NH}_3$ , as well as, considering normal and poor safety management plans.

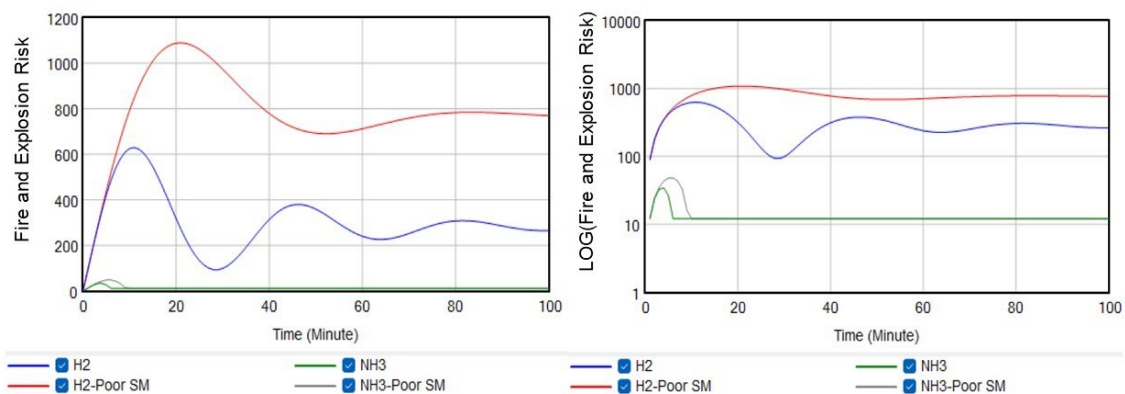


**Fig. 7.22- Comparison of the Fire and Explosion Risk associated with  $\text{GH}_2$  and  $\text{NH}_3$  considering good and poor safety management procedures using the developed SD-based model (left-normal scale, right-log scale)**

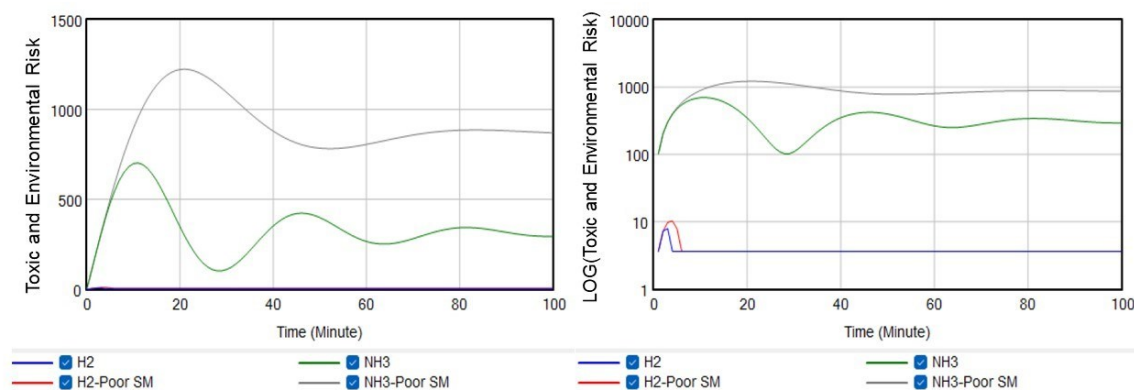


**Fig. 7.23- Comparison of the Toxicity and Environmental Risk associated with GH<sub>2</sub> and NH<sub>3</sub> considering good and poor safety management procedures using the developed SD-based model (left-normal scale, right-log scale).**

From the performed simulations, it is noted that the predominant risk associated with GH<sub>2</sub> is the fire and explosion risks, and the one linked to NH<sub>3</sub> is the toxic and environmental risk. This result was expected as it was clearly reported in the literature (Wen et al., 2023). It is a way to validate the proposed model. What is new is that as the delays were considered, it is important to highlight that these effects influence more the predominant risk associated with each hydrogen storage system.

Moreover, higher risk profiles were obtained when the safety management was considered poor, which is supported by the literature (Wijayanta et al., 2019). Also, the delay effects in the case of poor safety actions are weaker than for good safety. The action of the safety control measures leads to a gradual stabilization of the risk levels for both storage technologies. The maximum risk reached with good safety performance is lower than the minimum risk associated with a poor safety management application, reinforcing the idea that investing in safety will be of paramount importance for the adoption of storage hydrogen systems.

Parameterization of the *Safe Storage Pathways* model was based on literature values and indicative ranges for GH<sub>2</sub> and NH<sub>3</sub> storage, including typical failure rates, degradation trends, and environmental impact factors. The aim is to compare the dynamic behavior of the two storage options under representative conditions, not to reproduce a specific facility. Exploratory runs indicate that the relative trends between GH<sub>2</sub> and NH<sub>3</sub>, particularly in terms of evolving risk and sustainability indicators, are preserved under moderate parameter perturbations, suggesting that the comparative insights are structurally driven.

### 7.6.4- Graph-Theoretic Analysis of the Safe Storage Pathways (GH<sub>2</sub>–NH<sub>3</sub>) CLD

The graph-theoretic (GT) analysis of the Safe Storage Pathways (SSP) causal structure provides a quantitative interpretation of how technological, economic, and safety factors interact within the FRISE systemic framework. Figure 7.24 presents the resulting centrality distributions for the top fifteen nodes by Betweenness, PageRank, and HITS (Hub/Authority) indices.

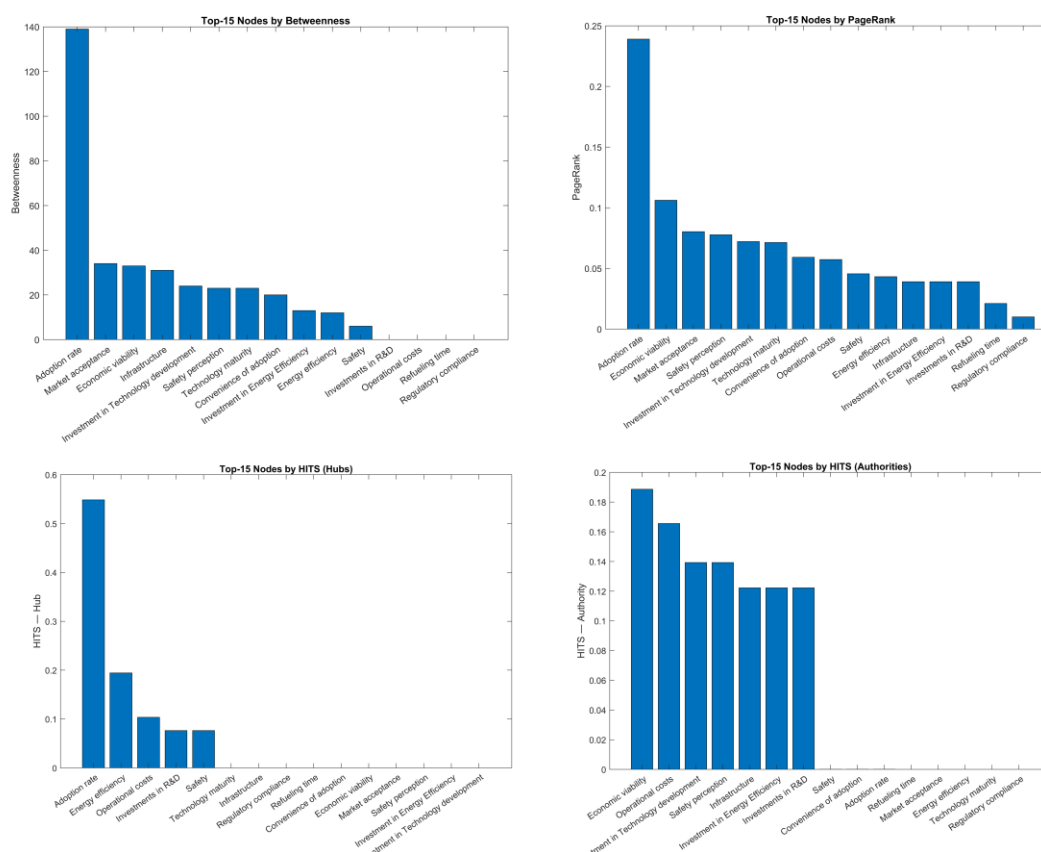


Fig. 7.24- GT metrics for the Safe Storage Pathways (GH<sub>2</sub>–NH<sub>3</sub>) CLD

#### *Network structure and connectivity*

The SSP CLD represents a moderately dense network (14 nodes, 35 directed links), characterized by strong reinforcing feedbacks among Adoption rate, Economic viability, and Market acceptance, and balancing feedbacks involving Operational costs and Safety perception. The PageRank and Betweenness distributions (Figure 7.24, top row) confirm a hierarchical but well-coupled structure dominated by Adoption rate as the system’s central driver, integrating influences from nearly all other domains—technological maturity, energy efficiency, safety, infrastructure, and regulation.

Adoption rate exhibits the highest PageRank (0.239) and Betweenness (139), confirming its role as a systemic integrator within the FRISE conceptualization: a state variable through which both reinforcing and balancing feedbacks converge. In network terms, Adoption rate serves as both a hub and a bridge—receiving signals from economic, safety, and technological loops while transmitting influence toward R&D investment and infrastructure growth. Such behavior typifies a control or pivot node, regulating the transition between innovation diffusion and risk stabilization (Sterman, 2000; Blokland & Reniers, 2020).

Economic viability (PageRank = 0.106; Betweenness = 33) and Market acceptance (PageRank = 0.080; Betweenness = 34) follow as key mediators, linking economic and social feedback subsystems. Their relatively high eigenvector centralities indicate their strong interdependence: as viability enhances acceptance and acceptance accelerates adoption, both contribute to the reinforcement of the cost–innovation cycle, consistent with empirical observations in emerging hydrogen markets (Duan et al., 2020; Apostolou & Xydis, 2019).

### ***Centrality interpretation: Dominant feedback roles***

The GT ranking (Figure 7.24, top-right) shows that technological and perceptual nodes—Technology maturity, Safety perception, and Investment in Technology development—also occupy central roles (PageRank  $\approx$  0.07–0.08). This indicates that safety–innovation coupling acts as a significant internal amplifier within the hydrogen and ammonia storage system.

Technology maturity holds an OutDegree of 3 and a harmonic closeness of 0.54, implying rapid influence propagation. It represents the structural backbone of the technology learning loop (R2 and R6 in Table 7.6), consistent with the reinforcing nature of technological progress and safety improvement described in previous subsections.

In contrast, Operational costs and Regulatory compliance display low betweenness and PageRank, reflecting their role as boundary or balancing nodes that constrain systemic growth rather than drive it. This aligns with the balancing loops identified in the CLD (B1 and B4), where cost escalation or regulatory pressure dampens the growth of adoption until compensatory investment in efficiency or compliance is made.

Interestingly, Safety and Infrastructure have moderate betweenness ( $\approx$  20–31) but lower PageRank ( $\sim$ 0.04), suggesting that while they are crucial intermediaries in propagation chains (e.g., between technology maturity and perception), they are not dominant sources or sinks of

influence. This confirms their role as transmission layers—physical enablers that support but do not independently determine the system’s long-term dynamic trajectory.

### ***HITS analysis: Directionality and knowledge flow***

The HITS (Hyperlink-Induced Topic Search) metrics (Figure 7.24, bottom row) differentiate between initiators of influence (hubs) and receivers of influence (authorities). The top HITS–Hub scores are associated with Adoption rate (0.56), Energy efficiency (0.18), and Operational costs (0.09), revealing these as primary initiators of systemic change. These nodes collectively represent the economic-technical stimulus subsystem, responsible for transmitting change impulses across the network. Their strong hub centralities indicate that improving efficiency or reducing operational costs not only enhances adoption directly but also indirectly propagates effects through R&D and safety investments—mirroring the reinforcing loops R1, R5, and R8 in Table 7.6.

On the other hand, the authority distribution identifies Economic viability (0.19), Operational costs (0.17), Market acceptance (0.14), and Safety perception (0.13) as the principal receivers of influence. This pattern highlights that economic and perceptual outcomes accumulate the effects of multiple feedbacks, serving as the evaluation layer of the system—where the cumulative impacts of technological progress, investment strategies, and regulatory compliance materialize.

This asymmetry between hubs (driving technological and adoption dynamics) and authorities (reflecting social and economic outcomes) reinforces the FRISE framework’s conceptual partition between driving functions (energy and innovation) and response functions (safety, perception, and sustainability).

### ***Systemic insights within the FRISE framework***

From a FRISE perspective, the SSP GT results validate the framework’s capacity to quantify systemic coupling between technological advancement, safety management, and socio-economic feedbacks. Three main insights emerge:

- **Dominance of adoption-mediated feedbacks:** The extremely high centrality of Adoption rate confirms it as the dynamic hinge between safety, efficiency, and perception. In systemic terms, adoption embodies the emergent state of system maturity—the variable through which the positive and negative feedbacks of safety, technology, and cost co-evolve.

- Economic and perceptual co-dependence: Economic viability and Market acceptance form a closely connected dyad, mediating the translation of technological progress into real-world uptake. Their high PageRank and moderate betweenness suggest stable yet responsive nodes—representing medium-term feedbacks that balance innovation acceleration with social acceptance (Khakzad et al., 2013; Sala et al., 2025).
- Delay and regulatory stabilization: Low-centrality nodes such as Regulatory compliance and Refueling time play stabilizing roles by introducing temporal delays and structural constraints that prevent uncontrolled feedback escalation. These findings are consistent with dynamic safety management theory (Leveson, 2011), where delay mechanisms maintain long-term system resilience by absorbing oscillations in growth and risk perception.

### ***Interpretation and implications***

The SSP graph structure resembles a directed acyclic core with cyclical reinforcement layers, suggesting that policy interventions aimed at safety and sustainability should prioritize nodes exhibiting dual influence—Adoption rate, Economic viability, and Technology maturity—to maximize systemic leverage.

From a design and policy standpoint:

- Strengthening energy efficiency and technology development channels increases the robustness of the reinforcing innovation loop (R1–R6).
- Enhancing safety perception and regulatory compliance supports adaptive balancing, minimizing volatility in adoption rates.
- Integrating feedback learning mechanisms (e.g., through R&D and data-driven inspection) ensures that social and technical domains co-adapt dynamically—a central tenet of the FRISE framework.

In conclusion, the GT results underscore that safe and sustainable hydrogen or ammonia storage development is not governed by isolated variables but by network-wide feedback coordination. Adoption emerges as both the outcome and the driver of system behavior, while safety, efficiency, and perception act as adaptive regulators that sustain stability in the face of innovation-driven growth.

### **7.6.5- Discussion: Dynamic Behavior, Delay Effects, and Adaptive Policy Responses within the FRISE Framework**

The Safe Storage Pathways (SSP) model, encompassing the comparative analysis of gaseous hydrogen (GH<sub>2</sub>) and ammonia (NH<sub>3</sub>) storage systems, illustrates the FRISE framework's capacity to capture the dynamic evolution of technological performance, safety integrity, and socio-economic feedbacks in energy transition infrastructures. The model outcomes, supported by the graph-theoretic (GT) analysis in Section 7.6.4, reveal that the systemic behaviour of storage safety and adoption dynamics is governed by a set of interdependent reinforcing and balancing loops (R1–R8 in Table 7.6) that collectively determine the pace, stability, and resilience of hydrogen storage deployment.

#### ***Dynamic feedback dominance and systemic coupling***

The GT results demonstrate that Adoption rate functions as the system's structural pivot, displaying the highest PageRank (0.239) and Betweenness (139). This confirms that adoption is both a dependent outcome of safety, efficiency, and cost dynamics and a driving force that reconfigures those same dynamics through investment and innovation feedbacks.

In FRISE terminology, this duality represents an adaptive systemic node, where reinforcing and balancing feedbacks converge to generate emergent patterns of technological evolution. Reinforcing loops such as R1 (Cost-driven adoption), R5 (Energy efficiency and cost reduction), and R7 (Safety and market acceptance) dominate the growth phase, amplifying performance and uptake through cost reduction, enhanced safety perception, and efficiency gains.

In contrast, balancing mechanisms embedded in R4 (Safety and regulatory compliance) and R8 (Energy efficiency and adoption) introduce the corrective dynamics that maintain long-term stability, consistent with system dynamics principles of bounded growth (Sterman, 2000; Leveson, 2011).

The interplay between reinforcing and balancing feedbacks produces S-shaped diffusion behaviour, characteristic of technology adoption and safety learning processes. In early phases, reinforcing loops drive rapid adoption, while in later stages, regulatory and cost-related feedbacks attenuate system acceleration, leading to a stable equilibrium defined by acceptable safety and performance thresholds. This structure reflects the FRISE framework's core premise: sustainable transitions emerge not from linear optimization but from multi-loop equilibrium among competing objectives—safety, efficiency, and socio-economic viability.



### ***Delay mechanisms and oscillatory adaptation***

Delays are intrinsic to the SSP model's systemic behavior, especially within the Technology maturity–Safety–Market acceptance cycle and the Safety and regulatory compliance loop. Time lags arise as policy, infrastructure, and public perception adapt more slowly than technological innovation, producing oscillatory responses in adoption and investment patterns (Khakzad et al., 2013; Ge et al., 2022).

For instance, safety improvements or cost reductions may initially accelerate adoption (reinforcing effect), but the delayed implementation of new safety standards or compliance audits can temporarily elevate perceived risk, reducing acceptance and slowing market growth. Such dynamics have been documented in emerging hydrogen systems, where policy adaptation lag and risk communication latency have periodically destabilized investment cycles (Duan et al., 2020; Valera-Medina & Bowen, 2018).

In the SSP model, these delays serve a stabilizing function, preventing uncontrolled positive feedback escalation. The CLD structure ensures that delayed regulatory enforcement and infrastructural inertia provide temporal damping, thereby reproducing real-world system resilience through self-correction mechanisms. This representation aligns with FRISE's ability to explicitly model temporal delays and feedback adaptation, distinguishing it from static or probabilistic safety analyses that overlook the evolving character of risk and performance.

### ***Adaptive policy responses and cross-domain learning***

The inclusion of Investments in R&D, Energy efficiency, and Safety perception as medium-centrality nodes underscores the importance of adaptive policy mechanisms in maintaining a balance between innovation acceleration and risk control.

In particular, the high hub score of Energy efficiency and the strong authority scores of Economic viability and Market acceptance indicate that technical and socio-economic domains interact through bidirectional learning: technological improvements feed into economic viability, while market feedback drives renewed investment in innovation and safety (Blokland & Reniers, 2020).

This co-evolutionary process, represented through the FRISE “Systemic Glue Layer,” allows the system to self-regulate through information and knowledge feedbacks, ensuring that each subsystem (technical, safety, social) adapts in response to changes in the others.

The Safety and regulatory compliance loop (R4) is particularly relevant for adaptive governance. It links operational management and societal perception, showing how continuous compliance and transparent communication strengthen public confidence while enabling safe technology diffusion. As regulatory standards evolve, compliance investments generate learning that propagates through Technology maturity and Market acceptance, embodying the learning–feedback–adaptation triad central to FRISE’s dynamic management philosophy (Leveson, 2011; CCPS, 2023).

### ***Dominant loops and resilience implications***

The GT metrics help identify which feedback loops dominate systemic resilience and sustainability.

- R1 (Cost-driven adoption) and R5 (Energy efficiency and cost reduction) provide the accelerative backbone, reinforcing economic and technological progress.
- R4 (Safety and regulatory compliance) and R7 (Safety and market acceptance) provide socio-technical dampening, translating safety performance into legitimacy and stability.
- R6 (Technology maturity and standards compliance) acts as a mediating loop, synchronizing technical improvement with institutional adaptation.

Together, these loops ensure that innovation-driven growth does not compromise safety integrity or public trust. Within the FRISE architecture, this configuration demonstrates resilience by design—a property achieved not by eliminating feedbacks but by balancing them through adaptive policy mechanisms and time-dependent learning (Sala et al., 2025; Blokland & Reniers, 2020).

### ***Model Validation***

Model validation for the Safe Storage Pathways (SSP) application was carried out using a three-tiered procedure consistent with system dynamics best practices (Sterman, 2000; Forrester & Senge, 1980) and the validation logic established in the previous case studies (Sections 7.4.5 and 7.5.5). The objective was to ensure that the model structure, behaviour, and policy responsiveness accurately represent the real-world dynamics of hydrogen and ammonia storage safety.

#### ***Structural validation***

The causal architecture of the SSP model was validated through comparison with empirical and theoretical literature on hydrogen and ammonia storage systems. The identified feedback loops (R1–R8) correspond directly to mechanisms documented in process safety and energy transition studies, including cost–adoption coupling, maturity–safety interaction, and regulatory balancing (Valera-Medina et al., 2018; Apostolou & Xydis, 2019; CCPS, 2023). The structural fidelity of reinforcing and balancing feedbacks was also verified through expert consultation with specialists in hydrogen process safety and chemical storage systems, confirming the physical and managerial plausibility of each causal link in the CLD.

### *Behavioral validation*

Simulated dynamic behaviors generated by the SSP model—such as S-shaped adoption curves, delayed safety improvement, and oscillatory adaptation in investment and regulatory responses—were cross-compared with empirical data and trends reported in hydrogen and ammonia safety research (Duan et al., 2020; Khakzad et al., 2013). The model successfully reproduced realistic temporal patterns, including the early acceleration of technology uptake driven by efficiency gains, followed by stabilization through regulatory intervention and market maturity. This behavioural similarity provides evidence of internal consistency between the model’s feedback logic and observed real-world system evolution.

### *Policy response validation*

Sensitivity analyses confirmed that the model reacts logically to policy interventions and parameter changes. For instance, strengthening safety investment or accelerating R&D reduces long-term risk accumulation and stabilizes adoption growth, while delayed regulation or low inspection frequency increases volatility and reduces system resilience. These responses align with both theoretical expectations from the FRISE framework and historical policy lessons from hydrogen demonstration projects (Leveson, 2011; Blokland & Reniers, 2020).

The consistency of the model’s behavioral elasticity—its capacity to adjust to policy feedback—demonstrates that FRISE accurately integrates adaptive governance within the SSP context.

The evolution of risk and sustainability indicators across the GH<sub>2</sub> and NH<sub>3</sub> storage pathways demonstrates how feedback loops governing degradation, maintenance, and environmental impact interact over time. Delays in maintenance or adaptation of storage practices can amplify the divergence between storage options, particularly when reinforcing mechanisms dominate

the early stages. These dynamics emphasize the importance of timely interventions in shaping long-term safety and sustainability outcomes.

Overall, the validation process supports the conclusion that the SSP model is structurally sound, behaviorally realistic, and dynamically adaptive. It replicates key patterns of technological learning, safety adaptation, and socio-economic feedback observed in actual hydrogen and ammonia storage systems. This consistency confirms the FRISE framework's ability to model realistic, feedback-driven transitions between safety performance and sustainability outcomes, providing a credible foundation for further simulation-based policy testing and optimization.

### ***Concluding remarks***

The SSP case study consolidates FRISE's role as a systemic decision-support framework for managing the interdependence between safety, sustainability, and socio-economic viability in hydrogen infrastructure. By integrating causal feedbacks, delay effects, and adaptive policy functions, the framework enables a dynamic interpretation of risk evolution, technological learning, and public response—dimensions often treated independently in conventional analyses. The GT-derived insights provide quantitative evidence of structural centrality, highlighting adoption, economic viability, and technology maturity as critical leverage points for policy and investment.

In summary, the FRISE framework, applied to GH<sub>2</sub> and NH<sub>3</sub> storage pathways, captures not only the static hazards and benefits of each technology but also their dynamic evolution under feedback-driven adaptation. This ability to represent and analyze evolving safety–sustainability interactions positions FRISE as a robust methodological bridge between engineering system safety, policy learning, and sustainable energy transition research.

### **7.7- Concluding Remarks: Validation of the FRISE Framework through Multi-Domain Applications**

The three applications presented in this chapter collectively demonstrate the robustness, flexibility, and scientific validity of the FRISE (Feedback-based Risk and Sustainability Evaluation) framework as a systemic modelling approach for emerging energy systems. Across hydrogen safety, explosion management, and storage pathways, the framework successfully captured the multi-layered feedback dynamics linking technological performance, process safety, environmental sustainability, and socio-economic adaptation.

The first case study, focused on hydrogen system safety, validated FRISE's capacity to model dynamic risk escalation and interdependence between process failures and safety management investment. The results revealed how cumulative failures, cascading events, and safety barriers co-evolve under time-dependent degradation mechanisms such as hydrogen embrittlement.

The second case study, on explosion safety management during hydrogen enrichment, extended this capability by coupling physical hazard propagation with socio-technical response dynamics. The framework successfully represented delay effects, oscillatory policy reactions, and feedback-driven mitigation, demonstrating its ability to simulate adaptive risk management under evolving technological and human factors.

Finally, the third case study comparing  $\text{GH}_2$  and  $\text{NH}_3$  storage pathways integrated safety, efficiency, and market acceptance within a unified structure. The FRISE-based Safe Storage Pathways model quantitatively highlighted how adoption, safety perception, and economic viability interact as core levers for sustainable technology diffusion.

Across these domains, FRISE proved capable of capturing complex cross-domain couplings—including feedback reinforcement, temporal delays, and adaptation mechanisms—beyond the scope of traditional deterministic or probabilistic safety models. The consistent validation of structure, behavior, and policy response (Sections 7.4.5, 7.5.5, and 7.6.5) confirms the framework's scientific soundness and generalizability.

Graph-theoretic analyses further supported this validation by quantifying causal dominance and identifying critical systemic nodes such as Adoption rate, Explosion risk, and Safety management effectiveness, which act as leverage points for resilience enhancement and sustainability optimization.

The cross-case insights converge on three overarching findings:

- Safety and sustainability are dynamically co-dependent, requiring integrated modelling of technological, managerial, and perceptual feedbacks.
- Delays and adaptive responses are intrinsic to socio-technical resilience, underscoring the need for time-sensitive policy design and continuous learning mechanisms.
- Systemic leverage emerges from feedback coordination, not from isolated interventions—reinforcing the FRISE framework's principle of holistic system governance.

In conclusion, the results of Chapter 7 empirically validate FRISE as a transdisciplinary modelling and decision-support tool for hydrogen safety and sustainability. Its systemic and graph-based architecture enables a shift from reactive risk management to proactive, adaptive, and feedback-informed governance of complex energy infrastructures.

This validation establishes the foundation for the subsequent chapters, where FRISE is extended toward cross-sectoral coupling and multi-modular integration, consolidating its role as a general framework for complex system resilience analysis in sustainable energy transitions.

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## **Chapter 8 – Application II: Fire Safety Engineering**

This chapter applies the FRISE framework to the domain of Fire Safety Engineering (FSE), providing a second validation of its integrative and adaptive modeling capabilities. Through a combination of Causal Loop Diagrams (CLDs), Graph Theory (GT) metrics, and System Dynamics (SD) simulations, the chapter demonstrates how FRISE captures the multidimensional interactions between fire risk, sustainability performance, economic feasibility, and social acceptability. Three progressively integrated models are developed. The first model analyzes structural feedbacks between sustainability and fire safety using CLD–GT analysis, identifying key leverage points such as Fire risk, Sustainability level, and Material use. The second model applies SD techniques to simulate occupant risk during fire growth and evacuation, introducing probabilistic elements to account for uncertainty and enabling the quantification of dynamic safety indicators. The third model evaluates long-term investment decisions in fire safety measures through a dynamic cost–benefit framework incorporating ALARP and Life Quality Index (LQI) criteria. Collectively, these models demonstrate FRISE’s ability to translate systemic interdependencies into actionable insights across scales—from design to operation to policy—thus validating its role as a unifying framework for safety–sustainability integration within the built environment.

### **8.1- Introduction**

Fire Safety Engineering (FSE) has evolved into a multidisciplinary field that integrates physical sciences, human behavior, and system design to ensure the protection of life, property, and the environment. However, the increasing complexity of modern built environments—characterized by high-rise structures, innovative materials, and stringent sustainability targets—has exposed the limitations of traditional analytical methods based on linear or event-sequence models. These approaches often fail to capture the dynamic interdependencies between safety measures, resource allocation, and societal responses, which are essential for understanding the evolving nature of fire risk. In this context, the FRISE framework (Framework for Risk–Integrity–Safety–Sustainability Evaluation) offers a robust systems-based methodology for exploring such complexities. Developed in the previous chapters, FRISE integrates qualitative and quantitative modeling tools—Causal Loop Diagrams (CLDs), Graph Theory (GT), and System Dynamics (SD)—to represent, quantify, and simulate the dynamic feedback structures that govern safety performance and sustainability in complex systems.

This chapter applies the FRISE framework to Fire Safety Engineering as a second validation domain, complementing its earlier application to hydrogen safety and sustainability. The overarching goal is to demonstrate the framework's transferability across sectors, emphasizing its capacity to handle both technical and socio-economic dimensions of safety. In FSE, fire dynamics, human evacuation behavior, regulatory constraints, and sustainability objectives interact in non-linear ways, generating emergent outcomes that are not predictable from the behavior of individual components. By capturing these feedback effects, the FRISE framework facilitates a holistic understanding of how fire safety investments, operational policies, and societal expectations coevolve over time, revealing the trade-offs and synergies inherent in designing safe and sustainable buildings.

The application developed herein builds upon a series of recent studies that collectively form the empirical basis for this chapter. The first study explores the interactions between fire safety and sustainability in building design, proposing an integrated Causal Loop Diagram that maps the reinforcing and balancing feedback loops among key variables such as material selection, building height, façade combustibility, and protection systems (Dueñas Santana et al., 2025a). This conceptual model, complemented by Graph Theory analysis, identifies the dominant nodes and pathways shaping safety–sustainability trade-offs, offering insights into potential leverage points for policy and design interventions. The second study focuses on modeling occupant risk during fire growth and evacuation, using a System Dynamics approach to quantify how fire progression, smoke development, and crowd movement interact over time (Dueñas Santana et al., 2025b). By incorporating probabilistic elements to account for uncertainty in human response and fire growth rates, this model provides a dynamic estimation of occupant risk and fatality likelihood, thereby extending the Risk Assessment and Safety Management modules of the FRISE framework. Finally, the third study addresses cost–benefit decision-making in fire protection, applying the principles of ALARP (As Low As Reasonably Practicable) and the Life Quality Index (LQI) within a System Dynamics environment to evaluate the long-term economic and societal outcomes of fire safety investments (Dueñas Santana et al., 2024a, 2024b). Through this formulation, the model integrates time-dependent costs, maintenance expenses, and potential damages, allowing a dynamic visualization of net benefits across different safety scenarios.

Together, these three models form a coherent multi-layered application of FRISE to FSE. The first model (CLD–GT) captures the structural dependencies and systemic trade-offs that define the design stage, highlighting the interplay between sustainability objectives and fire safety

requirements. The second model (SD–Occupant Risk) focuses on the operational phase, simulating the dynamic evolution of occupant safety during fire emergencies. The third model (SD–CBA) provides a policy-oriented perspective, translating technical and behavioral outcomes into economic and societal implications through cost–benefit dynamics. This sequence mirrors the methodological logic of the FRISE framework—from structure to behavior to decision—ensuring a progressive integration of conceptual, analytical, and evaluative layers.

By extending FRISE to the domain of Fire Safety Engineering, this chapter contributes to bridging the existing gap between performance-based fire design and sustainability-driven policy frameworks. It emphasizes the necessity of adopting systemic approaches capable of representing delayed effects, feedback interactions, and cross-domain couplings between safety, economy, environment, and society. Furthermore, this chapter illustrates how FRISE can serve as a meta-framework for multidisciplinary decision support, guiding the transition from static compliance-based approaches to adaptive, learning-oriented systems for fire risk management. The ensuing sections elaborate on the contextual foundations of this application, the methodological setup, and the results of the three integrated modeling studies, ultimately demonstrating how the FRISE framework provides a unified basis for analyzing and improving fire safety within the broader pursuit of sustainable development.

## **8.2- Contextual Background: Complexity in Fire Safety Engineering**

Fire Safety Engineering (FSE) has traditionally been guided by deterministic principles derived from thermodynamics, combustion science, and structural behavior under fire exposure. These principles have served as the foundation for designing active and passive protection systems—such as detection, suppression, and compartmentation—and for developing standardized codes and performance-based regulations. However, as modern society increasingly demands energy-efficient, sustainable, and adaptable buildings, the structure and operation of built environments have become markedly more complex. This complexity arises not only from the technological sophistication of modern buildings but also from the intricate interactions among technical, human, environmental, and organizational subsystems (Dueñas Santana et al., 2024; Beard & Santos-Reyes, 2002). Fire safety performance in such systems can no longer be accurately represented as a linear cause–effect sequence, but rather as a dynamic network of interdependent feedback mechanisms that evolve over time.

Complexity in FSE manifests at multiple levels. At the technical level, the introduction of new construction materials—particularly lightweight composites and bio-based products used to reduce embodied carbon—has created conflicting objectives between sustainability and fire safety. Materials that are environmentally advantageous often exhibit higher combustibility or produce toxic smoke, thus introducing trade-offs between safety and environmental goals (Dueñas Santana et al., 2025a). Building energy systems, such as photovoltaic façades and integrated battery storage, further increase the number of potential ignition sources and interaction pathways, complicating traditional fire load assessments. At the organizational and behavioral levels, variability in human response, maintenance practices, and regulatory compliance introduces non-linearities and feedback effects that can amplify or dampen system performance over time. For example, delayed maintenance in detection or suppression systems may remain unnoticed until a fire incident occurs, at which point the resulting failure triggers intensified regulatory intervention and subsequent changes in management behavior—an archetypal feedback process characteristic of complex adaptive systems (Sterman, 2002).

Furthermore, the increasing adoption of performance-based design (PBD) has shifted the focus of FSE from prescriptive rules toward dynamic performance evaluation. While this approach allows for more flexible and innovative solutions, it also demands a systemic understanding of interdependencies among design variables, risk tolerance, and human factors (Meacham et al., 2021). In this evolving landscape, the need for systems-based approaches becomes evident. Systems Thinking (ST) and System Dynamics (SD) provide the methodological foundation to capture these feedback-rich relationships, enabling the transition from open-loop to closed-loop reasoning in fire safety decision-making (Dueñas Santana, 2024; Sterman, 2002). Unlike conventional quantitative models, which often isolate physical or probabilistic aspects of fire behavior, a systems approach situates these phenomena within their socio-technical context—considering how policies, budgets, human actions, and learning processes interact with physical fire dynamics.

Within this framework, the FRISE model introduced in earlier chapters provides a structured foundation for addressing complexity in FSE. The five core modules - Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC) - form an integrated system that mirrors the multifaceted nature of fire safety problems. In the FSE context, the RA module corresponds to the probabilistic characterization of ignition, fire growth, and escalation potential within buildings. It incorporates physical phenomena such as heat release rates, smoke propagation, and detection reliability, all of which influence the

expected frequency and severity of fire events. The SM module captures the organizational and procedural dimensions of safety, encompassing maintenance of detection and suppression systems, training of occupants, and the effectiveness of emergency response. These processes act as dynamic balancing mechanisms that stabilize system performance in response to perturbations.

The ECO module becomes particularly relevant when assessing cost–benefit trade-offs in implementing safety features under limited budgets. Decisions regarding investment in sprinklers, fire-resistant materials, or evacuation infrastructure are influenced by financial constraints, regulatory thresholds, and perceived benefits. The ALARP (As Low As Reasonably Practicable) principle, widely used in fire safety design, embodies the core logic of this module by balancing the marginal cost of safety improvements against their expected risk reduction benefits (HSE, 2001; Dueñas Santana et al., 2024a). In parallel, the ENV module introduces considerations related to the environmental consequences of fire events—such as emissions from burning materials, the embodied carbon of fire-resistant components, and the environmental footprint of safety systems themselves. Finally, the SOC module integrates human and societal dimensions, including life quality indices, public perception, and regulatory pressure, which shape both the acceptance of safety measures and the societal valuation of risk reduction (Dueñas Santana et al., 2024b; Meacham et al., 2023).

By linking these modules, the FRISE framework facilitates a holistic view of fire safety as a complex socio-technical system rather than a purely engineering problem. For instance, a decision to install an advanced detection system (SM) entails not only economic implications (ECO) but also influences social trust and public confidence (SOC), which can in turn affect compliance and operational performance. Similarly, material choices intended to enhance sustainability (ENV) may alter ignition risk and therefore influence the overall risk profile (RA). These multi-directional interactions are the defining characteristics of dynamic complexity—where cause and effect are separated in both space and time, and where delayed feedbacks can generate policy resistance or unintended consequences (Meadows, 1999).

In this light, applying the FRISE framework to FSE allows the representation of building systems as evolving entities governed by feedback structures rather than static relationships. It provides a means to trace how safety investments, regulatory policies, and public perception dynamically shape fire risk and sustainability outcomes over time. This systems perspective not only enhances predictive insight but also supports adaptive management—where safety

policies are continuously refined through learning and feedback. The next section (8.3) describes how this conceptual foundation is operationalized through a three-stage methodological approach integrating Causal Loop Diagrams, Graph Theory metrics, and System Dynamics simulation, thereby enabling the comprehensive analysis of safety–sustainability interactions within the built environment.

### **8.3- Methodological Setup for FRISE–FSE Application**

The methodological setup for applying the FRISE framework to Fire Safety Engineering (FSE) follows the same systemic reasoning that guided its earlier implementation in the hydrogen safety domain (Chapter 7). However, the fire safety application introduces additional challenges related to the behavioral dynamics of occupants, the multi-objective optimization between safety and sustainability, and the economic valuation of risk mitigation under uncertainty. To address these challenges, this section establishes a three-tiered analytical structure that reflects the hierarchical logic of the FRISE framework: structural analysis, dynamic behavior analysis, and decision analysis. Each tier corresponds to one of the three models developed for this chapter—namely, (1) a Causal Loop Diagram (CLD) and Graph Theory (GT) analysis of fire safety–sustainability trade-offs, (2) a System Dynamics (SD) model of occupant risk during fire growth and evacuation, and (3) a System Dynamics model for dynamic cost–benefit analysis of fire protection measures. Together, these models enable a comprehensive exploration of how safety performance, resource allocation, and societal acceptance coevolve within the built environment.

#### **8.3.1- Conceptual Foundations and Structural Coupling within FRISE**

Within the FRISE framework, the FSE system is conceptualized as an interlinked network of feedback loops distributed across the five core modules: Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC). Each module provides a different lens for interpreting system behavior, and their interconnections form what is referred to as the Systemic Glue Layer—a dynamic coupling that allows multidirectional information exchange and feedback propagation across modules. For instance, fire incidents (RA) influence public perception (SOC) and regulatory pressure, which in turn affect investment levels (ECO) and safety management practices (SM). Similarly, sustainability-driven material choices (ENV) modify fire propagation characteristics (RA) and reshape the overall safety–sustainability balance.

The methodological process starts with the qualitative identification of these interdependencies using Causal Loop Diagrams (CLDs). The CLD provides the structural blueprint of the system, capturing the polarity (positive or negative) and type (reinforcing or balancing) of each feedback relationship. Once the structure is defined, Graph Theory (GT) analysis is employed to extract quantitative insights about network topology—identifying central nodes, hubs, authorities, and critical pathways. This step provides a systematic assessment of which variables exert the greatest structural influence (e.g., building height, material choice, automatic suppression system) and which are most responsive to external interventions (e.g., regulatory pressure, maintenance quality, public acceptance). In this sense, CLD–GT modeling serves as the first methodological layer of FRISE–FSE integration, focusing on structure before behavior.

The second methodological layer uses System Dynamics (SD) modeling. SD allows for the explicit representation of feedback mechanisms, accumulation effects (stocks), and time delays (flows), which are central to understanding fire safety evolution. The SD formulation captures the nonlinear interactions between technical and human subsystems and allows testing the effectiveness of alternative policies under dynamic conditions. In this application, the SD approach is implemented in two distinct but complementary models: one focusing on occupant risk dynamics during fire and evacuation (Dueñas Santana et al., 2025b) and another addressing the dynamic cost–benefit evolution of fire safety measures (Dueñas Santana et al., 2024a). Both share a consistent system-structural logic derived from the FRISE framework but differ in their temporal focus and outcome variables. The occupant-risk model explores short-term behavioral dynamics during an emergency event, while the cost–benefit model assesses long-term socio-economic sustainability of safety investments.

Finally, the third methodological layer performs an integrative synthesis of the results from the three models. This stage examines how the feedback structures, behavioral dynamics, and economic trade-offs align within FRISE’s modular configuration. Cross-model coupling is analyzed through key variables that serve as inter-modular connectors—such as Safety Investment Level, Regulatory Pressure, Public Acceptance, and Available Financial Resources—which appear recurrently across the models and represent critical levers of systemic performance. The integration process thus enables the translation of local model insights into a global systemic narrative, reinforcing the transdisciplinary nature of FRISE.

### 8.3.2- Sequential Model Integration and Analytical Logic

The implementation sequence is carefully designed to maintain internal consistency and scientific progression across modeling stages, following the structure–behavior–decision logic of FRISE.

The first stage, Model 1: CLD and Graph Theory Analysis of Safety–Sustainability Trade-offs, establishes the foundational structural representation of the system. This model, developed from the study *A Systems Thinking Approach to Balancing Fire Safety and Sustainability in Building Design* (Dueñas Santana et al., 2025a), synthesizes the literature on sustainable construction materials, building geometry, and fire safety technologies into an integrated feedback structure. By quantifying network properties through Graph Theory metrics (PageRank, Betweenness, Eigenvector Centrality), the model identifies the most influential nodes and the dominant feedback mechanisms. These insights reveal the inherent conflicts and synergies between environmental and safety objectives, framing the systemic boundaries for subsequent modeling.

The second stage, Model 2: System Dynamics Model of Occupant Risk During Fire and Evacuation, captures the dynamic interaction between fire growth, smoke spread, and occupant evacuation. Developed in *Modeling Occupant Risk During Fire Growth and Evacuation Using a System Dynamics Approach* (Dueñas Santana et al., 2025b), the model includes stocks for occupants at risk, evacuating occupants, and fatalities. The flows between these stocks are controlled by parameters such as fire intensity, visibility, alarm response, and exit flow rate. Feedbacks between these parameters—such as the influence of smoke layer height on evacuation rate—allow simulation of real-time changes in occupant risk. Probabilistic modeling is introduced to represent uncertainty in human response times and fire growth scenarios, providing a robust framework for risk assessment under variable conditions. This stage corresponds primarily to the RA and SM modules of FRISE.

The third stage, Model 3: System Dynamics Model for Cost–Benefit Analysis of Fire Safety Measures, addresses long-term economic and societal implications of fire protection investments. Based on *Using System Dynamics for Cost–Benefit Analysis of Fire Safety Engineering Features* (Dueñas Santana et al., 2024a, 2024b), this model incorporates the ALARP principle and the Life Quality Index (LQI) as guiding metrics for evaluating risk acceptability and social welfare optimization. By modeling cumulative costs, cumulative damages, and cumulative benefits as interacting stocks, the model provides dynamic



visualizations of net benefits over time. Differences in cost evaluation between the private and societal perspectives are explicitly represented, aligning with the ECO and SOC modules of FRISE. The output of this model connects financial feasibility and societal acceptability to technical performance metrics derived from the previous stages.

### **8.3.3- Integrative Visualization and Cross-Model Coherence**

This methodological integration assures that FRISE's application to Fire Safety Engineering is not a collection of isolated models, but a unified analytical ecosystem capable of representing both micro-level behavioral dynamics and macro-level policy implications. The approach thus extends beyond conventional fire safety assessment by embedding safety performance within its broader social, economic, and environmental context—realizing the core vision of FRISE as a comprehensive framework for sustainable and adaptive safety management.

## **8.4- Model 1: Fire Safety–Sustainability Trade-offs (CL + GT Analysis)**

### **8.4.1- CLD development for Fire Safety-Sustainability Trade-offs**

This study demonstrates how Systems Thinking can be used to analyse and understand the complex interactions between fire safety and sustainability in building design by proposing a new conceptual model (CLD). This demonstration is done by a case study whereby a selected work of literature ((B. Meacham et al., 2023)) is analysed in depth. The methodology is systematically structured in four stages:

- (1) identification of causal relationships: using a scientific study (B. Meacham et al., 2023), causal relationships between relevant variables are established;
- (2) feedback loop development and classification: each loop is classified as either reinforcing or balancing based on the number of negative causal relationships;
- (3) integrated Causal Loop Diagram (CLD): all validated feedback loops are integrated into a unified CLD. This CLD provides a clear, visual representation of the interactions between fire safety and sustainability, highlighting explicitly the interdependencies and the resulting system behaviour.
- (4) Application of Graph Theory metrics to the developed CLD.

For developing the integrated Causal Loop Diagram and visualizing feedback structures, Vensim software is utilized considering its ease for creating clear, communicative CLD diagrams.

By investigating (B. Meacham et al., 2023), 18 feedback loops have been identified linked with the critical variables of fire safety and sustainability, such as building height, surface material,

façade combustibility, attic design, insulation type, window area, ventilation system, local energy system, cooking systems (stoves), inspection and maintenance routines, automatic extinguishing systems, advanced detection technologies, waste management, and building characteristics (Table 8.1).

**Table 8.1- Feedback loops integrated in the CLD for FSE**

| No. | Code | Loop                                    | Causal sequence                                                                                                                                                                                                      | Meaning                                                                                                                                                                                                                       |
|-----|------|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 01  | BL1  | Building height and material selection  | Building height → (+) Material Usage → (-) Sustainability Level → (-) Pressure for Sustainable Material (wood) → (+) Fire Risk → (-) Building height                                                                 | Taller buildings require more materials, lowering sustainability and increasing pressure for sustainable combustible materials (e.g., wood), which raises fire risk; the increased risk then limits further height increases. |
| 02  | RL1  | Surface material (concrete)             | Concrete Material Usage → (+) Carbon Footprint → (-) Sustainability Level → (-) Pressure for Sustainable Material (wood) → (+) Fire Risk → (+) Concrete Material Usage                                               | Greater concrete use worsens sustainability, creating pressure to reduce concrete use, indirectly increasing fire risk and ultimately reinforcing the need for concrete again.                                                |
| 03  | BL2  | Façade combustibility                   | Combustible Façade Material (FM) → (+) Fire Risk → (+) Required Fire Protection (FPL) → (+) Material Use → (-) Sustainability Level → (-) Pressure to increase sustainability → (-) Combustible Façade Material (FM) | More combustible façades raise fire risk and the need for protection, reducing sustainability and discouraging further combustible façade use—stabilizing façade design choices.                                              |
| 04  | BL3  | Attic openness and compartments         | Open Attic → (+) Fire Spread Rate → (+) Fire Risk → (+) Required Fire Protection (FPL) → (+) Material Use → (-) Sustainability Level → (+) Open Attic                                                                | Open attics increase fire risk, prompting more protection and material use, lowering sustainability and balancing design decisions on attic openness.                                                                         |
| 05  | BL4  | Open floor design and fire risk         | Open Floor Plan → (+) Flame Spread Rate → (+) Fire Risk → (+) Need for Partitioned Layout → (-) Open Floor Plan                                                                                                      | Open floor layouts accelerate flame spread and fire risk, leading to design corrections toward more compartmentation, stabilizing interior openness.                                                                          |
| 06  | BL5  | Windows and insulation – fire risk      | Window Area → (-) Energy Efficiency → (-) Need for Insulation → (+) Amount of Flammable Material → (+) Fire Risk → (-) Window Area                                                                                   | Larger window areas reduce energy efficiency, prompting more insulation with combustible materials and elevating fire risk, which then reduces window size—producing oscillatory equilibrium.                                 |
| 07  | BL6  | Windows and insulation – sustainability | Window Area → (-) Energy Efficiency → (-) Need for Insulation → (+) Material Use → (-) Sustainability Level → (-) Pressure to reduce window area → (-) Window Area                                                   | Window size affects energy efficiency and sustainability, leading to counter-pressures that stabilize optimal window proportions.                                                                                             |
| 08  | BL7  | Ventilation systems trade-off           | Fire Dampers (Mechanical Ventilation) → (-) Fire Risk → (+) Material Use → (-) Sustainability Level → (-) Fire Dampers (Mechanical Ventilation)                                                                      | Mechanical dampers enhance safety but increase material use and lower sustainability, prompting shifts toward natural ventilation—balancing ventilation design.                                                               |

| No. | Code | Loop                                     | Causal sequence                                                                                                                                                                        | Meaning                                                                                                                                                          |
|-----|------|------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 09  | BL8  | Local energy production and fire safety  | Local Energy Production Capacity → (+) Fire Load → (+) Fire Risk → (+) Need for Fire Protection → (+) Material Use → (-) Sustainability Level → (+) Local Energy Production Capacity   | Increasing on-site energy production elevates fire risk and material demand, reducing sustainability and feeding back on local-generation choices.               |
| 10  | BL9  | Gas stoves – fire safety                 | Gas Stoves → (+) Ignition Sources → (+) Fire Risk → (-) Gas Stoves                                                                                                                     | Gas stoves heighten ignition potential, raising fire risk and discouraging their continued use, balancing adoption levels.                                       |
| 11  | BL10 | Gas stoves – sustainability              | Gas Stoves → (+) Carbon Footprint → (-) Sustainability Level → (-) Pressure toward Electric/Induction Stoves → (-) Gas Stoves                                                          | The high carbon footprint of gas stoves triggers shifts toward cleaner cooking technologies, reinforcing the transition to electric or induction systems.        |
| 12  | BL11 | Inspection and maintenance quality       | Inspection Quality → (+) Reliability of Protection Systems → (-) Fire Risk → (+) Perceived Need for Inspection → (+) Inspection Quality                                                | Better inspection improves system reliability and reduces fire risk; higher perceived risk further motivates inspection efforts—creating a stabilizing feedback. |
| 13  | BL12 | Automatic extinguishing – sustainability | Sprinkler Coverage → (+) Material Use → (-) Sustainability Level → (-) Pressure to reduce Sprinkler Coverage → (-) Sprinkler Coverage                                                  | Greater sprinkler coverage lowers sustainability, producing corrective pressure that limits excessive system expansion.                                          |
| 14  | BL13 | Automatic extinguishing – fire safety    | Sprinkler Coverage → (-) Fire Risk → (+) Perceived Need for Sprinkler Coverage → (+) Sprinkler Coverage                                                                                | Expanded sprinkler coverage decreases fire risk, which in turn moderates the motivation for further investment, balancing safety levels.                         |
| 15  | BL14 | Advanced detection – sustainability      | Advanced Detection System (ADS) → (+) Material Use → (-) Sustainability Level → (-) Pressure to reduce ADS → (-) ADS                                                                   | More advanced detection increases material use and reduces sustainability, leading to pressures that limit over-installation.                                    |
| 16  | BL15 | Advanced detection – fire safety         | Advanced Detection System (ADS) → (-) Fire Risk → (+) Need for ADS → (+) ADS                                                                                                           | Improved detection lowers risk and thus the urgency for further expansion, generating natural equilibrium in ADS deployment.                                     |
| 17  | BL16 | Indoor waste storage                     | Indoor Waste Storage → (+) Fire Risk → (+) Required Fire Protection (FPL) → (+) Material Use → (-) Sustainability Level → (+) Preference for Indoor Storage → (+) Indoor Waste Storage | Storing waste indoors increases fire risk and reduces sustainability, eventually discouraging excessive indoor storage.                                          |
| 18  | BL17 | Site vegetation and accessibility        | Vegetation → (+) Sustainability Level → (+) Landscaping → (-) Firefighter Accessibility → (-) Fire Risk → (-) Vegetation                                                               | Vegetation enhances sustainability but impedes fire-service access, increasing fire risk and prompting vegetation control, stabilizing green-area design.        |

The analysis based on the set of 18 feedback loops reveals a complex interplay between sustainability and fire safety in building design, explicitly represented through distinct reinforcing (RL) and balancing loops (BL). Reinforcing loop RL1 (Surface material selection) underscores inherent systemic instabilities where increasing concrete usage raises the carbon footprint, lowers sustainability, increases pressure for sustainable materials (such as wood),

subsequently increasing fire risk, and eventually reinforcing the use of concrete again. Such loops highlight points of potential escalation or instability requiring active management and intervention.

Balancing loops, including BL1 (Building height and material selection), emphasize natural regulatory dynamics (Dueñas Santana et al., 2024). For example, increased building heights elevate material use, negatively impacting sustainability, which increases pressure for combustible sustainable materials like wood. The resultant higher fire risk eventually limits building height, achieving a self-balancing equilibrium. Similar stabilization effects are seen in loops BL2 (Façade combustibility), BL3 (Attic openness), BL4 (Open floor design), BL5 and BL6 (Windows and insulation materials), and BL7 (Ventilation systems). The current analysis implicitly assumes insulation materials as predominantly plastic-based and thus inherently combustible. Loops BL8 (Local energy production), BL9 and BL10 (Gas stoves regarding fire safety and sustainability, respectively), BL11 (Inspection quality), and BL12 and BL13 (Automatic extinguishing systems) collectively manage dynamic trade-offs, balancing material usage, safety, and sustainability impacts. Likewise, loops BL14 and BL15 (Advanced detection systems concerning sustainability and fire safety), BL16 (Indoor waste storage), and BL17 (Site vegetation and accessibility) explicitly illustrate the self-corrective dynamics present in the system, preventing extremes in either sustainability or fire safety measures.

The identification between balancing and reinforcing loops facilitates a deeper understanding of systemic dynamics. The integrated Causal Loop Diagram (CLD) based on these loops highlights predominant balancing feedback, demonstrating inherent robustness and equilibrium tendencies in the system. Following explicit identification and correction, an integrated CLD is developed to visualize the holistic interplay of these loops clearly (Fig. 8.1-8.2). After the integration of the 18 developed feedback loops, 111 new loops emerged starting from the variable “Fire risk”, while 109, from “Sustainability level”, indicating a highly-interconnected system. The integrated CLD, combining all loops explicitly, illustrates the dynamic interplay between fire safety and sustainability, identifying a predominant presence of balancing loops. The preponderance of balancing loops explicitly indicates a robust system that naturally regulates itself towards equilibrium states, moderating extreme behaviors. However, reinforcing loops remain critical focal points for active management to prevent unintended escalations, especially in areas related to material choices. The CLD analysis provides a refined perspective emphasizing equilibrium-maintaining mechanisms while explicitly highlighting areas of potential instability requiring strategic oversight.

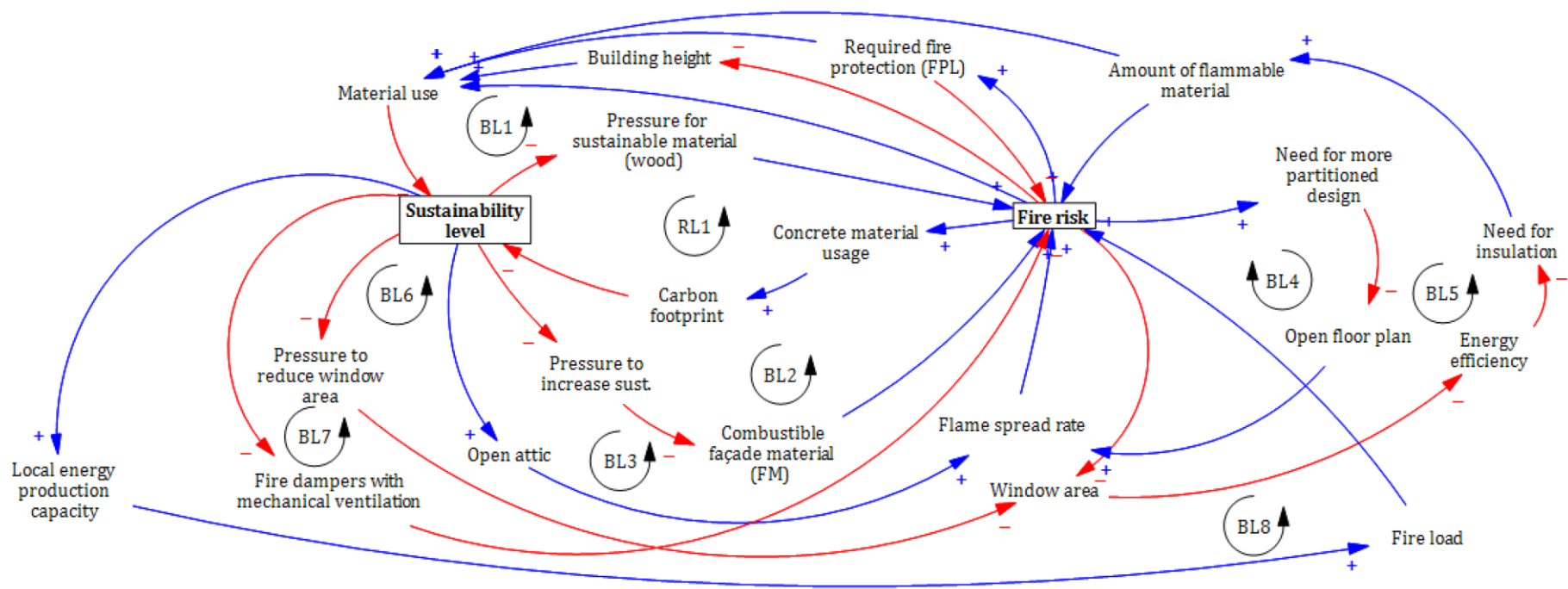


Fig 8.1- Causal Loop Diagram for balancing sustainability and fire safety considering the integrated feedback loops 01-09

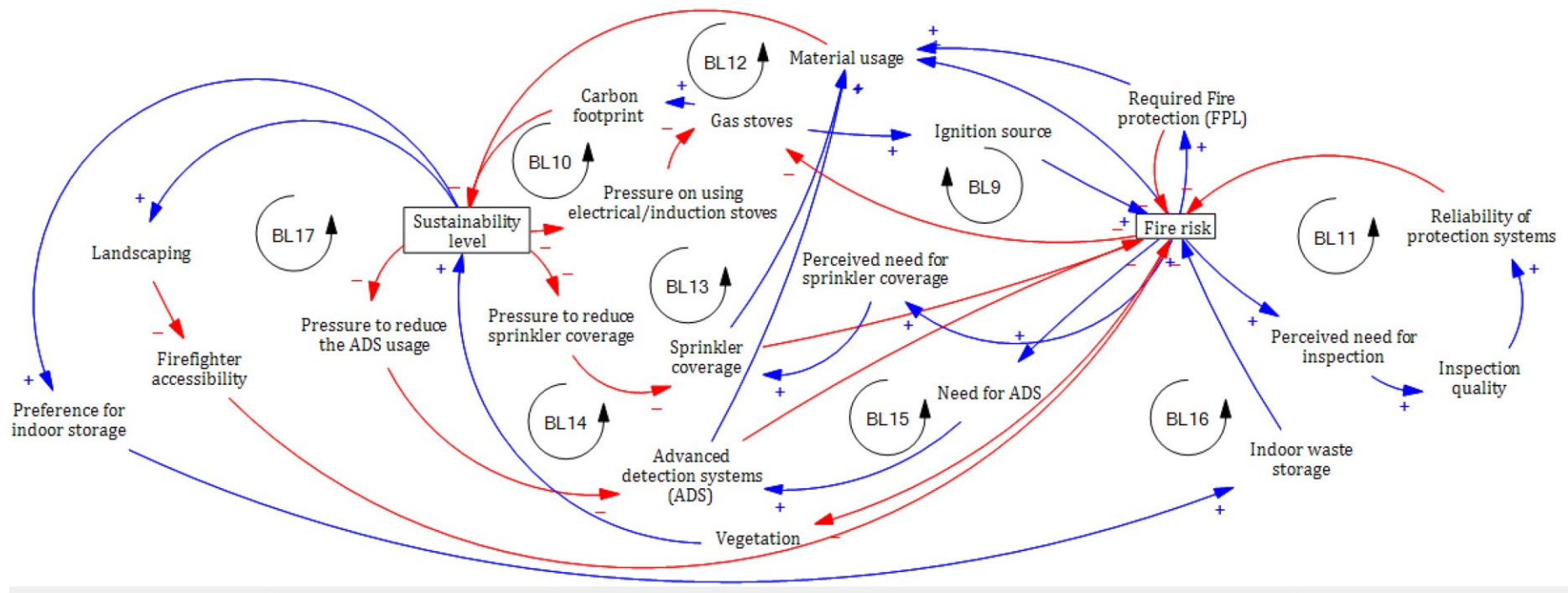


Fig 8.2- Causal Loop Diagram for balancing sustainability and fire safety considering the integrated feedback loops 10-18

#### **8.4.2- Graph Theory Analysis of the Fire Safety–Sustainability CLD**

The graph-theoretic (GT) analysis performed on the Fire Safety Engineering (FSE) causal loop diagram (CLD) provides quantitative insight into the network structure linking safety, sustainability, and technological variables within the FRISE framework. The resulting directed network comprises 46 nodes and 120 signed causal connections, representing positive and negative feedbacks among design, management, and risk-related factors. The analysis reveals a highly interconnected system where Fire risk and Sustainability level act as the primary hubs and integrators of systemic behavior.

##### ***Network Centrality Results***

The PageRank distribution (Figure 8.3) shows that Fire risk (0.161) holds the dominant structural importance within the network, followed by Sustainability level (0.117), Material use (0.093), and Required fire protection (FPL) (0.046). These nodes form the core of the system's causal architecture. Their high PageRank and eigenvector centrality values indicate that they are not only heavily connected but also linked to other influential nodes, amplifying their systemic impact. The close coupling between Fire risk and Sustainability level confirms their reciprocal influence: increased material demand or fire protection measures reduce sustainability, while lower sustainability targets encourage the adoption of flammable materials, closing the feedback loop.

The betweenness centrality analysis further emphasizes Fire risk (1028.9) and Sustainability level (742.1) as critical mediators of information flow through the network. High betweenness values signify that these nodes lie on a large proportion of causal paths, suggesting they control the propagation of changes between otherwise weakly connected subsystems. In practice, this means that policy or design interventions aimed at either variable will reverberate through multiple domains—ranging from material selection and energy efficiency to safety management and regulatory compliance. Material use also displays elevated betweenness (266.2), reflecting its role as a structural intermediary linking safety performance to sustainability indicators.

Nodes associated with protective systems, such as Sprinkler coverage, Advanced detection systems (ADS), and Required fire protection (FPL), exhibit moderate centrality values and comparable PageRank scores (~0.026). This suggests that although these elements are essential to mitigating fire risk, their influence remains localized within the safety management subsystem. By contrast, Carbon footprint and Energy efficiency form connecting bridges

between environmental and safety considerations. Their intermediate betweenness scores (~70–150) reflect their function as translators of sustainability targets into material and design trade-offs.

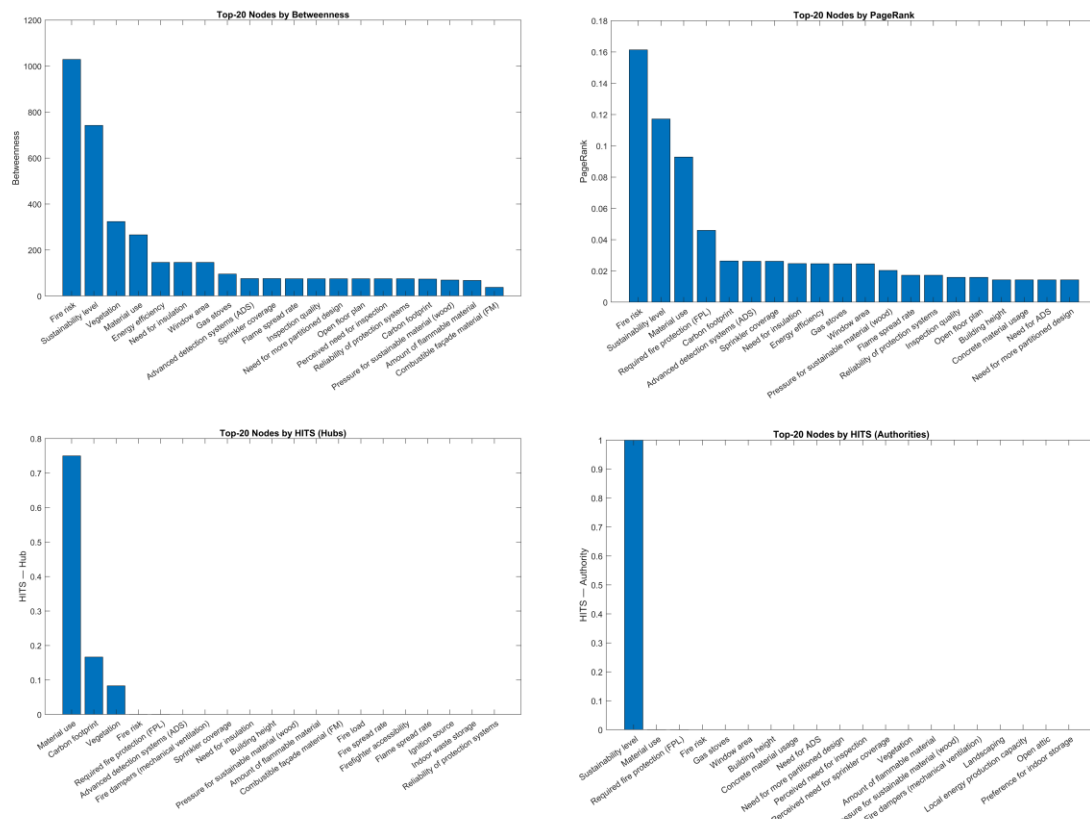


Fig. 8.3- GT results of the developed CLD for FSE

### HITS Analysis and Network Roles

The Hyperlink-Induced Topic Search (HITS) algorithm offers complementary insights into the structural hierarchy of the CLD. The hub–authority decomposition highlights Material use and Carbon footprint as the most significant hubs (values > 0.7), meaning they serve as principal sources of outgoing influence across the system. Their causal outputs reach multiple subsystems—from environmental performance to fire dynamics—underscoring the multidimensional implications of material choices. Conversely, Sustainability level and Fire risk emerge as the dominant authorities (scores > 0.9), representing endpoints that integrate the incoming effects from various nodes. The asymmetry between hub and authority distributions indicates a strongly hierarchical structure, where a few design variables (notably material-related) exert disproportionate control over systemic outcomes.



### ***Interpretation within the FRISE Framework***

Overall, the GT results corroborate the qualitative findings from the CLD interpretation. The FSE system is characterized by a dense web of feedbacks connecting design choices, operational safety, and sustainability objectives. The prominence of Fire risk and Sustainability level confirms the structural duality of the framework: the former anchors the Safety Management (SM) and Risk Assessment (RA) modules, while the latter represents the Environmental (ENV) and Economic (ECO) dimensions. Their interdependence defines the principal feedback loop of the FRISE–FSE model, mediating trade-offs between protective investments, environmental burdens, and societal expectations.

Moreover, the high harmonic closeness of Sustainability level (0.55) compared to Fire risk (0.53) indicates that sustainability-related effects propagate more evenly across the network, while safety-related effects are more concentrated around key structural links. This suggests that sustainability-oriented policies (e.g., low-carbon materials or energy efficiency standards) can indirectly influence a broader set of variables over time, whereas safety interventions have faster but more localized impacts.

In summary, the GT analysis validates the conceptual understanding of fire safety–sustainability interactions as a core attractor structure within the FRISE framework. It identifies Fire risk, Sustainability level, and Material use as leverage points whose regulation is essential for achieving balanced design policies. The results also reveal that introducing systemic metrics, such as PageRank or betweenness centrality, provides a quantitative means to prioritize interventions across socio-technical networks.

## **8.5- Model 2: Dynamic Model of Occupant Risk During Fire and Evacuation (SD)**

### **8.5.1- Conceptual foundations for model 2**

This model is developed following the methodology shown in Figure 8.3 is divided into five main stages. Stage 1 focuses on identifying and connecting the factors linked with occupant risk during fire growth and evacuation. For this purpose, a review of the state-of-the-art is conducted, specifically, the SFPE Handbook of Fire Protection Engineering is adopted (Hurley et al., 2016). After that, an SD model is built to compute the expected number of occupants at risk, the number of occupants being evacuated, and the expected fatalities. This estimation is done by defining three stocks (which represent the cumulative levels of each variable). In order to estimate the probability of fatality (necessary for the fatality rate), probabilistic models are introduced (Stage 3) which allow also for considering the uncertainties in the dynamic risk

computation. Next, a case study is chosen for a generic retail store and simulated using the developed SD model. By analyzing the simulation results, different areas related to the occupant movement during evacuation are identified which can help for informed decision-making. Finally, Stage 5 aims to assess different scenarios (by varying the control variables) for obtaining the dynamic occupant risk profiles and their effects on each identified area (or phase) during the evacuation. Occupants at risk is computed according to the Eq. (8.1), where  $A_E \times p''$  (area of the enclosure times the occupant load density), represents the number of occupants at risk at the beginning of the fire.

$$\text{Occupants at risk} = A_E \times p'' - \int_0^t (\text{Evacuation rate} + \text{Fatality rate}) dt \quad (8.1)$$

The number of occupants at risk is decreased by the effect of the evacuation rate (which represents the number of occupants being evacuated per time) and the fatality rate (which refers to the number of fatalities occurring per time). Equations 8.2 and 8.3 represent the stocks “Occupants evacuated” and “Fatalities” respectively.

$$\text{Occupants evacuated} = \int_0^t (\text{Evacuation rate}) dt \quad (8.2)$$

$$\text{Fatalities} = \int_0^t (\text{Fatality rate}) dt \quad (8.3)$$

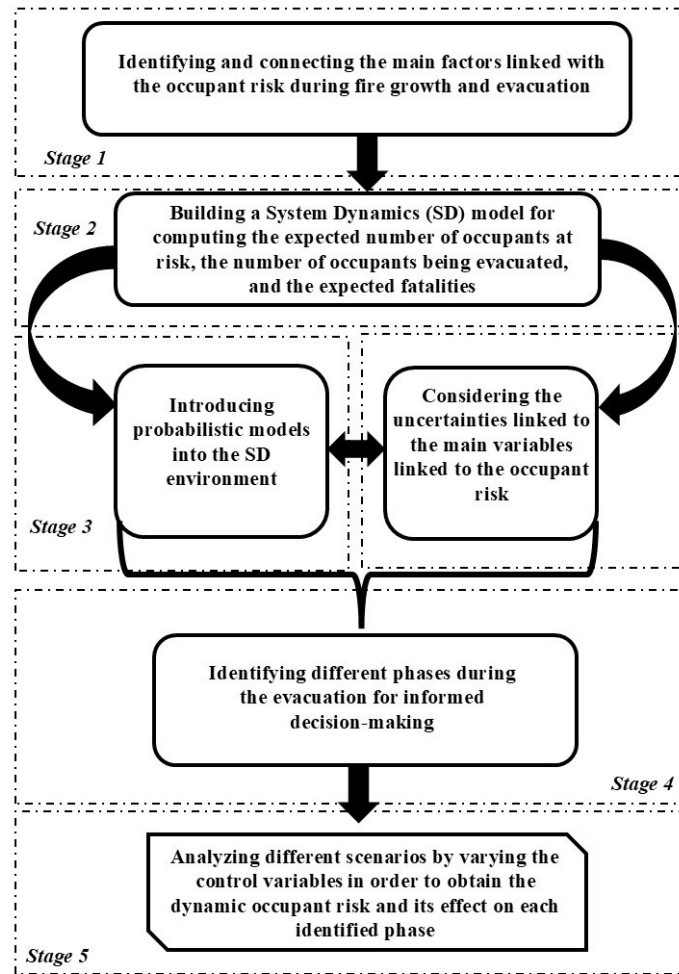


**Fig. 8.4- Methodology proposed for model 2 development**

According to the hydraulic model for assessing emergency movement, the safe egress can be determined by a comparison between the Required Safe Egress Time (RSET) and the Available Safe Egress Time (ASET). The RSET represents the required time until a safe place is reached for each occupant, while the ASET represents the time until the untenable conditions are reached. Therefore if the RSET is below the ASET, the occupants at risk reached a safe place before the untenable conditions occurred. In this research, the untenable conditions are defined by when the smoke layer height reaches a critical smoke-free layer height (following the two-zone model structure). In the developed model, the smoke layer height is compared against the critical height, taking into account uncertainties in the fire development. For this purpose, it is necessary to introduce probabilistic models into the SD for considering uncertainties linked to the fire development and evacuation factors (Table 8.2).

The Required Safe Egress Time (RSET) is computed according to Eq. (8.4).

$$RSET = t_{\text{detection and warning}} + t_{\text{recognition and response}} + t_{\text{travel and queuing}} \quad (8.4)$$

The “Evacuation rate” is determined by considering the following assumptions: (1) It is activated after a delay time (the RSET) is reached. In other words, the successful evacuation for a generic occupant can only be achieved after the RSET (for this person). For this purpose a delay function (software *Vensim*) is used; (2) Once the rate is active, the flow of persons depends on the occurrence (or not) of queue conditions: if the occupant flow rate is below the flow capacity of the door then the evacuation rate is controlled by the individual RSET, otherwise the evacuation rate is controlled by the flow capacity of the door (queue formation).

The “Fatality rate” depends on the number of occupants at risk and on the probability of fatality. For computing the probability of fatality, it is necessary to assess the untenable conditions which are represented by the comparison of the smoke layer elevation with the critical smoke-free layer height. For this purpose, a Boolean function is introduced which takes the value of 1 when the smoke layer elevation reaches the critical smoke fire layer height and 0 otherwise.

**Table 8.2- Probabilistic models introduced in the SD environment (De Sanctis, 2016)**

| Random variable                              | Probability Distribution | Expected value                 | Standard deviation            |
|----------------------------------------------|--------------------------|--------------------------------|-------------------------------|
| Fire growth rate (kW/s <sup>2</sup> )        | Lognormal                | 0.0236                         | 0.03                          |
| Critical smoke-free layer height (m)         | Lognormal                | 1.8                            | 0.16                          |
| Model uncertainty (smoke)                    | Normal                   | 1.0                            | 0.1                           |
| Occupant load density (pers/m <sup>2</sup> ) | Gamma                    | 0.076                          | 0.068                         |
| Model uncertainty (alarm) (s)                | Normal                   | 0                              | 0.32                          |
| Door flow capacity (pers/s/m)                | Normal                   | 1.75                           | 0.11                          |
| Model uncertainty RSET                       | Lognormal                | 1                              | 0.2                           |
| Recognition and response time (s)            | Lognormal                | 32                             | 16                            |
| Movement velocity- <i>v</i> (m/s)            | Weibull                  | 1.34                           | 0.16                          |
| Location <i>x</i> (m)                        | Uniform <sup>a</sup>     | $-\sqrt{2}/2 \cdot \sqrt{A_E}$ | $\sqrt{2}/2 \cdot \sqrt{A_E}$ |
| Location <i>y</i> (m)                        | Uniform <sup>a</sup>     | 0                              | $\sqrt{2}/2 \cdot \sqrt{A_E}$ |

<sup>a</sup> For the Uniform distribution, lower and upper bounds are listed instead of the expected value and standard deviation.

In order to consider a realistic approach, both the evacuation and fatality rates depend on the number of occupants still at risk at a given time, closing two feedback loops (balancing loops). This dynamic consideration is one of the main advantages of SD modeling.

The relative smoke layer elevation at time  $t$  ( $z_l/H$ ) is calculated according to Eq. (8.5), where  $k_v$  is the entrainment coefficient,  $\alpha_n$ , the fire growth rate and  $H$  is the enclosure height.

$$\frac{z_L}{H} = \left[ 1 + \frac{2 \cdot k_v \cdot \alpha_n^{1/3} \cdot t^{5/3}}{5 \cdot \left( \frac{A_E}{H^2} \right) H^{4/3}} \right]^{-3/2} \quad (8.5)$$

The time for travel and queuing is determined by Eq. (8.6); while the time for detection and warning is calculated using Eq. (8.7) in the case of detection by the fire alarm system, and following an exponential distribution with parameter  $\lambda$  as shown in Eq. (8.8) in the case of visual detection.

$$t_{travel \text{ and } queuing} = \frac{\sqrt{x^2 + y^2}}{v} \quad (8.6)$$

$$t_{detection \text{ and } warning} = 2.511 - 0.364 \cdot \log(\alpha_n) + e(alarm) \quad (8.7)$$

$$\lambda = -\log(0.01) \cdot \sqrt{\frac{\alpha_n}{50}} \quad (8.8)$$

For testing scenarios considering different fire alarm delays, this variable is added to the SD model, and connected directly with the time for detection and warning in the case of detection by the fire alarm system.

### 8.5.2- Developing the System Dynamics model (Stages 1-3)

The SD model depicted in Fig. 8.5 provides a visual framework for analyzing the interaction between fire growth and evacuation processes. It captures fire progression through variables such as critical smoke layer height and relative smoke layer elevation.

Detection and recognition are influenced by delays and uncertainties, reflecting real-world variability in occupant response times. The model also incorporates occupant dynamics, tracking the number of individuals at risk and their movement during evacuation. Factors like velocity, queuing effects, and congestion are modeled alongside door flow capacity and specific flow, which determine the evacuation rate.

A key feature of the model is its feedback loops, where fire growth increases the risk to occupants, while efficient evacuation reduces the population exposed to danger. Delays in alarm activation or queuing congestion exacerbate risks, highlighting the importance of minimizing response times. The model integrates Required Safe Egress Time (RSET), encompassing detection, recognition, and movement times, to assess the safety of occupants. Additionally, probabilistic components, such as uncertainty in fire growth and detection systems, add realism to predictions, enabling the calculation of critical outcomes like evacuation success rates and probabilities of fatality. The model serves as a tool for evaluating fire safety in enclosed spaces by simulating dynamic interactions between fire and evacuation processes.

A linear evacuation model treats fire growth, smoke spread, detection, and evacuation as separate, one-way processes with fixed rates, failing to account for dynamic interactions like congestion, adaptive response times, and evolving risk levels. This oversimplification could lead to inaccurate predictions of fatalities and evacuation efficiency. In contrast, a feedback-loop-based model continuously updates variables based on real-time conditions for instance dynamically altering evacuation rate based on congestion.

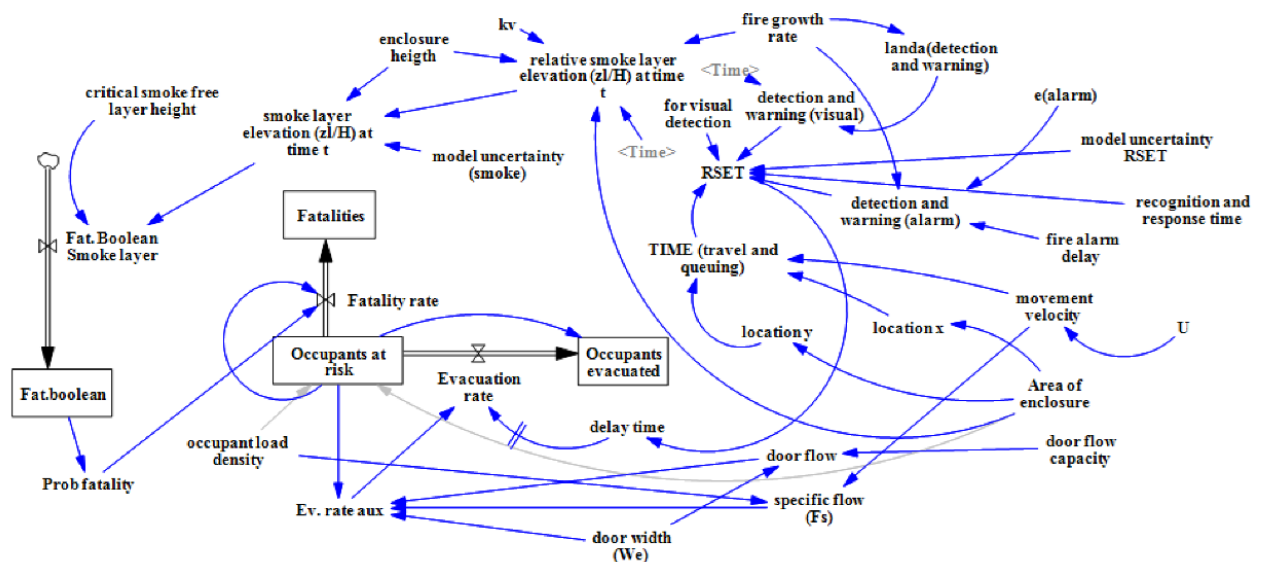


Fig. 8.5- SD developed for model 2

### 8.5.3- Identifying evacuation phases by using the developed SD model (Stage 4)

The input data for analyzing a first case study consisting of a retail store of 9000 m<sup>2</sup> (Area of the enclosure), door width of 1.5 m, fire alarm delay of 60 seconds, and enclosure height of 3.5 m. Figure 8.6 illustrates the simulation results of the SD model for this case study. The graph is divided into four distinct areas: A1, A2, A3, and A4, representing different stages of the incident and response. Three curves are depicted: the blue line for "Occupants at risk," the green line for "Occupants evacuated," and the red line for "Fatalities."

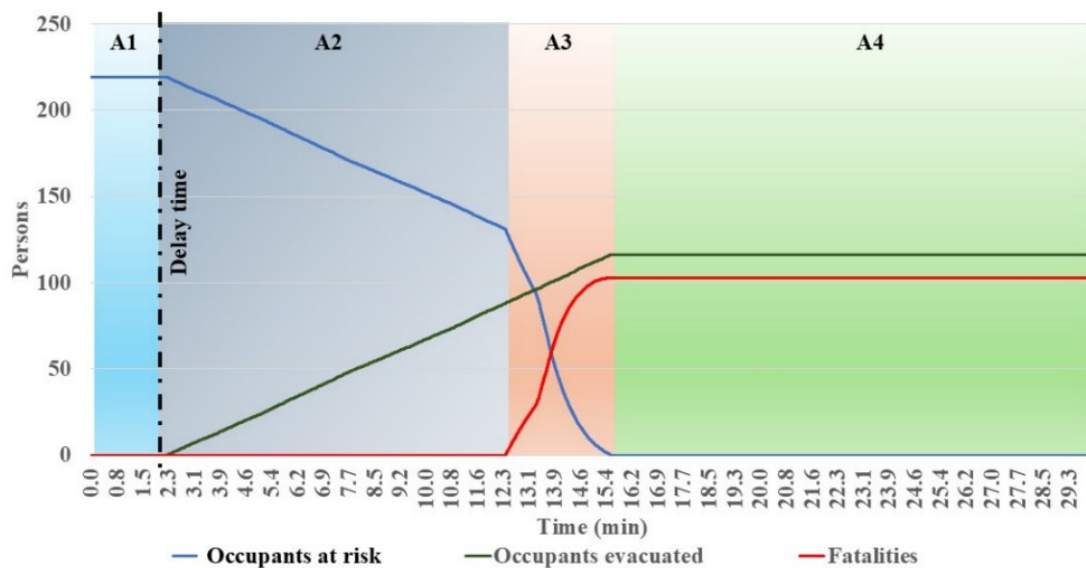


Fig. 8.6- Simulation results from the application of the SD model for a case study

In Area A1, the fire incident is at its initial stage, and the delay time before evacuation begins is evident. During this time, no occupants are evacuated, and no fatalities are recorded. The "Occupants at risk" curve remains constant at a high level, reflecting the total number of individuals present before evacuation efforts commence. This delay time indicates the time taken for the evacuation (RSET).

Moving into Area A2, evacuation begins as reflected by the gradual decrease in the "Occupants at risk" curve and the corresponding increase in the "Occupants evacuated" curve. The transition from A1 to A2 marks the onset of evacuation procedures, where the system effectively starts reducing the number of people exposed to risk. The slope of these curves reflects the efficiency of the evacuation process; a steeper slope suggests faster evacuation, while a gentler slope indicates slower progress. During this stage, fatalities remain minimal or

absent, suggesting that the evacuation process is successfully managing the situation for the majority.

In Area A3, the dynamics become more critical. This stage represents the situation where there is a probability that the critical smoke-free layer height is reached by the actual smoke layer. The "Fatalities" curve begins to rise sharply during this period, indicating the failure to evacuate all individuals safely.

Finally, in Area A4, the incident stabilizes, marked by the plateauing of all three curves. The "Occupants at risk" curve reaches zero, indicating that no one remains in a hazardous situation. The "Occupants evacuated" curve stabilizes at its maximum value, representing the total number of successfully evacuated individuals. The "Fatalities" curve also levels off, showing the final count of lives lost. This stage reflects the resolution of the event, where all dynamic processes related to risk and evacuation have concluded.

Overall, this figure provides a comprehensive visualization of the evacuation process under fire conditions, highlighting the importance of minimizing delay time (A1) and maximizing the efficiency of evacuation (A2 and A3) to reduce fatalities (A3 and A4). This enhances informed risk management during evacuation.

#### 8.5.4- Analyzing different scenarios during the evacuation (Stage 5)

The final stage consists of performing different scenarios considering a credible variation of the variables: fire alarm delay, door width, area of the enclosure, enclosure height, and distinguishing between fire visual detection or fire detection by the alarm.

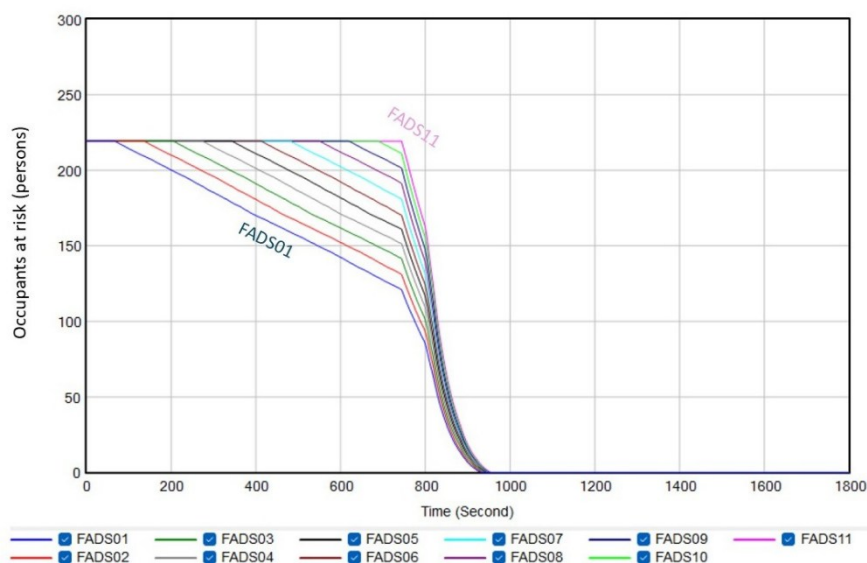


Fig. 8.7- Simulation results for the “Occupants at risk” for different fire alarm delays



Figures 8.7-8.9 present the outcomes of the SD model simulating fire evacuation scenarios under varying Fire Alarm Delay (FAD) times, ranging from 0 seconds (FADS01) to 600 seconds (FADS11), with a step of 60 seconds per scenario. These scenarios analyze the impact of delay times on the number of occupants at risk, the number of evacuated occupants, and the number of fatalities.

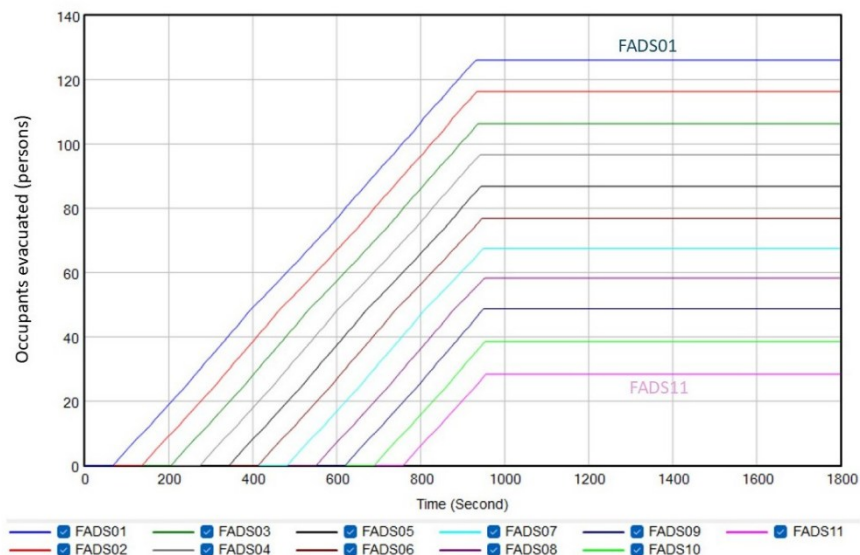


**Fig. 8.8- Simulation results for the “Occupants evacuated” for different fire alarm delays**

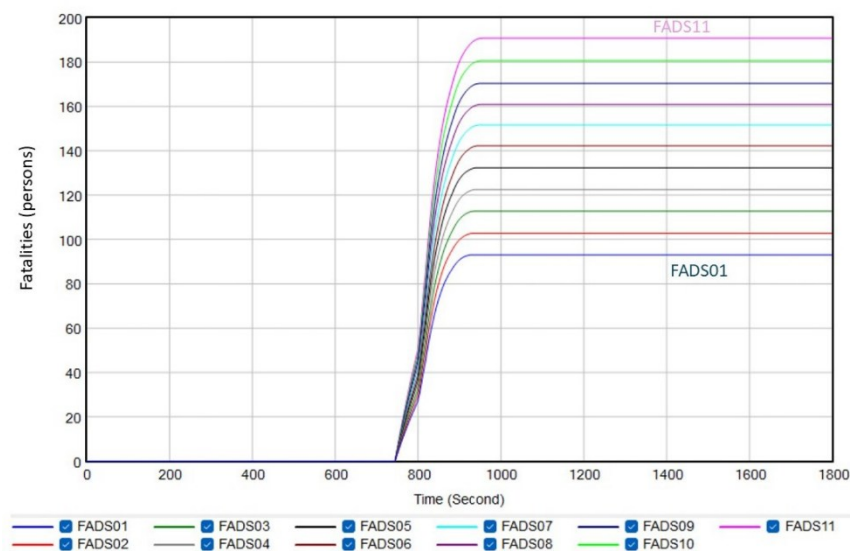


**Fig. 8.9- Simulation results for the “Fatalities” for different fire alarm delays**

Figure 8.7 illustrates the occupants at risk as a function of time for the 11 scenarios. In FADS01 (0-second delay), the number of occupants at risk decreases rapidly due to immediate alarm activation and prompt evacuation initiation. For scenarios with increasing FAD times (e.g., FADS03, FADS05, FADS11), the downward slope becomes progressively delayed and less steep. This indicates that occupants remain at risk for longer periods in scenarios with extended alarm delay times, as evacuation starts later. For FADS11 (600 seconds), the delay leads to a significant proportion of occupants remaining at risk for a prolonged time, highlighting the critical impact of delayed alarms.

Figure 8.8 shows the number of occupants evacuated over time. In scenarios with shorter FAD times (FADS01 and FADS02), evacuation begins earlier and progresses more quickly, reaching a higher number of evacuated occupants in a shorter timeframe. Conversely, scenarios with longer FAD times (e.g., FADS09 and FADS11) experience a delayed onset of evacuation, and the total number of evacuees is markedly lower. This delayed evacuation initiation underscores the reduced efficiency of evacuation efforts as alarm delays increase, particularly in high-risk scenarios.

Figure 8.9 presents the number of fatalities over time. For FADS01, the fatalities are minimal in the beginning compared to the other scenarios. However, as FAD times increase (e.g., FADS05, FADS09, and FADS11), the fatalities rise significantly. In FADS11, where the delay reaches 600 seconds, the fatalities are the highest, with a steep rise occurring after the delayed evacuation starts. This figure demonstrates the severe consequences of extended alarm delays, where prolonged exposure to hazardous conditions leads to a greater number of casualties.

In summary, these figures collectively emphasize the critical importance of minimizing fire alarm delays to ensure rapid evacuation and reduce both the number of occupants at risk and fatalities. Scenarios with shorter FAD times exhibit better outcomes in terms of evacuation efficiency and safety, while longer delays result in delayed evacuation, higher risks, and a significant increase in fatalities.

Figures 8.10-8.12 illustrate the results under varying door width scenarios (DWS01-DWS06, with door widths ranging from 1.0 meters to 3.5 meters, step 0.5 m). Figure 8.10, showing the number of occupants at risk over time, reveals that wider doors significantly expedite the reduction of occupants at risk. For instance, scenarios like DWS06, with the widest door, exhibit a sharp and early decline in the number of at-risk occupants compared to narrower doors like DWS01. This indicates that wider exits are crucial for minimizing the time individuals are exposed to hazardous conditions.

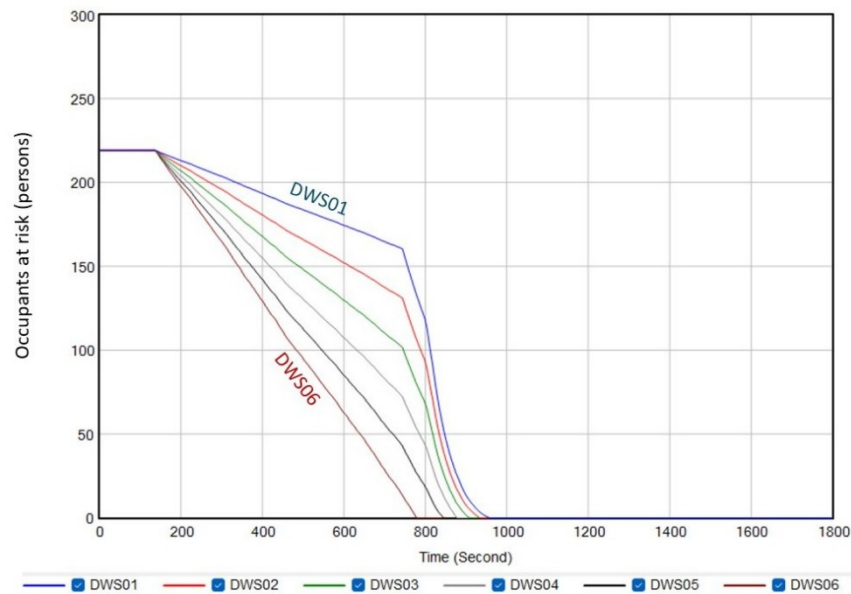


**Fig. 8.10-** Simulation results for the “Occupants at risk” for different door widths

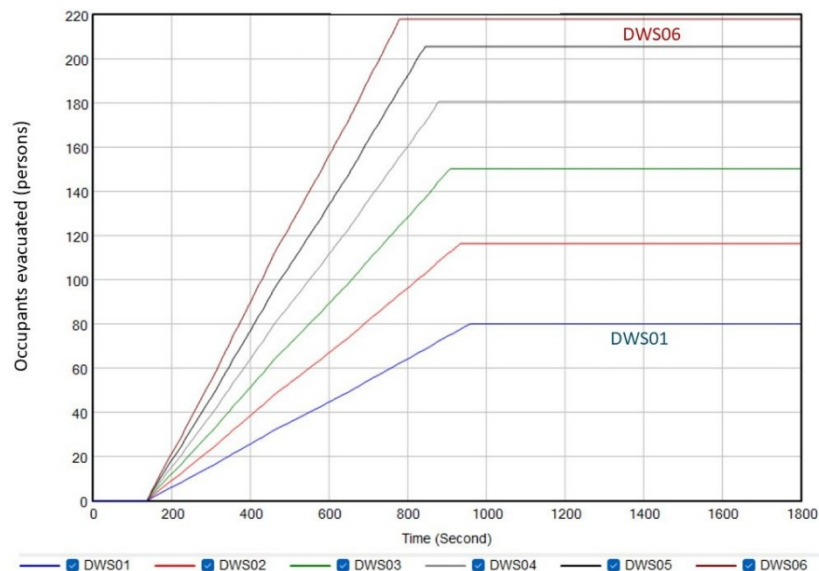


**Fig. 8.11-** Simulation results for the “Occupants evacuated” for different door widths

Figure 8.11 highlights the number of occupants evacuated as a function of time. It demonstrates that scenarios with wider doors facilitate much faster evacuation rates. In particular, DWS06

achieves full evacuation significantly earlier than DWS01, which suffers from a bottleneck effect due to its narrower door width. This bottleneck delays the evacuation process, prolonging the time needed to reach safety. In contrast, wider doors allow more occupants to exit simultaneously, significantly improving evacuation efficiency.

Figure 8.12, showing fatalities over time, underscores the critical role of door width in ensuring safety. Scenarios with narrower doors, such as DWS01, result in substantially higher fatalities, with fatalities stabilizing later in the timeline. Conversely, wider doors, such as those in DWS06, lead to fewer fatalities and earlier stabilization. This outcome highlights that narrow doors prolong evacuation times, increasing exposure to hazardous conditions, while wider doors significantly reduce fatalities by enabling faster and more effective evacuation.

The analysis underscores the importance of increasing door width to enhance evacuation performance. Wider doors reduce the number of occupants at risk, accelerate the evacuation process, and minimize fatalities by decreasing exposure time to dangerous environments. These findings highlight the critical need to optimize door width, particularly in scenarios where rapid evacuation is essential for safety; however, a cost-benefit analysis is necessary to justify the increased door width.

Moreover, an assessment of the occupant risk, evacuation rates, and the probability of fatality under different scenarios (EHS01-EHS05) corresponding to increasing enclosure heights from 2.0 meters (EHS01) to 4.0 meters (EHS05) is performed. For the "Occupants at Risk," there is a rapid decline in occupant risk as time progresses, with steeper declines in scenarios with smaller enclosure heights. EHS01, corresponding to a height of 2.0 meters, shows the sharpest reduction in risk within a very short timeframe, while EHS05, with a height of 4.0 meters, demonstrates a slower decline, however, this decline is due to a rapid increase of the number of fatalities.

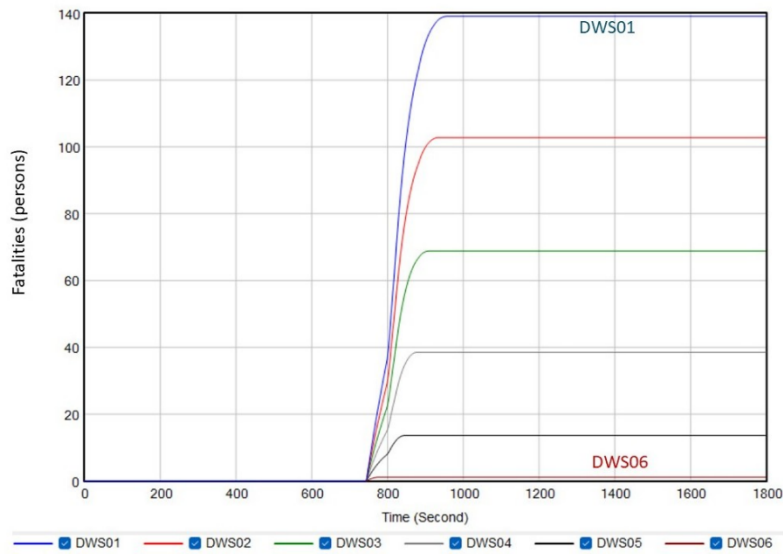


**Fig. 8.12- Simulation results for the “Fatalities” for different door widths**

Fig. 8.13 shows the "Probability of Fatality" demonstrates the relationship between time and the likelihood of fatalities across the scenarios. EHS01, with the smallest enclosure height, exhibits a near-immediate rise to a high fatality probability, suggesting that lower enclosure heights lead to rapid fatality risk escalation. On the other hand, EHS05 shows a more gradual increase, highlighting that higher enclosures delay the onset of critical fatality risks. These findings underscore the importance of optimizing enclosure height and evacuation strategies to minimize risk and fatalities during emergencies.

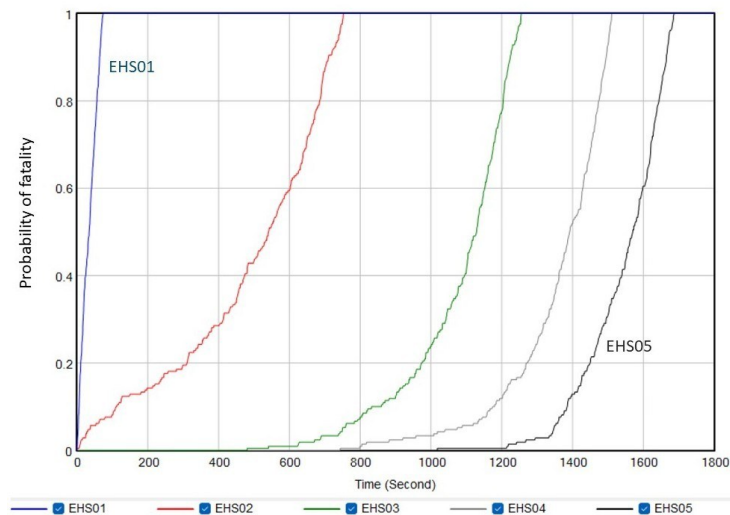


**Fig. 8.13- Probability of fatality for different enclosure heights**

In the case of the “Area of the enclosure”, higher values imply a larger number of occupants at risk, but conversely also a slower increase of the smoke layer height. This results in a larger number of occupants evacuated, and lower values of probability of fatalities. When visual detection occurs, the delay time decreases, therefore, the number of fatalities decreases as well, increasing the evacuation efficiency.

Developing a feedback-based evacuation model highlights the importance of adaptive mechanisms in fire safety planning. On the one hand, linear models provide basic estimations but fail to capture dynamic interactions between fire growth, human response, and evacuation efficiency. Feedback loops, on the other hand, offer a more accurate, realistic, and responsive model that accounts for congestion, detection variability, and evolving risk levels. By incorporating feedback loops, evacuation strategies can be optimized for real-world conditions, ensuring that emergency response plans effectively reduce casualties and improve overall safety.

#### **8.5.5- Linking the occupant-risk model to the FRISE framework**

The occupant-risk SD model operationalizes FRISE in Fire Safety Engineering. Within FRISE, the stock Occupants at risk corresponds to the Risk Assessment (RA) module’s evolving exposure, while Occupants evacuated and Fatalities represent outcome states that close the main balancing loops through their influence on subsequent management and design decisions. The endogenous rates—Evacuation rate and Fatality rate—embody Safety Management (SM) actions and hazard progression, respectively, and their dependence on the current number of occupants at risk creates the requisite feedback structure for adaptive behavior.

The hazard sub-system is parameterized through the smoke layer evolution and probabilistic fire growth, which implement RA’s representation of uncertainty. The response sub-system captures SM levers through RSET components (detection/warning, recognition/response, travel/queuing) and capacity constraints at exits. The explicit RSET–ASET comparison provides a testable criterion for tenability that connects physical modelling with decision variables, enabling FRISE’s Systemic Glue Layer to transmit information between technical performance and governance choices. For instance, a longer alarm delay or reduced door width increases RSET dominance, accelerates the crossing of the ASET threshold, and elevates the probability of fatality—effects that propagate to SOC and ECO via elevated perceived risk and expected loss.

The scenario analyses clarify how this coupling operates across FRISE modules. Reducing the fire-alarm delay chiefly acts through SM (earlier activation of evacuation flows), but the resultant reduction in expected fatalities per event is an input to ECO (lower expected loss and a higher net benefit of detection upgrades) and to SOC (higher perceived safety and acceptance). Increasing door width modifies the queuing component of RSET, improving egress capacity and steepening the decline of Occupants at risk; this change simultaneously reduces the need for additional suppression in Model 1's structure (lower perceived risk diminishes the pressure for protection), linking SM back to RA and to ENV through reduced material use. Varying enclosure height shifts the ASET trajectory through smoke dynamics, demonstrating that architectural decisions classified under ENV and ECO modules can strengthen or erode the safety margin even when SM policies are held constant. Likewise, changes in area of the enclosure alter both initial exposure (through occupant load density) and smoke development, showing how planning choices at design time condition SM effectiveness at runtime.

At the framework level, the GT results from Section 8.4 position Fire risk, Sustainability level, and Material use as the structural attractors of the system. The occupant-risk model provides the temporal mechanism by which these attractors influence consequences: higher material use (e.g., insulation to meet energy targets) increases combustible load and, through faster smoke descent, reduces ASET; the SD model then quantifies how much additional detection capability or door capacity is required to recover an acceptable RSET–ASET margin. In this sense, Model 2 furnishes the causal throughput between the structural diagnosis of Model 1 and the decision economics of Model 3. Its outputs—time series of expected fatalities, evacuated occupants, and probability of fatality—are the RA→ECO transfer quantities that determine expected annual loss, risk reduction achieved per investment, and ultimately the ALARP/LQI compliance evaluated in Section 8.6.

Finally, the probabilistic layer embedded in Model 2 implements FRISE's commitment to decision-making under uncertainty. By propagating distributions for fire growth, detection performance, occupant load, and movement, the model estimates not only mean outcomes but also variability and tail risk. These distributional outputs provide the SOC module with evidence on reliability and residual risk, inform the ECO module's valuation under risk aversion, and feed back into SM as performance targets (e.g., maximum allowable alarm delay to keep the probability of fatality below a threshold). Through these bidirectional couplings, the occupant-risk SD model acts as the dynamic core that connects physical tenability, human

behavior, and policy levers within the FRISE meta-framework, enabling coherent evaluation of design alternatives and emergency management strategies across safety, sustainability, and societal acceptance.

### **8.6- Model 3: Cost–Benefit Analysis of Fire Safety Measures**

The third application of the FRISE framework to Fire Safety Engineering focuses on integrating economic and societal dimensions into safety decision-making through a dynamic Cost–Benefit Analysis (CBA) model. In contrast to the previous model—where the emphasis was placed on the physical and behavioral evolution of fire risk—this section evaluates how investments in fire protection systems can be optimized under the As Low As Reasonably Practicable (ALARP) principle while incorporating the Life Quality Index (LQI) as a measure of the societal value of life safety. The model uses a System Dynamics (SD) approach to account for the temporal evolution of costs, benefits, and damages, allowing for a dynamic visualization of how safety investments perform over time, rather than as static averages.

#### **8.6.1- Conceptual Foundations and Integration within FRISE**

Within the FRISE framework, this CBA model operationalizes the Economic (ECO) and Social (SOC) modules while maintaining feedback with the Safety Management (SM) and Risk Assessment (RA) modules. Figure 8.14 (input data from Van Coile et al., 2019) shows the structure of the developed SD model, where the three main stocks—Cumulative Cost, Cumulative Damage, and Cumulative Benefit—interact dynamically to determine the Total Net Benefit of a given safety investment.

Each stock evolves over time according to inflows and outflows defined by installation expenses, maintenance, reduction in damage due to safety features, and potential residual losses. These temporal dependencies correspond to the delayed feedback loops characteristic of FRISE’s systemic glue layer: initial investments (ECO) affect long-term damage reduction (RA) and, indirectly, societal welfare (SOC). This dynamic representation enables decision-makers to explore how benefits accrue and costs evolve, considering the uncertainty of fire occurrence and variability in system performance.

The ALARP principle is implemented by identifying the range where incremental cost exceeds proportional risk reduction—an inherently balancing feedback. When coupled with the LQI, this approach provides a risk-informed valuation that considers not only economic feasibility but also improvements in life expectancy and quality, linking technical outcomes to social acceptability. Hence, the FRISE framework supports a multi-criteria decision process, where



technical safety (RA–SM) interacts with social valuation (SOC) through economic performance (ECO).

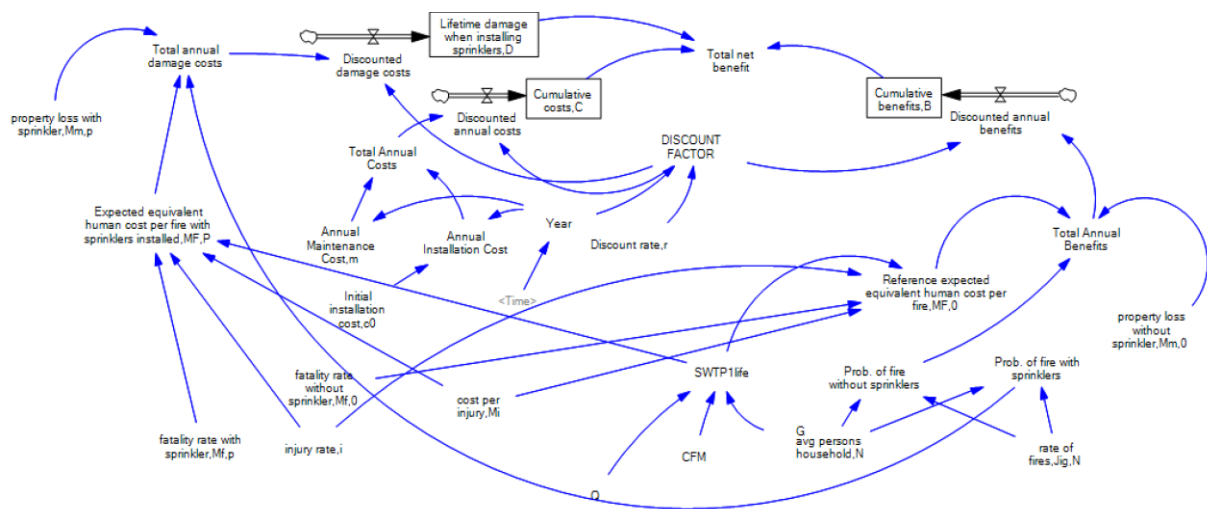


Fig. 8.14- System Dynamics model for the total net benefits from sprinklers installation in Australian single-family residences

### 8.6.2- System Dynamics Structure and Case Studies

The CBA-SD model was applied to three case studies adapted from the research of Van Coile et al., (2019) representing different fire safety features with varying cost structures and effectiveness.

#### ➤ Case Study 1: Sprinklers in Australian single-family residences

The first application evaluates the dynamic net benefits of installing sprinklers in detached dwellings. The SD model (Figure 8.14) simulates the cumulative investment, maintenance, and expected damage reduction over time. The resulting CBA curve (Figure 8.15) indicates that, under average cost and damage assumptions, sprinkler installation does not satisfy the ALARP criterion at a societal level. The total cost per unit risk reduction exceeds the acceptable threshold, implying that mandatory implementation is not economically justified. However, private stakeholders might still adopt this measure under specific high-risk conditions (e.g., remote locations or elderly occupants), where the private valuation of safety is higher than the societal baseline.

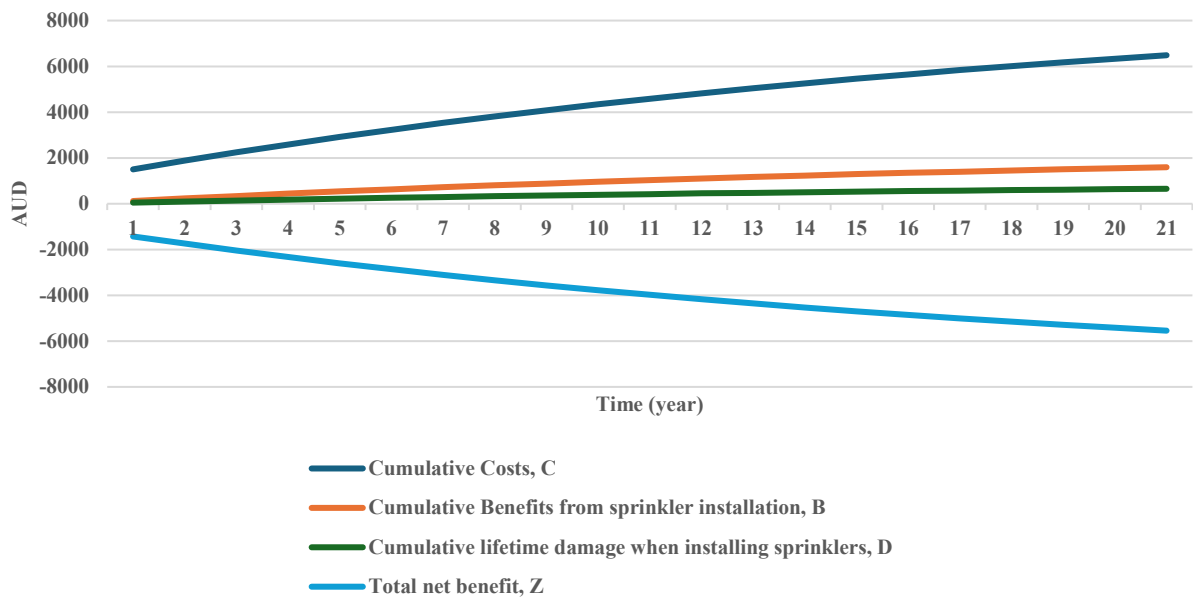


Fig. 8.15- Cost-benefit analysis from sprinklers installation in Australian single-family residences

➤ Case Study 2: Generalized sprinkler requirement across different sprinkler classes

The second study extends the analysis to multiple sprinkler classes, accounting for differences in reliability, cost, and maintenance intervals. The SD representation (Figure 8.16) and its corresponding results (Figure 8.17) reveal that, for high-reliability systems, the benefit–cost ratio improves significantly over time due to reduced expected damages and fatalities. Although high-performance systems require higher initial investment, the cumulative benefits eventually surpass cumulative costs, particularly from the societal perspective when LQI-weighted benefits are included. This illustrates the ECO–SOC coupling within FRISE: the economic benefit of reduced risk translates into an increased social value through higher life quality indices.

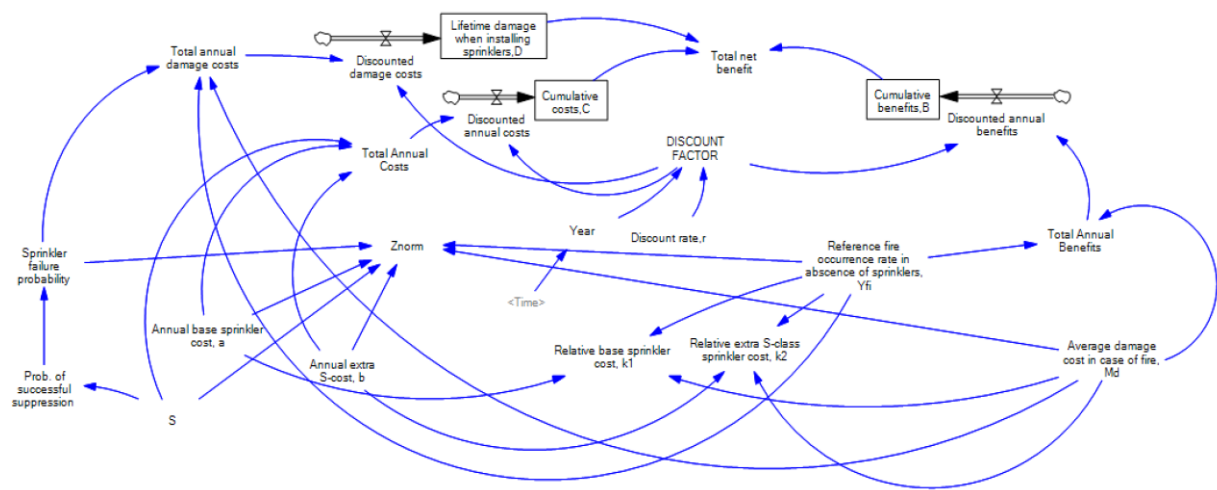


Fig. 8.16- System Dynamics model for the total net benefits from sprinkler installation considering different sprinkler classes

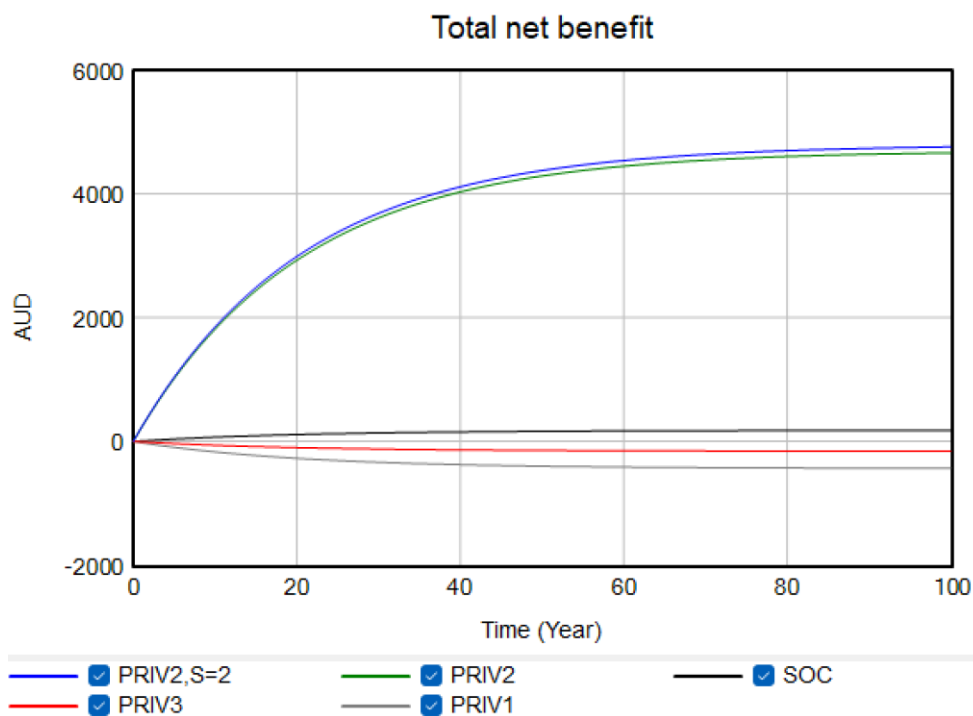


Fig. 8.17- Cost-benefit analysis from sprinkler installation considering different sprinkler classes

### ➤ Case Study 3: Exit width requirements for retail spaces

The third case examines door width as a preventive design parameter. The SD model (Figure 8.18) relates construction cost increases to reductions in expected fatalities and damage. As shown in the resulting CBA curve (Figure 8.19), a door width equal to or slightly exceeding the ALARP-derived value yields the optimal balance between cost and safety. Beyond this point, additional widening produces diminishing returns, representing a classic balancing loop between economic efficiency and safety enhancement. Within FRISE, this example links the

SM and ECO modules: increasing physical capacity (SM) directly affects the risk level (RA), which then feeds back into investment decisions and societal acceptability (SOC).

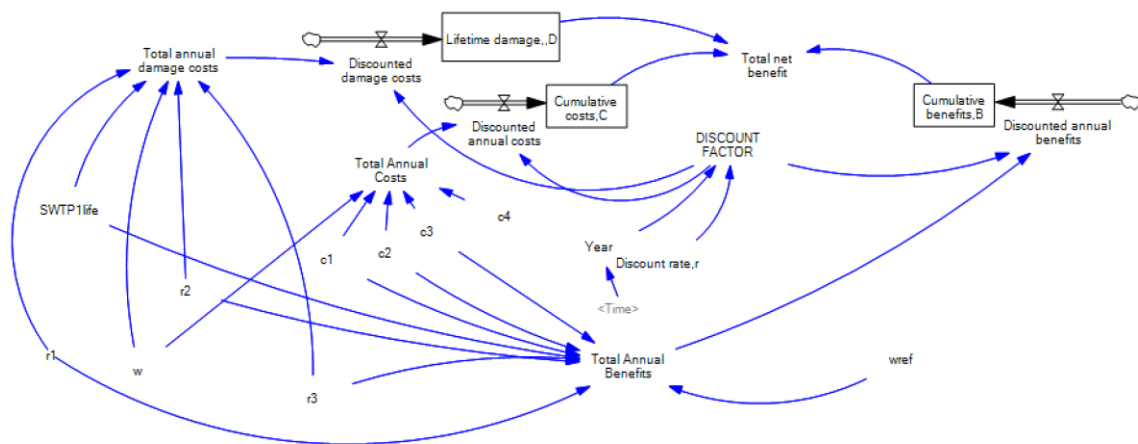


Fig. 8.18- System Dynamics model for the total net benefits considering exit width requirement for retail spaces

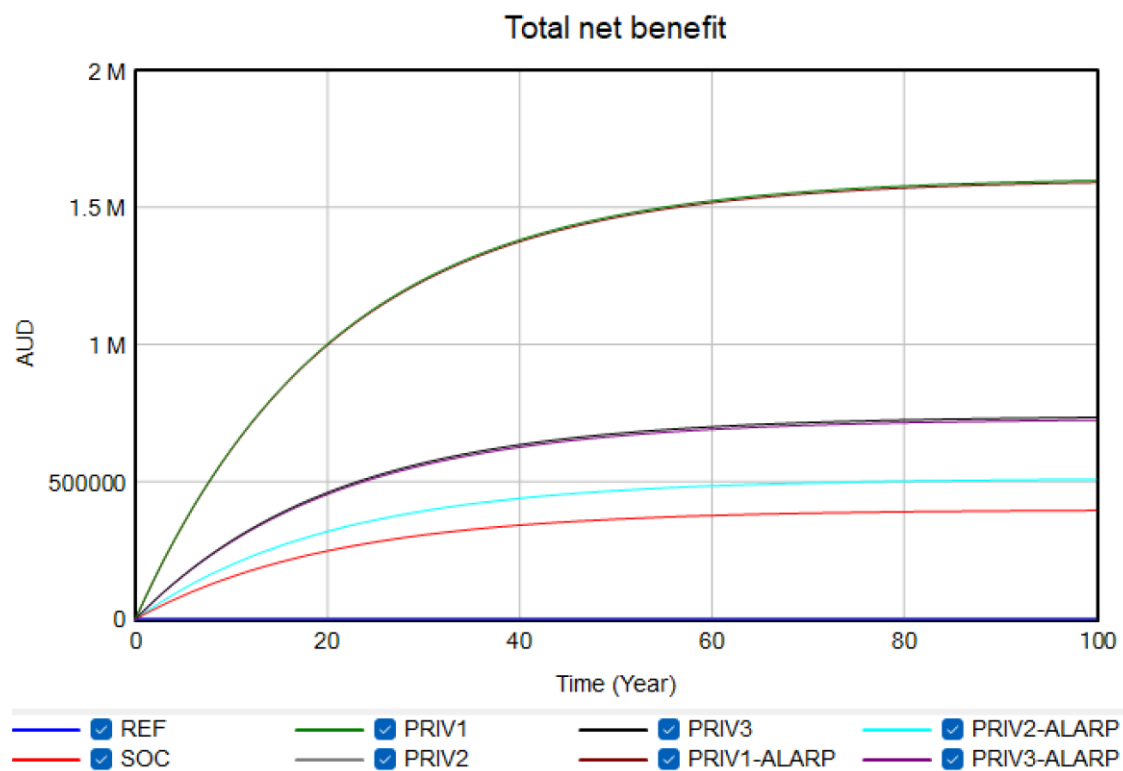


Fig. 8.19- Cost-benefit analysis considering exit width requirement for retail spaces

### **8.6.3- Dynamic Interpretation and FRISE Coupling**

The SD-based CBA model captures the time dependency and feedback interactions that traditional static ALARP evaluations overlook. As safety investments are implemented, initial costs act as a short-term negative feedback on economic balance, while risk reduction produces a delayed positive feedback through reduced expected damages and improved life quality. The temporal integration of these effects allows for distinguishing between short-term financial burdens and long-term societal gains, making the model particularly relevant for policy evaluation and infrastructure planning.

Within the FRISE framework, the outputs of Model 3 act as the ECO–SOC interface, linking quantitative economic performance with qualitative social acceptability. The ALARP threshold represents the system’s balancing boundary between risk tolerance and financial expenditure, while the LQI provides the societal amplification factor that defines how strongly safety improvements are valued in welfare terms. Together, these elements extend the FRISE meta-model beyond physical safety performance (as represented in Models 1 and 2) toward integrated sustainability and governance assessment.

Dynamic CBA results also create backward coupling with the other FRISE modules:

- From ECO to RA, investment decisions alter the residual risk profile modeled in the occupant-risk SD model (Section 8.5).
- From ECO to SM, financial feasibility influences maintenance cycles and reliability of detection and suppression systems.
- From ECO/SOC to ENV, life-cycle cost optimization aligns with material selection and environmental performance goals derived from the fire safety–sustainability CLD (Section 8.4).

This systemic coupling underscores FRISE’s central premise: safety investments should not be judged solely on static cost-effectiveness but on their ability to produce adaptive, long-term societal value.

### **8.6.4- Discussion and Implications for Policy**

The CBA-SD model demonstrates that the FRISE framework can integrate technical, economic, and social dimensions of fire safety into a unified analytical platform. The dynamic assessment highlights that certain safety measures—such as sprinkler installation in low-risk dwellings—may not be justified at the societal level under ALARP criteria, whereas design

features like adequate door width consistently yield positive net benefits and higher societal utility.

By incorporating the LQI, the model extends beyond cost minimization toward social welfare maximization, aligning fire safety policy with broader sustainability and resilience objectives. This integration exemplifies FRISE's capacity to guide adaptive policy design, where regulatory thresholds, investment priorities, and public acceptance evolve together through evidence-based feedback.

### **8.7- Concluding Remarks: Application of FRISE to Fire Safety Engineering**

The application of FRISE to Fire Safety Engineering confirms the framework's versatility as a systems-based decision-support tool capable of bridging the gap between technical, managerial, and societal aspects of safety. Through its modular architecture—comprising the Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC) modules—FRISE successfully integrates the diverse disciplines that govern fire safety performance in modern buildings.

The CLD–GT analysis (Model 1) established that Fire risk and Sustainability level are structural attractors of the FSE system. Their dominance within the causal network reveals the central tension between environmental targets and safety imperatives in sustainable building design. Material selection, façade combustibility, and inspection quality emerged as systemic leverage points where design interventions or regulatory measures can produce substantial improvements in both safety and sustainability outcomes. This structural insight forms the foundation for the dynamic analyses that follow.

The SD occupant-risk model (Model 2) demonstrated FRISE's ability to represent time-dependent risk evolution under uncertainty. By coupling physical fire dynamics with behavioral and organizational responses, the model simulated how evacuation efficiency and fatality probability evolve under varying alarm delays, door widths, or enclosure geometries. These results revealed the importance of dynamic feedbacks—particularly between RSET and ASET—and illustrated how design and management strategies influence real-time safety performance. Within FRISE, this model operationalized the RA–SM interface and provided the quantitative outputs required for subsequent cost–benefit evaluation.

The final SD–CBA model (Model 3) extended the analysis to the economic and social valuation of safety measures, linking technical risk reduction with societal welfare through the ALARP and LQI approaches. Its results underscored that while some measures—like sprinklers in low-

risk dwellings—may not satisfy societal cost-effectiveness thresholds, design interventions such as optimal door widths provide consistent positive net benefits. This dynamic cost–benefit perspective reinforced FRISE’s capacity to connect the ECO and SOC modules, closing the loop between risk performance, economic feasibility, and public acceptance.

Taken together, these three models demonstrate that FRISE not only unifies previously disconnected analytical domains in FSE but also enables cross-scale feedback interpretation. Structural dependencies identified through GT analysis (Model 1) inform behavioral dynamics (Model 2), whose outputs then drive decision metrics in the CBA framework (Model 3). This integrated progression—structure → behavior → decision—represents the systemic logic at the heart of FRISE. The resulting synthesis supports adaptive safety management strategies that align engineering design, economic evaluation, and social policy under a single conceptual and computational umbrella.

Beyond its methodological contributions, this chapter highlights the broader implications of systems thinking in fire safety practice. By capturing delayed effects, non-linear trade-offs, and feedback propagation across domains, FRISE offers a scientifically rigorous foundation for future performance-based and sustainability-driven fire safety policies. It also facilitates evidence-based communication between engineers, economists, regulators, and stakeholders—transforming complex technical data into actionable systemic insights. Hence, FRISE provides not only a modeling approach but also a governance framework for integrating resilience, sustainability, and societal well-being into next-generation fire safety strategies.

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## **Chapter 9 – Application III: Energy Sustainability and Hydrogen Economy**

This chapter extends the operational scope of the FRISE framework toward macro-scale sustainability transitions, applying it to the analysis of the hydrogen economy as a paradigmatic case of a complex socio-technical system. The chapter demonstrates how the integrated methodology—combining Causal Loop Diagrams (CLDs), System Archetypes, and Graph-Theoretic (GT) analysis—can represent the dynamic interdependencies among economic, environmental, and social dimensions of energy sustainability. Building upon the conceptual foundations and modular applications presented in previous chapters, this final application translates FRISE from micro-level fire safety systems to global energy transition governance. The purpose is to explore how feedback mechanisms, policy adaptation, and public perception interact to shape the trajectory of hydrogen-based energy systems and to validate the FRISE framework as a multi-scale analytical architecture capable of capturing complexity, resilience, and sustainability within the energy domain.

### **9.1- Introduction**

The third application of the FRISE framework extends the analysis from micro- and meso-scale fire and safety systems toward a macro-scale sustainability challenge: the global transition to a hydrogen-based energy system. The hydrogen economy represents one of the most complex socio-technical transformations currently underway, involving tightly coupled interactions among technological innovation, environmental constraints, market dynamics, social acceptance, and policy evolution. Understanding its behavior requires a holistic approach capable of capturing non-linear feedbacks, adaptive behaviors, and systemic delays that shape long-term energy transition pathways.

In this context, the FRISE framework is applied to model the hydrogen economy as a complex adaptive system where economic growth, environmental performance, and social legitimacy co-evolve. This application builds upon the three-paradigm model—Sustainability, Complexity, and Systems Thinking—developed in earlier research and used here to interpret the interdependencies among the economic, environmental, and social dimensions of sustainability. The objective is to identify how feedback structures among these subsystems influence the stability, resilience, and direction of the hydrogen transition and to locate leverage points for steering the system toward sustainable trajectories.

The methodological focus of this chapter differs from the dynamic modeling cases studies introduced in Chapter 7. While preliminary System Dynamics (SD) structures were developed to support causal tracing and policy testing, the emphasis here lies on qualitative systemic integration rather than quantitative simulation. The hydrogen CLD presented in this chapter therefore serves as a conceptual integration layer that synthesizes the findings from previous modules—risk assessment, safety management, economic evaluation, environmental sustainability, and social dynamics—into a unified macro-system representation.

Through this approach, the chapter aims to:

- Develop and interpret an Integrated Causal Loop Diagram that represents the sustainability feedbacks of the hydrogen economy;
- Identify dominant system archetypes governing the evolution of hydrogen production, technology diffusion, and public acceptance; and
- Perform a cross-modular analysis linking the energy sustainability domain to the overall FRISE architecture, thereby demonstrating the framework’s capacity to operate across scales—from local safety management to global energy policy.

The resulting insights contribute to a systemic understanding of how the hydrogen economy can evolve under combined economic, environmental, and social pressures, providing guidance for adaptive policy design and long-term sustainability governance.

## **9.2- Conceptual Foundations: The Three-Paradigm (3P) Model and its Link to Energy Systems**

The theoretical foundation supporting this application is the Three-Paradigm (3P) Model—Sustainability, Complexity, and Systems Thinking—previously established in Chapter 2 as the philosophical and methodological basis of the FRISE framework. The present section recalls its essential logic only to clarify how it underpins the analysis of the hydrogen economy as a dynamic, multi-scale system.

At the macro level, the sustainability paradigm provides the normative orientation of the model, defining the long-term goals of environmental integrity, economic viability, and social well-being. In the context of energy transitions, these three dimensions interact continuously: technological progress and market expansion may accelerate decarbonization but can also introduce new environmental or social burdens if feedback mechanisms are ignored. The sustainability paradigm therefore establishes the evaluative criteria by which systemic performance is assessed within this chapter.

The complexity paradigm introduces the scientific lens through which the hydrogen economy is interpreted. Energy systems are inherently complex: they comprise numerous interdependent actors—industrial sectors, governments, consumers, and research institutions—whose actions co-evolve across temporal and spatial scales. Feedback loops, delays, and emergent properties dominate their behavior, leading to outcomes that are often non-linear and counterintuitive. Understanding such phenomena requires viewing the energy system not as a set of isolated components but as an adaptive network where interventions can trigger ripple effects throughout the entire socio-technical landscape.

Finally, the systems thinking paradigm operationalizes these principles through qualitative system modeling tools, notably Causal Loop Diagrams (CLDs) and System Archetypes. This paradigm enables the translation of abstract sustainability and complexity concepts into a structured representation of causal relationships. Within the FRISE framework, systems thinking functions as the methodological bridge that connects disciplinary modules—risk assessment, safety management, economics, environmental performance, and societal acceptance—into a coherent systemic architecture.

Applied to the hydrogen economy, the 3P integration allows the identification of multi-domain feedback structures that shape transition dynamics. For instance, technological innovation (economic subsystem) reduces emissions (environmental subsystem) but depends on public support and regulatory incentives (social subsystem). These interactions produce reinforcing and balancing feedbacks that determine the pace and stability of hydrogen adoption. By framing such relations through the 3P lens, the model clarifies how interventions in one domain—such as subsidy policies or safety regulations—propagate through the others, influencing overall sustainability outcomes.

In summary, the 3P model provides the conceptual backbone for interpreting the hydrogen economy as a complex adaptive system pursuing sustainable equilibrium. It ensures that the subsequent modeling and analysis presented in this chapter—particularly the integrated CLD and cross-modular synthesis—remain anchored in a holistic perspective that values systemic coherence over sectoral optimization. This orientation is consistent with the overarching philosophy of the FRISE framework, which seeks to connect safety, resilience, and sustainability across scales and disciplines.

### 9.3- Methodology for Modeling Hydrogen Sustainability

The methodological approach adopted in this chapter follows the principles of the FRISE framework, applying its systemic workflow to the macro-scale context of energy sustainability. The goal is to capture, in an integrated manner, the dynamic interdependencies among economic growth, environmental performance, technological innovation, and social acceptance that define the evolution of the hydrogen economy.

Unlike the detailed System Dynamics (SD) modeling undertaken in Chapter 7, where dynamic risk and probabilistic behavior were simulated quantitatively, the present chapter focuses on qualitative system integration. The emphasis is placed on identifying the dominant feedback mechanisms and leverage points that govern the system's evolution rather than on reproducing its precise temporal dynamics.

To achieve this, the modeling process was structured into five main stages:

- Stage 1 – Identification of Key Variables and Subsystems

The first step consisted of identifying the relevant factors influencing the sustainability of the hydrogen economy. This process combined literature review, expert consultation, and insights derived from previous FRISE modules (economic, environmental, social, safety). Variables were categorized under three primary subsystems: (1) Economic subsystem – representing investment flows, cost competitiveness, and market diffusion; (2) environmental subsystem – covering emissions, renewable integration, and environmental degradation feedbacks; (3) social and policy subsystem – including public acceptance, regulatory incentives, and technological learning capacity. These variables formed the structural foundation of the causal architecture represented in the CLD model.

- Stage 2 – Integration of Feedback Structures and Causal Links

At this stage, causal relationships among variables were systematically defined using polarity analysis (positive or negative influence). Reinforcing and balancing loops were identified and validated through consistency checks based on system behavior logic and evidence from prior research.

The result was a high-density causal network in which feedback loops across subsystems—economic growth, innovation, emissions, and policy support—emerged as the main drivers of systemic dynamics. The hydrogen CLD thus integrates both intra-domain and cross-domain causalities, establishing the conceptual groundwork for multi-scale sustainability analysis.

### ➤ Stage 3 – Construction of the Integrated Hydrogen CLD

Using *Vensim* software, the identified variables and causalities were formalized into a single Integrated Causal Loop Diagram (CLD), merging the multiple subsystems into one coherent structure. The CLD includes more than two hundred feedback loops, classified as: (1) Reinforcing loops (R): representing growth, innovation, and self-amplifying processes that accelerate system transitions; and (2) Balancing loops (B): capturing constraints, resource limits, and regulatory or environmental feedbacks that stabilize or counteract growth.

This integrated CLD, presented later in Section 9.4, provides a holistic view of the hydrogen economy as a self-organizing socio-technical system. It serves as a qualitative simulation environment that helps visualize potential leverage points and unintended feedback effects associated with policy interventions.

### ➤ Stage 4 – Identification of System Archetypes

To interpret the behavior patterns emerging from the CLD, recurring feedback structures were analyzed and matched to System Archetypes commonly observed in complex adaptive systems. These include Fixes that Fail, Limits to Growth, Shifting the Burden, and Success to the Successful.

Each archetype helps explain systemic challenges observed in the hydrogen transition—such as technological lock-in, subsidy dependency, and policy resistance—and provides a diagnostic lens for evaluating long-term sustainability strategies.

### ➤ Stage 5 – Cross-Modular Synthesis and Graph-Theoretic (GT) Analysis

Finally, the qualitative insights from the CLD were combined with network metrics obtained from the Cross-Modular analysis (see Section 9.8). By interpreting the hydrogen system as part of the overall FRISE network, it becomes possible to quantify variable centrality, influence pathways, and inter-modular linkages (e.g., between safety, environmental, and socio-economic domains).

This step closes the FRISE loop by situating the hydrogen sustainability problem within a unified systemic architecture that spans all five previously developed modules.

Overall, the methodology adopted in this chapter integrates systemic conceptualization with structural formalization. The CLD developed for this study represents the intermediate level between qualitative reasoning and quantitative simulation. While it does not perform dynamic

calculations, it encapsulates the feedback architecture necessary to understand the system's complexity and to support future SD implementations.

Through this workflow, the hydrogen sustainability model operates as a conceptual interface between theoretical paradigms and practical policy analysis, demonstrating how the FRISE framework can be extended to large-scale socio-technical transitions while maintaining systemic consistency across scales.

#### **9.4- Integrated Causal Loop Diagram (CLD) for Hydrogen Sustainability**

The Integrated Causal Loop Diagram (CLD) developed for this study represents the central outcome of the systemic modeling process applied to the hydrogen economy. It combines the economic, environmental, and social subsystems identified in Stage 1 (Section 9.3) into a single macro-structure that captures the principal feedback interactions driving sustainability performance. The diagram is reproduced in Figure 9.1, where blue arrows denote reinforcing (positive) influences and red arrows indicate balancing (negative) feedbacks, while dashed links represent delayed responses in the system.

##### **9.4.1- General Structure and Subsystem Integration**

The CLD integrates over 200 feedback loops distributed across three interconnected domains:

- Economic and Technological Subsystem – governing investment flows, cost competitiveness, technology innovation, and industrial capacity.
- Environmental Subsystem – describing greenhouse gas emissions, renewable integration, and environmental degradation feedbacks.
- Social and Policy Subsystem – encompassing public acceptance, regulatory incentives, energy security concerns, and the political economy of energy transitions.

Each domain contains its own internal feedbacks but is also cross-linked with the others through bidirectional causal relationships. For instance, technological investments (economic subsystem) reduce production costs and emissions (environmental subsystem), which in turn improve public perception and regulatory support (social subsystem), reinforcing subsequent investments. The CLD thus acts as a systemic synthesis of the multiple feedback structures identified throughout the thesis: it extends the micro-level risk and safety interactions modeled in previous chapters toward a macro-level representation of sustainability transitions. Within the FRISE framework, this diagram corresponds to the macro-integration layer that unifies technical safety, environmental integrity, and societal resilience into one dynamic conceptual structure.

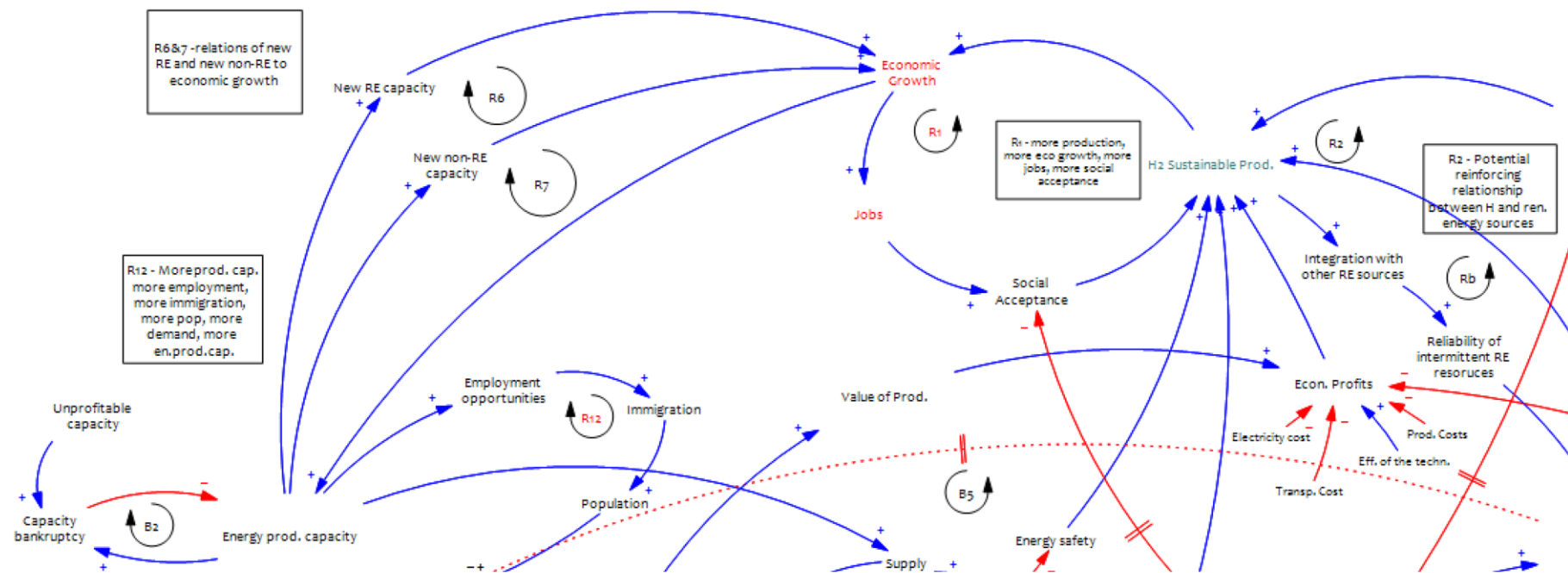


Fig. 9.1a- Integrated Causal Loop Diagram (CLD) for Hydrogen Sustainability (Top left)

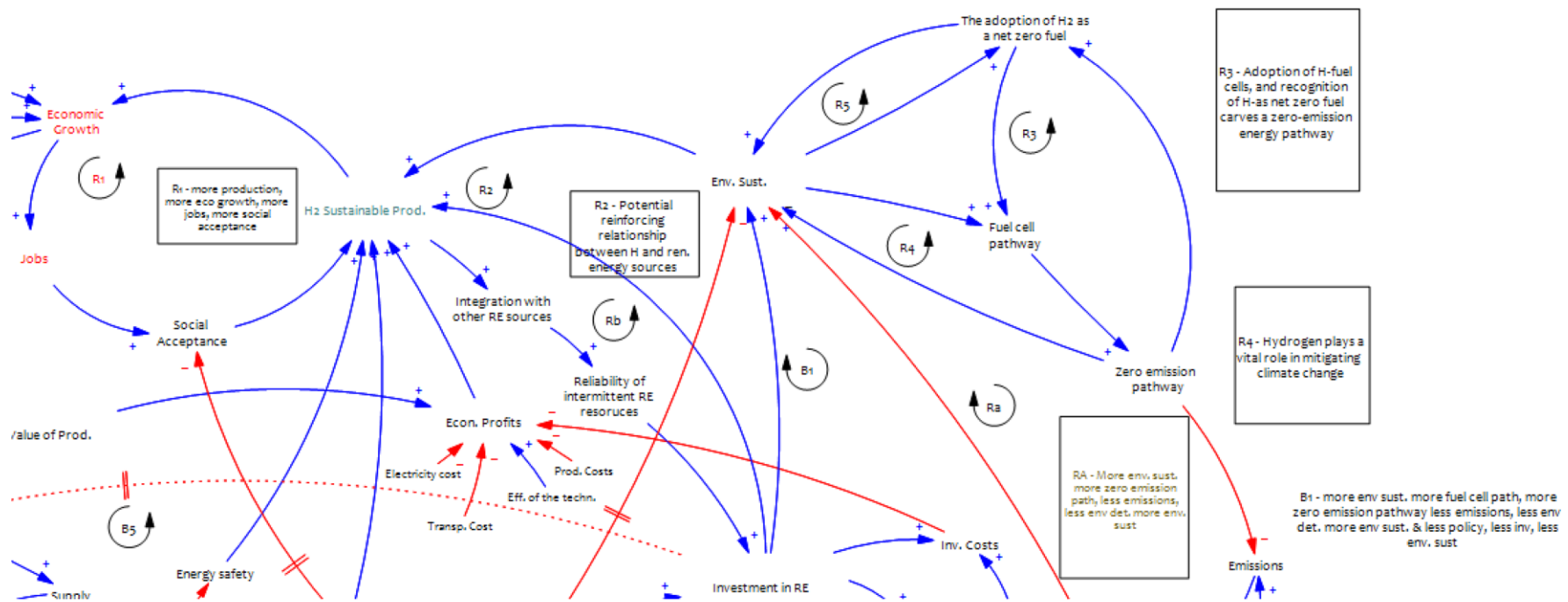


Fig. 9.1b- Integrated Causal Loop Diagram (CLD) for Hydrogen Sustainability (Top right)



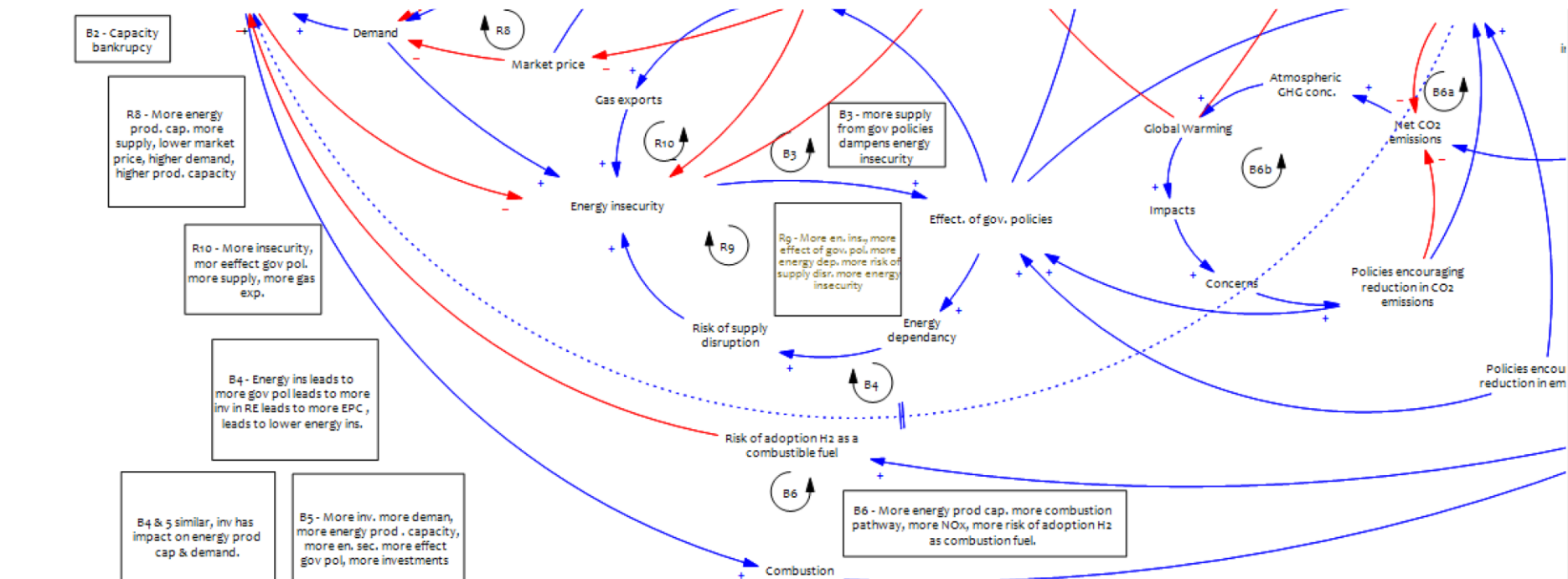


Fig. 9.1c- Integrated Causal Loop Diagram (CLD) for Hydrogen Sustainability (Bottom left)



The construction of the integrated CLD drew extensively on previous system dynamics and system thinking studies addressing energy and hydrogen transitions. Table 9.1 summarizes the most relevant conceptual and computational models reported in the literature, which provided the reference structures and causal assumptions adopted in this work. Each of these models contributes partial insights—technological diffusion, policy impact, or market evolution—that were subsequently integrated into the comprehensive CLD developed here.

**Table 9.1- Causal Loop Diagram and Forrester diagrams related to the sustainability of the energy sector reported by the literature**

| No. | Title                                                                                                                        | Aim                                                                                                                                                                                                                                 | Reference                                            |
|-----|------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|
| 01  | Hydrogen vehicle-infrastructure                                                                                              | To model the simple relationship between complementary goods in a vehicle-fueling station                                                                                                                                           | (Meyer & Winebrake, 2009)                            |
| 02  | The Bass diffusion model                                                                                                     | Creating a model for predicting the timing of initial purchases of new products.                                                                                                                                                    | (Bass, 1969; Meyer & Winebrake, 2009; Sterman, 2002) |
| 03  | Hydrogen Vehicle and Infrastructure Simulator for Integrated and Operational Transportation Networks (H <sub>2</sub> VISION) | To simulate the diffusion paradigm related to H <sub>2</sub> Fuel Cell Vehicles and refueling infrastructures.                                                                                                                      | (Meyer & Winebrake, 2009)                            |
| 04  | The CLD of the Australian energy sector                                                                                      | Designing a conceptual model of the energy sector. Analyzing the potential consequences of current energy development policies using the model. Offering suggestions for improving policies towards sustainable energy development. | (Laimon et al., 2022)                                |
| 05  | Modeling the development of the Green Hydrogen industry in China under diverse subsidy scenarios.                            | Simulating the development of the Green Hydrogen industry in China while considering various subsidy scenarios.                                                                                                                     | (Li et al., 2022)                                    |
| 06  | Coordinated Development Capacity (CDC) of China's hydrogen energy industry chain                                             | Simulating the CDC of the hydrogen energy industry chain in China from 2016 to 2030.                                                                                                                                                | (Gao & An, 2022)                                     |
| 07  | Hydrogen energy (Australia and Global)                                                                                       | To model the hydrogen energy system.                                                                                                                                                                                                | (Yusaf et al., 2022)                                 |
| 08  | System dynamics model for Green Hydrogen industry development                                                                | To study the policy impact under different terminal demand scenarios in China.                                                                                                                                                      | (Yang et al., 2023)                                  |

Based on the synthesis of these studies, the most representative feedback loops were extracted, harmonized, and merged into a unified systemic representation of hydrogen sustainability. Table 9.2 lists the twenty-one feedback loops incorporated into the integrated CLD, indicating their polarity (reinforcing R / balancing B), causal structure, and conceptual meaning. The numbering (R1–R13, B1–B8) corresponds directly to the loops highlighted in Figure 9.1 and discussed in Sections 9.4.2 and 9.4.3.

**Table 9.2: Feedback loops integrated in the CLD model**

| No. | Loop name | Feedback loop                                                                                                                                                                                                                                  | Meaning                                                                        | Impact on hydrogen sustainability                                                                                                                                                                                                                                                                                                                                                                                                 | Dominant Subsystem (Quadrant)      |
|-----|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|
| 01  | R1        | H <sub>2</sub> Sustainable Production (SP) --- + Economic growth --- + Jobs --- + Social Acceptance --- + H <sub>2</sub> SP                                                                                                                    | Economic-social interdependency                                                | Potential for a self-reinforcing cycle where sustainable hydrogen production not only contributes to economic growth and job creation but also strengthens social acceptance and further investment in sustainable practices.                                                                                                                                                                                                     | Economic– Technological (Top Left) |
| 02  | R2        | H <sub>2</sub> SP --- + Integration with other RE sources --- + Reliability of intermittent RE resources --- + Investment in RE --- + H <sub>2</sub> SP                                                                                        | RE integration reliability                                                     | Potential for a mutually reinforcing relationship between sustainable hydrogen production and renewable energy sources. By integrating hydrogen production with other renewable energy systems, improving reliability, and increasing investment in renewable energy infrastructure, the sustainability of hydrogen production can be enhanced, further promoting the transition to a cleaner and more sustainable energy system. | Economic– Technological (Top Left) |
| 03  | R3        | Fuel cells pathway --- + Zero emission pathway --- + The adoption of H <sub>2</sub> as a net zero fuel --- + Fuel cells pathway                                                                                                                | Fuel cells pathway advantages                                                  | Reinforcing cycle where the adoption of hydrogen fuel cells, coupled with the recognition of hydrogen as a net-zero fuel, contributes to sustainability by providing a zero-emission energy pathway. This supports efforts to mitigate climate change, reduce air pollution, and transition towards a more sustainable energy future.                                                                                             | Environmental (Top Right)          |
| 04  | R4        | Environmental sustainability --- + Fuel cells pathway --- + Zero emission pathway --- + Environmental sustainability                                                                                                                           | Relation of fuel cells with environmental sustainability                       | By prioritizing sustainable production methods and promoting zero-emission technologies, hydrogen plays a vital role in mitigating climate change, reducing air pollution, and advancing environmental conservation efforts.                                                                                                                                                                                                      | Environmental (Top Right)          |
| 05  | R5        | Environmental sustainability --- + The adoption of H <sub>2</sub> as a net zero fuel --- + Environmental sustainability                                                                                                                        | Sustainable adoption of H <sub>2</sub> as a net zero fuel                      |                                                                                                                                                                                                                                                                                                                                                                                                                                   | Environmental (Top Right)          |
| 06  | B1        | Environmental sustainability --- + Fuel cells pathway --- + Zero emission pathway --- - Emissions --- + Environmental deterioration --- + Policy encouraging reduction in emissions --- + Investments in RE --- + Environmental sustainability | Interdependencies among fuel cells, emissions and environmental sustainability | By prioritizing policies and investments that encourage emissions reduction and promote clean energy technologies, it is possible to mitigate environmental degradation and advance toward a more sustainable future.                                                                                                                                                                                                             | Environmental (Top Right)          |

|    |     |                                                                                                                                                                                                    |                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                         |
|----|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|
| 07 | R6  | New non- RE capacity --- + Economic growth --- + Energy production capacity --<br>- + New non-RE capacity                                                                                          | Non-RE capacity relation with the economic growth | Balancing economic growth with environmental sustainability requires careful consideration of transitioning towards cleaner and more sustainable energy sources such as renewable energy and implementing energy efficiency measures.                                                                                                                                                                                                                            | Economic– Technological (Top Left)      |
| 08 | R7  | Energy Production Capacity (EPC) --- + New RE capacity --- + Economic growth --<br>- + EPC                                                                                                         | New RE capacity relation with the economic growth | To capture the interconnectedness of energy production capacity, market dynamics, economic growth, and their implications for hydrogen production sustainability. Balancing the expansion of renewable energy capacity with market stability and demand-side considerations is crucial for promoting sustainable energy systems and accelerating the transition towards a low-carbon economy.                                                                    | Economic– Technological (Top Left)      |
| 09 | B2  | EPC --- + Capacity bankruptcy --- - EPC                                                                                                                                                            | Capacity bankruptcy                               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Economic– Technological (Top Left)      |
| 10 | R8  | EPC --- + Supply --- - Market price --- - Demand --- + EPC                                                                                                                                         | EPC relation with market supply and demand        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Economic– Technological (Top Left)      |
| 11 | R9  | Energy insecurity --- + Effectiveness of government policies (EGP) --- + Energy dependency --- + Risk of supply disruptions --- + Energy insecurity                                                | Energy insecurity relations                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Energy Security–Policy (Bottom Left)    |
| 12 | R10 | Energy insecurity --- + EGP --- + Supply --<br>- + Gas exports --- + Energy insecurity                                                                                                             | Energy insecurity relation with gas exports       | The importance of effective government policies, investment in renewable energy, and diversification of energy sources in promoting energy security and sustainability, including in the context of hydrogen production. By addressing energy insecurity through strategic policies and investments, countries can mitigate risks, enhance resilience, and accelerate the transition to a more sustainable energy future.                                        | Cross-Sectoral / Global (Bottom Right)  |
| 13 | B3  | Energy insecurity --- + EGP --- + Supply --<br>- - Energy insecurity                                                                                                                               | Energy insecurity relation with energy supply     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Energy Security–Policy (Bottom Left)    |
| 14 | B4  | Energy insecurity --- + EGP --- + Investment in RE --- (delay) --- + EPC --- - Energy insecurity                                                                                                   | Energy insecurity relation with EPC               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Energy Security–Policy (Bottom Left)    |
| 15 | B5  | Energy insecurity --- + EGP --- + Investment in RE --- (delay) --- - Demand --<br>- + Energy insecurity                                                                                            | Energy insecurity relation with energy demand     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Energy Security–Policy (Bottom Left)    |
| 16 | R11 | Emissions --- + Environmental deterioration --- + Policies encouraging reduction in emissions --- + Investments in RE --- + EPC --- + Combustion pathway --<br>- + Nitrogen oxides --- + Emissions | Emissions relations with investments in REB       | The importance of policies encouraging emission reduction, investments in renewable energy, and the development of sustainable energy production pathways to mitigate environmental deterioration and promote hydrogen production sustainability. By prioritizing cleaner energy technologies and reducing emissions associated with hydrogen production processes, countries can advance towards a more sustainable and environmentally friendly energy future. | Global–Emission Dynamics (Bottom Right) |

|    |     |                                                                                                                                                                                                                                                                                                                                       |                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                         |
|----|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|
| 17 | B6  | EPC --- + Combustion pathway --- + Nitrogen oxides --- + Risk of adoption of hydrogen as a combustion fuel --- - EPC                                                                                                                                                                                                                  | Risk of adoption of hydrogen as a combustion fuel relation with the EPC | Potential trade-offs and challenges associated with using hydrogen in combustion pathways. While hydrogen offers the potential for clean combustion and reduced greenhouse gas emissions, the formation of NOx and other pollutants presents a significant challenge to its widespread adoption. Balancing the benefits and risks of using hydrogen in combustion processes requires careful consideration of emission control technologies, regulatory measures, and technological advancements to ensure sustainable hydrogen production and utilization. | Global–Emission Dynamics (Bottom Right) |
| 18 | R12 | EPC --- + Employment opportunities --- + Immigration --- + Population --- + Demand --- + EPC                                                                                                                                                                                                                                          | Capacity-social interdependencies                                       | This feedback loop illustrates how the expansion of energy production capacity can stimulate economic growth, attract immigrants, and contribute to population growth, which in turn drives up energy demand and reinforces the need for further expansion of EPC. However, it's essential to consider the sustainability implications of this cycle, including environmental impacts, resource depletion, and the transition to cleaner energy sources, to ensure long-term energy security and environmental stewardship.                                 | Economic–Technological (Top Left)       |
| 19 | R13 | Net CO <sub>2</sub> emissions --- + Atmospheric Green House Gases concentrations --- + Global warming --- + Impacts --- + Concerns --- + Policy encouraging reductions in CO <sub>2</sub> emissions --- + Investment in RE --- + Uncertainty unfulfilling demand growth --- + Inversion in non-RE --- + Net CO <sub>2</sub> emissions | Environmental-investment interdependencies                              | These feedback loops underscore the complex interactions between CO <sub>2</sub> emissions, climate change impacts, policy interventions, investment decisions, and uncertainties in shaping the sustainability of hydrogen production and the broader energy system. Achieving long-term sustainability requires concerted efforts to reduce CO <sub>2</sub> emissions, transition to renewable energy sources, and address concerns about climate change through informed policies, strategic investments, and international cooperation.                 | Global–Emission Dynamics (Bottom Right) |
| 20 | B7  | Net CO <sub>2</sub> emissions --- + Atmospheric Green House Gases concentrations --- + Global warming --- + Impacts --- + Concerns --- + Policy encouraging reductions in CO <sub>2</sub> emissions --- + Investment in RE --- - Net CO <sub>2</sub> emissions                                                                        | Environmental-investment relations                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Global–Emission Dynamics (Bottom Right) |
| 21 | B8  | Net CO <sub>2</sub> emissions --- + Atmospheric Green House Gases concentrations --- + Global warming --- + Impacts --- + Concerns --- + Policy encouraging reductions in CO <sub>2</sub> emissions --- - Net CO <sub>2</sub> emissions                                                                                               | Environmental-emission relations                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Social–Policy (Bottom Left)             |

#### **9.4.2- Dominant Reinforcing Loops (R)**

The following reinforcing feedback loops (R1–R13) represent the growth and self-amplifying processes within the hydrogen economy:

##### *R1 – Innovation–Competitiveness Loop*

Increased research investment enhances technological efficiency, which reduces production costs and stimulates further market demand and investment. This loop drives technological learning and cost reduction over time.

##### *R2 – Renewable Integration Loop*

Greater renewable energy penetration reduces carbon intensity of hydrogen production, improving environmental performance and policy incentives, which further encourage renewable deployment and green hydrogen adoption.

##### *R3 – Employment–Economic Growth Loop*

Industrial expansion increases job creation and economic growth, which expand investment capacity for hydrogen technologies and infrastructure.

##### *R4 – Public Acceptance–Market Expansion Loop*

Higher public trust and awareness raise social acceptance, facilitating market diffusion and infrastructure deployment, which further reinforce societal confidence.

##### *R5 – Policy Credibility Loop*

Effective regulation and stable incentives attract private investment and technological innovation, improving performance metrics that, in turn, validate and strengthen political commitment.

##### *R6 – Infrastructure Capacity Loop*

Expanded production and storage capacity lowers supply risk, improves market reliability, and motivates continued infrastructure development.

##### *R7 – Export Competitiveness Loop*

Improved hydrogen production efficiency increases export potential and economic returns, promoting reinvestment into capacity and R&D.

#### *R8 – Learning Curve Loop*

Increased deployment experience reduces unit costs through technological learning, reinforcing further diffusion.

#### *R9 – Environmental Reputation Loop*

Visible emission reductions enhance national and corporate reputation, stimulating policy support and investment inflows.

#### *R10 – Global Synergy Loop*

International cooperation accelerates technology transfer and economies of scale, reinforcing global capacity expansion.

#### *R11 – Cross-Sector Integration Loop*

Coupling hydrogen with mobility and industrial decarbonization sectors broadens the demand base, attracting larger investments that feed back into supply development.

#### *R12 – Trust and Safety Performance Loop*

Improved safety management and risk control enhance public confidence and license to operate, promoting broader hydrogen use—a connection that links this macro-model back to the FRISE safety modules.

#### *R13 – ESG and Investment Attraction Loop*

Better environmental, social, and governance (ESG) indicators attract sustainable finance, enabling further innovation and sustainability improvements.

Together, these loops form the growth engine of the hydrogen economy, describing how innovation, confidence, and policy support can create self-reinforcing momentum toward large-scale adoption.

### **9.4.3- Balancing Loops (B)**

In contrast, the balancing feedback loops (B1–B8) introduce constraints, trade-offs, and stabilizing mechanisms that prevent unchecked expansion:

#### *B1 – Resource and Cost Constraint Loop*

Rapid capacity expansion increases material and energy demand, raising production costs and slowing further investment—a classic “limits to growth” effect.



### *B2 – Policy Adjustment Loop*

Subsidy expenditures and budgetary pressures trigger policy revisions that may dampen incentives and slow market diffusion.

### *B3 – Public Opposition Loop*

Negative perceptions arising from safety incidents or land-use conflicts increase social resistance, leading to stricter regulations and delayed projects.

### *B4 – Environmental Degradation Loop*

If hydrogen production relies on non-renewable sources, emission rebound effects occur, undermining sustainability gains and prompting regulatory correction.

### *B5 – Market Saturation Loop*

As adoption grows, marginal returns on investment decline, stabilizing production and limiting further growth rates.

### *B6 – Energy Security Loop*

Dependence on imported equipment or rare materials can constrain supply chains, slowing technology diffusion.

### *B7 – Technological Obsolescence Loop*

Rapid innovation can render existing infrastructure outdated, discouraging reinvestment and introducing pauses in expansion cycles.

### *B8 – Social Equity Loop*

Uneven distribution of economic benefits provokes social backlash, pressuring governments to redistribute subsidies or modify industrial strategies.

The coexistence of reinforcing and balancing feedbacks defines the dynamic equilibrium of the hydrogen economy. When reinforcing loops dominate, rapid expansion and innovation occur; when balancing loops strengthen, the system stabilizes or reorients. Managing this interplay is therefore central to effective energy policy design.

## **9.4.4- Systemic Interpretation within the FRISE Framework**

After building the new conceptual CLD model for sustainable hydrogen production as a case study considering the feedback loops reported in the literature (Table 9.2) for the sustainability

of the energy sector, 216 loops are identified (starting with the variable H<sub>2</sub> Sust. Prod). This quantity is significantly larger than the reported in previous studies. This is due to the fact that when the interdependencies are considered (among the economy, the environment, and the society), the complexity of this system emerges, and therefore, more reinforcing and balancing loops appear. This proves that the newly proposed three-paradigm model is able to capture the complexity of the energy sector (as a complex system considering hydrogen sustainable production as a case study) using the FRISE framework.

Figure 9.2 shows the causes tree of the variable Hydrogen Sustainable Production (H<sub>2</sub> Sust. Prod.) obtained using *Vensim*. Causal Tracing proves to be a potent tool for navigating through a model, identifying the factors responsible for driving changes. It illustrates the main factors directly related to the sustainability of hydrogen production such as the economic profits, the effectiveness of government policies, energy safety, environmental sustainability, investment in renewable energy, and social acceptance. Simultaneously, the main variables linked to these aforementioned factors are exposed.

Figure 9.3 shows the relationship between the length of each loop and the absolute frequency of each length. The average is around 13, which means that around 27% of the variables are involved in each loop by average. However, the length range is wide between 3 and 24, having 9, 14, and 15 lengths the highest frequencies.

From a FRISE perspective, the integrated hydrogen CLD functions as a macro-scale manifestation of systemic interdependence.

- The economic loops (R1, R3, R5, R7) parallel the Economic Module (ECO) of FRISE, emphasizing resource flows and profitability.
- The environmental loops (R2, R9, B4) mirror the Environmental Module (ENV), highlighting emission control and renewable integration.
- The social loops (R4, R12, B3, B8) align with the Social Module (SOC), focusing on culture, trust, and regulatory legitimacy.
- The technological and safety aspects (R6, R10, R11, B7) connect to the Risk Assessment (RA) and Safety Management (SM) modules, ensuring continuity between micro- and macro-scale applications.

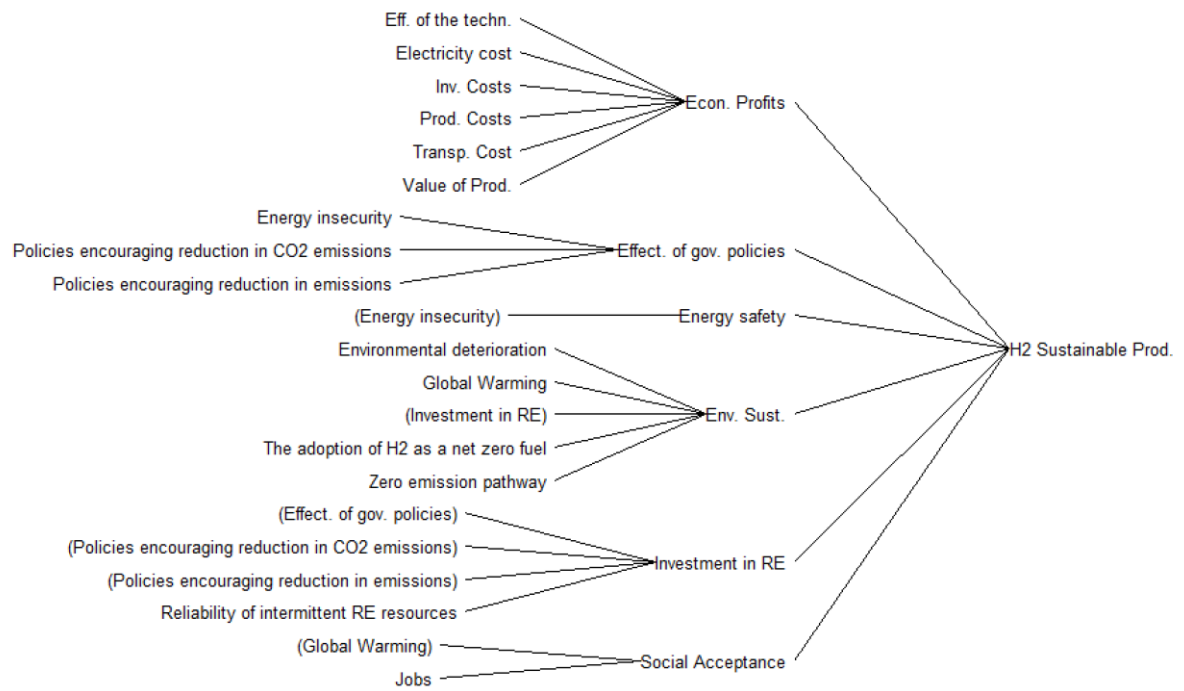


**Fig. 9.2- Causes tree for hydrogen sustainable production**

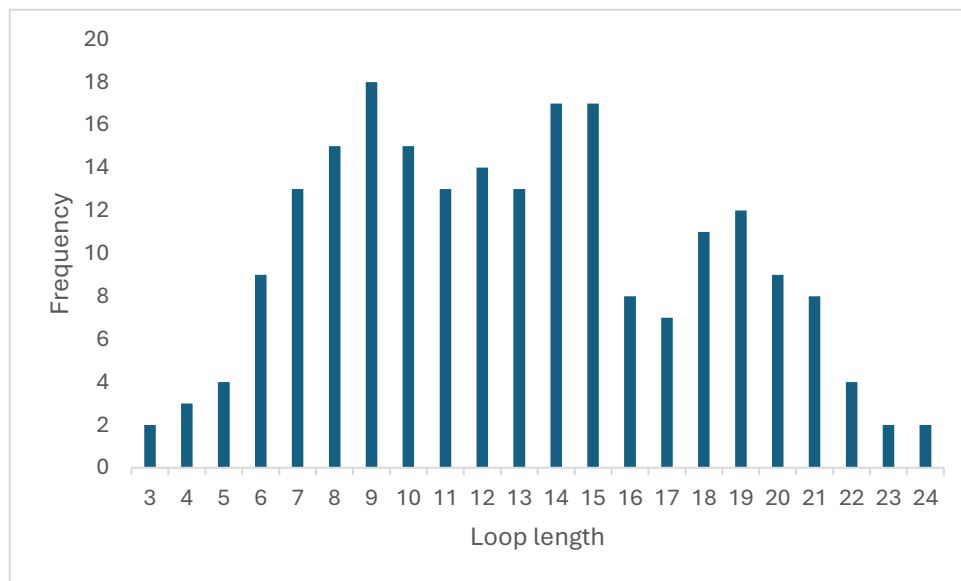


**Fig. 9.3- Relationship between the loop length and absolute frequency**

This systemic alignment confirms that the FRISE framework is structurally coherent across scales: the same conceptual architecture that described fire safety interactions at the building level now explains energy sustainability transitions at the global level.

#### 9.4.5- Insights from the Integrated CLD

The integrated model reveals that sustainability in the hydrogen economy is an emergent property of multiple intertwined feedbacks rather than the result of any single policy or technological factor. The system exhibits both virtuous and vicious cycles:

- Virtuous cycles occur when innovation, renewable integration, and public trust reinforce one another, leading to accelerated decarbonization.
- Vicious cycles arise when cost pressures, safety concerns, or inequitable benefits undermine social legitimacy and investment confidence.

Consequently, the hydrogen transition cannot be managed through linear planning or isolated interventions; it demands systemic governance that accounts for feedback interactions, delay effects, and cross-sectoral dependencies.

In summary, the integrated CLD for hydrogen sustainability provides a comprehensive qualitative representation of the hydrogen economy as a complex adaptive system. It constitutes the conceptual nucleus of the FRISE macro-application, linking technological, economic, environmental, and social dimensions through feedback logic. The following section (9.5) builds upon this representation by identifying System Archetypes that characterize recurrent behavioral patterns within the system and offer practical insight into policy leverage and system design.

#### **9.4.6-Validation and Graph-Theoretic (GT) Metrics of the Hydrogen CLD**

The structural validation of the integrated hydrogen sustainability model was performed through a graph-theoretic (GT) analysis. This approach aimed to verify whether the most central variables in the network corresponded to the theorized leverage points and feedback structures identified in the qualitative CLD. Using the MATLAB routine `cld_H2_GT.m`, the directed and signed causal network was analyzed to compute standard network-theoretic indicators, including in-degree, out-degree, betweenness, harmonic closeness, eigenvector centrality, PageRank, and the HITS hub–authority measures. The resulting metrics are summarized in the dataset output and visualized in Figure 9.1a–d, which presents the twenty most influential nodes according to PageRank, betweenness, and HITS rankings.

The quantitative structure of the network confirms the central role of Investment in Renewable Energy (RE) as the most influential and highly connected node in the system. It achieved the highest PageRank ( $\approx 0.064$ ) and betweenness value ( $\approx 977$ ), with a comparatively high harmonic closeness index, indicating that it lies on a large proportion of the shortest causal paths across the network. This dominant position highlights its function as a cross-subsystem broker linking environmental, economic, and policy domains. In systemic terms, Investment in RE acts as the main lever through which climate policies, energy security mechanisms, and hydrogen

adoption pathways converge, making it the principal transmission point for both stabilizing and destabilizing feedbacks within the model.

A second highly central cluster of variables corresponds to Energy Insecurity, Effectiveness of Government Policies, and Energy Production Capacity (EPC). These nodes occupy strategic bridging positions between subsystems. Energy Insecurity exhibits a very high eigenvector centrality (normalized to 1.00) and PageRank ( $\approx 0.060$ ), confirming its involvement in multiple influential feedback loops, particularly those governing energy supply resilience and policy adaptation (R9, R10, B3–B5). The variable Effectiveness of Government Policies shows equally strong brokerage characteristics, with high betweenness ( $\approx 402$ ) and PageRank ( $\approx 0.055$ ), functioning as the key mediator between insecurity, market behavior, and renewable investment. Together, these variables form the backbone of the policy–security subsystem, which aligns with the Fixes that Fail and Shifting the Burden archetypes: short-term policy interventions may relieve immediate insecurity but risk reinforcing long-term structural dependence unless systematically linked to renewable investment.

The third dominant node, Energy Production Capacity (EPC), recorded a high betweenness ( $\approx 684$ ) and eigenvector value ( $\approx 0.72$ ) as well as the largest out-degree (7), confirming its position as a central transmitter of influence. In the HITS analysis, EPC emerges as the top hub in the network, indicating that it functions as a major broadcaster of causal effects to multiple subsystems. This structural position reflects its economic significance and supports its interpretation as the operational core of the Growth and Underinvestment and Limits to Success archetypes. Within these patterns, insufficient investment or infrastructural constraints around EPC may amplify systemic vulnerabilities and eventually limit overall growth.

Beyond these structural anchors, the climate–policy cascade—comprising Net CO<sub>2</sub> Emissions, Atmospheric Greenhouse Gas Concentrations, Global Warming, Impacts, Concerns, and Policies Encouraging CO<sub>2</sub> Reduction—forms a continuous mid-level chain of nodes characterized by moderate PageRank (0.02–0.04) and betweenness values. Although these variables are essential conduits for sustainability-oriented feedback, their systemic influence is largely mediated through Investment in RE, which acts as the critical junction linking environmental awareness and economic action. The hydrogen-specific nodes—H<sub>2</sub> Sustainable Production, Fuel Cells Pathway, and Zero Emission Pathway—occupy mid-range positions in the network (PageRank  $\approx 0.027$ – $0.029$ ; betweenness  $\approx 135$ – $216$ ), confirming that they serve primarily as reinforcing subloops rather than structural controllers. Their systemic behavior

reflects their function as outcome variables that depend on the performance of upstream economic and policy drivers.

Market dynamics are also strongly represented in the quantitative topology. The Supply node demonstrates high eigenvector centrality ( $\approx 0.59$ ) and consistent PageRank ( $\approx 0.027$ ), while Demand appears among the ten most influential nodes. This pattern confirms the presence of the self-reinforcing supply–price–demand loop (R8), which amplifies diffusion effects across the system and validates the model’s inclusion of economic propagation mechanisms. Conversely, social variables such as Social Acceptance show moderate PageRank but low betweenness, suggesting that although public trust contributes to reinforcement within local adoption cycles, it exerts limited structural control across subsystems. This observation aligns with the model’s logic, where social legitimacy and awareness are emergent properties of broader environmental and economic performance.

The visual inspection of the network metrics (Figure 9.4) corroborates these interpretations. In the betweenness and PageRank distributions, Investment in RE and EPC dominate as global connectors, while Energy Insecurity and Policy Effectiveness form a secondary policy bridge. The HITS results further differentiate between broadcasting and receiving functions: EPC and Investment in RE appear as the leading hubs, disseminating influence across the system, whereas Energy Insecurity, Policy Effectiveness, and climate-related nodes rank high as authorities, representing causal endpoints where feedback accumulates.

Overall, the GT results confirm a coherent and interpretable structure. The centrality hierarchy closely mirrors the hypothesized feedback dominance derived from the CLD and the archetypal analysis, demonstrating high face validity. The model’s quantitative topology also reproduces the multi-scale logic of the FRISE framework: dominant economic and policy levers control the flow of feedback across environmental and social domains, while hydrogen-specific and behavioral variables play primarily reinforcing roles within subsystems. This coherence supports the conclusion that the CLD accurately captures the macro-systemic configuration of the hydrogen economy.

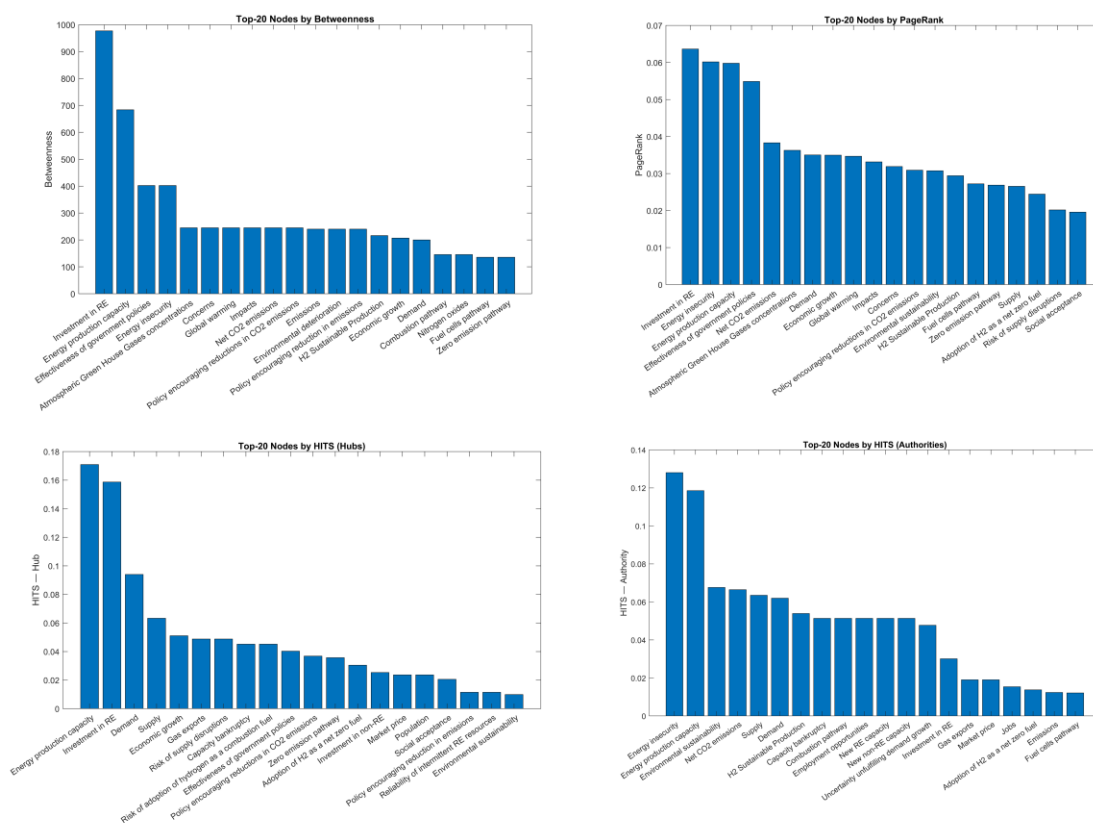


**Fig. 9.4- GT metrics obtained from the integrated CLD for energy sustainability**

From a methodological standpoint, the GT validation strengthens the reliability of the model by showing that the most connected and influential variables correspond to theoretically meaningful leverage points. The observed structural parallels between this macro-scale network and the meso- and micro-scale applications presented in previous chapters demonstrate the scalability and internal consistency of the FRISE framework. The hydrogen sustainability system thus exhibits a network architecture governed by a limited number of high-centrality nodes—principally Investment in RE, Energy Production Capacity, and Energy Insecurity—which mediate interactions between multiple domains. Their identification through GT analysis provides robust quantitative confirmation of the CLD’s systemic validity and reinforces the interpretation of the hydrogen economy as a tightly coupled socio-technical system driven by policy, energy capacity, and investment feedbacks.

## 9.5- System Archetypes in the Hydrogen Economy

The complex structure of the integrated hydrogen CLD (Figure 9.1 a–d) gives rise to recurrent dynamic patterns known as System Archetypes (SAs). These archetypes (Table 9.3), introduced in Chapter 2, reappear here at a macro-systemic scale, linking the 3P model (Sustainability–Complexity–Systems Thinking) with the FRISE framework.

Each archetype describes a characteristic configuration of reinforcing and balancing loops that produces recognizable behaviors in socio-technical systems. Understanding them provides guidance for diagnosing sustainability challenges and identifying effective leverage points. The following subsections discuss the eight main archetypes identified in the integrated hydrogen sustainability system.

**Table 9.3- System Archetypes in the Hydrogen Economy**

| <b>System Archetype</b>    | <b>Core Feedback Loops</b> | <b>Systemic Behavior / Dynamic Pattern</b>                                                                                                       | <b>Leverage Strategy for Sustainable Transition</b>                                                                                       |
|----------------------------|----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Fixes that Fail            | R10, B3–B5                 | Short-term policy fixes (e.g., subsidies or fossil-based hydrogen) temporarily stabilize supply but increase long-term dependence and emissions. | Couple short-term stabilization policies with structural reforms; ensure temporary measures feed long-term sustainability pathways.       |
| Shifting the Burden        | R5, R9, B8                 | Reliance on symptomatic solutions such as transitional fuels or subsidies delays fundamental changes toward renewable hydrogen.                  | Prioritize systemic solutions (R&D, infrastructure, education) over compensatory fixes; phase-out fossil incentives with clear timelines. |
| Growth and Underinvestment | R6–R8, B2                  | Rapid market expansion outpaces investment in sustainable capacity, causing reliability decline and reinforcing underperformance.                | Increase early investment in green infrastructure, innovation, and skills; align policy incentives with long-term capacity growth.        |
| Limits to Success          | R1–R2, R4, B1              | Initial growth of sustainable hydrogen is constrained by physical, resource, or regulatory limits that reduce expansion rates.                   | Identify potential bottlenecks early; diversify renewable inputs, enhance efficiency, and apply anticipatory planning to overcome limits. |
| Drifting Goals             | R1, R12, B8                | Progressive relaxation of sustainability standards and shifting objectives reduce alignment with long-term decarbonization goals.                | Institutionalize fixed sustainability targets; establish periodic reviews and transparent accountability mechanisms.                      |
| Success to the Successful  | R7, R8, R12                | Dominant technologies attract most resources, crowding out emerging sustainable alternatives and reducing system diversity.                      | Ensure balanced R&D funding, technology-neutral policies, and plural innovation ecosystems to maintain adaptability.                      |
| Escalation                 | R11, R13, B6–B7            | Competitive pressures among nations and firms escalate investment and resource use, amplifying environmental impacts.                            | Promote cooperative frameworks and global sustainability standards to direct competition toward shared decarbonization goals.             |
| Tragedy of the Commons     | R11, R13, B7               | Overexploitation of shared resources (renewables, water, land, materials) undermines collective sustainability and equity.                       | Strengthen governance of common resources, apply life-cycle management, and enforce equitable use regulations.                            |



### **9.5.1- Fixes that Fail – Short-Term Solutions and Long-Term Instability**

This archetype (loops R10, B3–B5 in Figure 9.1 c) describes a situation where short-term policy interventions—such as subsidizing grey or blue hydrogen to stabilize markets—temporarily relieve energy insecurity but reinforce dependency on carbon-intensive pathways. Over time, the “fix” generates unintended consequences: higher emissions, technology lock-in, and delayed renewable investment.

The corrective balancing loops emerge only after significant deterioration, increasing system volatility.

In the 3P–FRISE context, this archetype highlights the temporal imbalance between rapid policy responses (Complexity → delay effects) and long-term sustainability objectives (Sustainability → adaptive management). Leverage lies in coupling emergency measures with structural transitions, ensuring that short-term relief contributes to long-term system transformation.

### **9.5.2- Shifting the Burden – Dependence on Transitional Fuels and External Support**

The Shifting the Burden structure (loops R5, R9, B8) is closely related but emphasizes reliance on symptomatic rather than fundamental solutions. In hydrogen systems, this appears as preference for fossil-based hydrogen (blue or grey H<sub>2</sub>) because of its immediate availability and lower cost, while delaying the deployment of green H<sub>2</sub> infrastructure.

The symptomatic reinforcing loop sustains the current system, while the fundamental solution—renewable-based production—remains underdeveloped. This archetype warns that policy dependency and economic inertia can erode long-term innovation. Systemic leverage requires shifting investment from short-term compensation (subsidies) toward capacity-building, R&D, and institutional reform that enable self-sustaining transitions.

### **9.5.3- Growth and Underinvestment – Rapid Expansion without Structural Capacity**

The Growth and Underinvestment archetype (loops R6–R8 and B2 in Figure 9.1 a) describes how rapid industrial growth can exceed the rate of infrastructure and R&D investment needed for sustainability.

As global demand for hydrogen rises, production capacity expands, but investment in renewable supply chains and skilled workforce often lags. Underinvestment reduces system reliability, which in turn discourages further financing—a self-reinforcing decline. This archetype demonstrates that capacity constraints and delayed investment constitute hidden

limits to sustainability. Addressing it requires early, sustained investment in green technologies, education, and infrastructure, ensuring that the growth of demand is matched by the growth of sustainable capacity.

#### **9.5.4- Limits to Success – Resource and Environmental Constraints**

In the Limits to Success configuration (loops R1–R2, R4, B1), early achievements in sustainable hydrogen production encounter physical or regulatory constraints that slow further expansion.

Resource scarcity (renewable land, water, or rare materials), or stricter environmental standards, act as balancing forces that counteract reinforcing innovation. When these limits are reached, stakeholders may revert to less sustainable production routes to meet demand. Proactive management of this archetype involves anticipatory governance—identifying potential bottlenecks and investing in diversification, material efficiency, and regulatory flexibility.

Within FRISE, it illustrates how the environmental module constrains the economic one, preserving systemic balance.

#### **9.5.5- Drifting Goals – Erosion of Sustainability Ambition**

The Drifting Goals archetype (loops R1, R12, B8 across Figures 9.1 a and c) captures the gradual relaxation of sustainability standards as economic or political pressures intensify.

Over time, performance benchmarks are adjusted downward—e.g., redefining “low-carbon hydrogen” thresholds—to maintain short-term viability. This drift undermines credibility and long-term environmental objectives. Leverage lies in institutionalizing explicit, time-bound targets and embedding feedback mechanisms for regular goal review. Maintaining alignment between policy intent and performance outcomes prevents the erosion of systemic resilience.

#### **9.5.6- Success to the Successful – Technological and Market Lock-in**

This archetype (loops R7, R8, R12) emerges when established technologies attract more investment and policy support, reinforcing their dominance and marginalizing emerging innovations.

The resulting concentration of resources perpetuates existing production paradigms—such as large-scale electrolysis—while alternative pathways (e.g., photochemical, biomass-derived H<sub>2</sub>) struggle to scale. Balancing incentives across technologies and regions is essential to avoid innovation monocultures.

Within the FRISE framework, this archetype demonstrates the need for diversity and redundancy in socio-technical systems to sustain adaptability.

#### **9.5.7- Escalation – Competitive Pressures and Resource Overconsumption**

The Escalation pattern (loops R11, R13 and B6–B7 in Figure 9.1 d) depicts how national or corporate competition for leadership in hydrogen markets can generate self-reinforcing increases in production, investment, and resource use. Each actor’s progress is perceived as a challenge by others, leading to an acceleration in spending and resource exploitation.

While this can spur innovation, it also increases environmental footprints and price volatility. Mitigating this archetype requires international coordination and shared standards to channel competitive dynamics toward collective sustainability goals. Global monitoring and cooperation thus represent key balancing mechanisms.

#### **9.5.8- Tragedy of the Commons – Overuse of Shared Environmental and Resource Assets**

Finally, the Tragedy of the Commons archetype appears implicitly across environmental and global-emission loops (R11, R13 and B7). Hydrogen production depends on shared resources—renewable electricity, water, land, and critical materials.

When each stakeholder seeks to maximize individual benefit, cumulative extraction exceeds sustainable thresholds, degrading common environmental goods. To counter this behavior, governance of shared resources is vital. Integrating life-cycle accounting, water-use regulation, and circular-economy principles prevents collective overexploitation and ensures long-term viability of the hydrogen sector.

#### **9.5.9- Synthesis and Policy Insights**

The eight archetypes identified—Fixes that Fail, Shifting the Burden, Growth and Underinvestment, Limits to Success, Drifting Goals, Success to the Successful, Escalation, and Tragedy of the Commons—represent the core dynamic structures of the hydrogen economy.

Their coexistence confirms that sustainability challenges arise not from isolated failures but from systemic feedback interactions among economic, environmental, and social domains. Within the FRISE framework, these archetypes act as diagnostic instruments to:

- Detect structural weaknesses (e.g., underinvestment, dependency, or goal drift);
- Identify leverage points for adaptive policy (e.g., early capacity investment, policy coupling, resource governance); and

- Translate complex feedback behavior into strategic decision-making rules for sustainable energy governance.

By recognizing and managing these archetypes, policymakers can move from reactive interventions to proactive system design, aligning the hydrogen transition with the overarching goals of safety, resilience, and sustainability.

### **9.6- Discussion: Systemic Insights for the Hydrogen Economy**

The results of the integrated hydrogen sustainability model and its graph-theoretic validation provide a coherent systems-level understanding of how the hydrogen economy behaves as a complex socio-technical system. The analysis demonstrates that the hydrogen transition is not governed by any single driver, policy, or technological solution, but by the interaction of multiple feedback structures that jointly determine its long-term stability and sustainability. Within the FRISE framework, this application represents the macro-scale synthesis in which the economic, environmental, and social modules converge, revealing emergent patterns that govern system-wide evolution.

The graph-theoretic results confirm that the hydrogen economy is structurally organized around a small set of highly influential variables—Investment in Renewable Energy (RE), Energy Production Capacity (EPC), Energy Insecurity, and Effectiveness of Government Policies. These nodes act as systemic control points through which most causal paths intersect, effectively mediating the dynamics of all other variables in the network. The position of Investment in RE as the global broker of feedbacks indicates that renewable deployment is the main integrative mechanism linking economic growth, emission reduction, and social acceptance. This finding aligns with the conceptual interpretation of the Fixes that Fail and Shifting the Burden archetypes, where temporary reliance on conventional energy sources postpones but does not replace the need for structural investment in renewable capacity. As the network metrics show, such investment not only improves environmental performance but also enhances policy credibility and public confidence, reinforcing a virtuous cycle of sustainability and innovation.

Similarly, Energy Production Capacity emerges as a key operational hub that transmits perturbations between subsystems. Its high connectivity and hub centrality indicate that capacity expansion decisions exert strong cascading effects on market dynamics, emission levels, and employment. This structural position explains why underinvestment or technological bottlenecks in EPC can produce systemic stagnation—a manifestation of the

Growth and Underinvestment and Limits to Success archetypes. Conversely, balanced growth supported by adequate infrastructure and policy foresight can transform EPC into a stabilizing node that maintains equilibrium among supply, demand, and environmental constraints.

The policy subsystem—represented by Energy Insecurity and Effectiveness of Government Policies—plays a dual role as both a driver and a response mechanism within the system. The high eigenvector and authority scores of these nodes illustrate their sensitivity to feedback accumulation: policy actions respond to the state of the system but also reshape it through regulatory adaptation. This bidirectional relationship reflects the complexity of energy governance, where the interplay between short-term security objectives and long-term sustainability goals determines the pace and direction of transition. The model thereby confirms the presence of the Fixes that Fail dynamic at a policy scale: without continuous structural learning and feedback monitoring, policies risk addressing symptoms rather than underlying causes.

The climate-policy cascade—linking Net CO<sub>2</sub> Emissions, Greenhouse Gas Concentrations, Global Warming, Impacts, Concerns, and Policy Responses—forms a mid-level subsystem that regulates environmental feedbacks. Although each variable individually exhibits moderate centrality, their serial interconnection constitutes a coherent regulatory pathway that channels information and political attention toward Investment in RE. This pattern mirrors real-world policy feedback cycles, where public and environmental pressures are translated into regulatory interventions. The structural location of this chain within the network illustrates how the environmental dimension operates as a “slow variable” that shapes policy perception and technological adaptation through delayed but persistent influence.

The hydrogen-specific nodes—H<sub>2</sub> Sustainable Production, Fuel Cell Pathway, and Zero Emission Pathway—occupy intermediate positions in the network, signifying that they are products of system behavior rather than independent levers of change. Their moderate PageRank and betweenness values suggest that technological advancement in hydrogen production, while essential for environmental outcomes, depends fundamentally on upstream investment and policy stability. This insight reinforces the interpretation of the hydrogen economy as a dependent subsystem embedded within a larger socio-economic and political context. Achieving sustainable hydrogen production, therefore, requires addressing systemic dependencies rather than focusing solely on technological optimization.

From a socio-political perspective, Social Acceptance exhibits a supportive yet secondary role within the network hierarchy. Its position as a reinforcing variable indicates that public trust amplifies successful transitions but cannot initiate them independently. This result resonates with the conceptual understanding developed in earlier FRISE modules, where social legitimacy was identified as a derivative function of perceived safety, transparency, and economic fairness. In the context of hydrogen, visible progress in renewable deployment and safety assurance is essential to sustain acceptance, completing the feedback loop between technological credibility and societal endorsement.

The overall network topology reveals a high degree of connectivity and modular interdependence, consistent with the FRISE assumption that sustainability transitions exhibit fractal-like systemic behavior across scales. The hydrogen CLD reproduces the same architectural features observed in previous applications at smaller scales—strong coupling between technical, economic, and regulatory domains; dominant broker nodes linking modules; and the coexistence of reinforcing and balancing feedbacks that jointly determine system resilience. This structural homology provides strong evidence of the internal coherence and scalability of the FRISE framework. It demonstrates that the methodological workflow—comprising CLD development, system archetype identification, and GT validation—can be consistently applied from micro-level safety systems to macro-level sustainability transitions.

From a policy and governance standpoint, the insights derived from this analysis emphasize the need for systemic alignment between investment, regulation, and innovation. The identification of Investment in RE as the main network broker underscores that sustained financial and policy commitment to renewables is the principal enabler of a stable hydrogen transition. The centrality of Energy Insecurity and Policy Effectiveness reveals that managing uncertainty and ensuring institutional adaptability are equally critical. Without integrated governance that coordinates short-term energy security measures with long-term decarbonization strategies, reinforcing loops may give rise to rebound effects that undermine sustainability objectives. Conversely, well-calibrated policies that leverage feedback awareness can transform potential instabilities into self-regulating mechanisms, steering the hydrogen system toward equilibrium.

Finally, the GT analysis validates the structural fidelity of the CLD by confirming that the empirically meaningful leverage points coincide with the theoretically derived ones. The coherence between the quantitative network topology and the qualitative system logic enhances

the credibility of the model and consolidates the FRISE framework as a robust methodological architecture for multi-domain sustainability analysis. In this sense, the hydrogen economy application not only extends the framework to a macro-systemic domain but also provides empirical evidence of its capacity to integrate diverse subsystems—risk, safety, economics, environment, and society—into a single, consistent representation. The hydrogen transition thus emerges as a paradigmatic example of a complex adaptive system whose evolution is governed by feedback, delay, and interdependence, embodying the principles of sustainability, complexity, and systems thinking at the core of the FRISE approach.

### **9.7- Cross-Modular Integration Layer of the FRISE framework**

The Cross-Modular (CM) layer represents the integrative structure through which the five FRISE modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—interact as a cohesive socio-technical system. Unlike the single-domain causal structures analyzed in previous sections, the CM system establishes multi-directional causalities that link operational, managerial, environmental, economic, and societal dimensions. The result is a dynamic meta-network in which risk, sustainability, and resilience are no longer contained within disciplinary boundaries but co-evolve through regulatory, behavioral, and performance-driven feedback loops.

Figure 9.5 illustrates the integrated causal loop diagram (CLD) obtained from the modular synthesis, showing how each subsystem retains its internal balancing and reinforcing feedbacks while new cross-connections generate higher-order interactions. These cross-modular linkages are not simply additive; they create emergent coupling effects that govern how disturbances propagate between technical reliability, organizational adaptation, environmental performance, and social legitimacy. Such coupling is fundamental to achieving holistic system resilience, as emphasized in systemic safety literature (Bouloiz et al., 2013; Cozzani et al., 2014; Zio, 2016; Reniers & Cozzani, 2013).

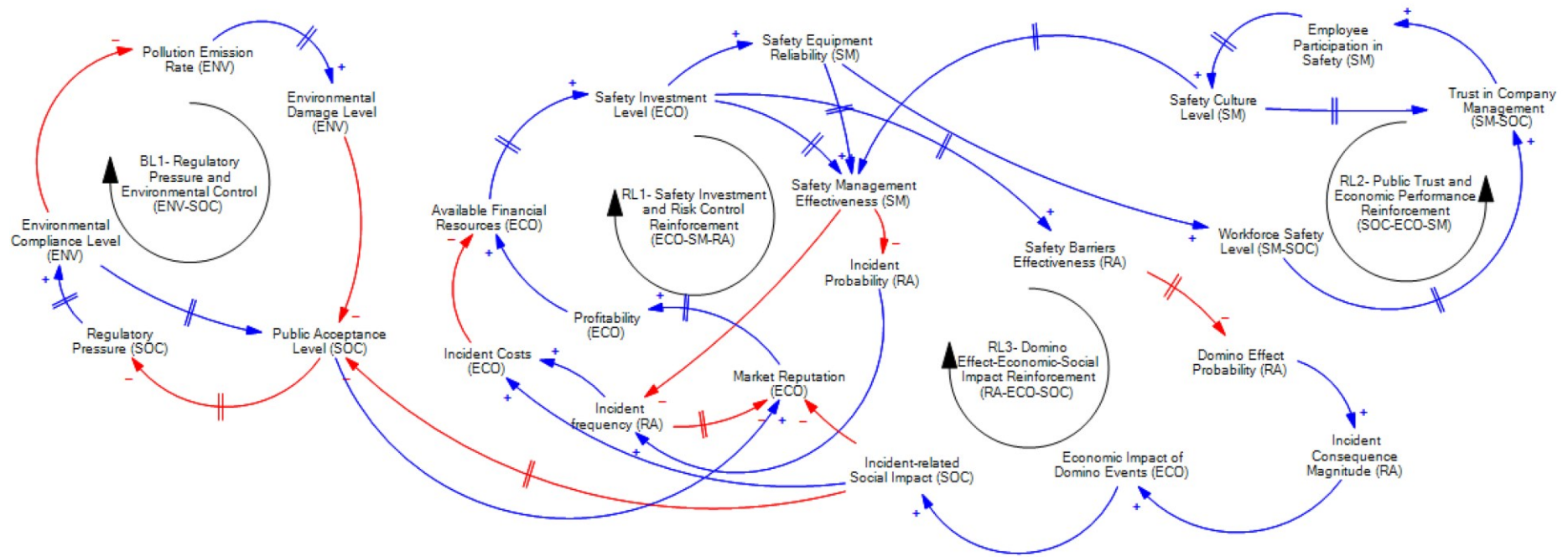


Fig. 9.5- Cross-modular layer representation for the FRISE framework



### 9.7.1- Feedback Loops of the Cross-Modular (CM) System

Three dominant systemic feedback structures emerge from the integrated network (Table 9.4). Each loop connects variables belonging to different FRISE modules, thereby defining the cross-domain dynamics that govern systemic evolution.

#### **(1) RL<sub>1</sub> – Safety Investment and Risk Control Reinforcement (ECO–SM–RA)**

This reinforcing loop bridges the Economic, Safety Management, and Risk Assessment subsystems. Increases in available financial resources (AFR) stimulate higher safety investment (SIL), which enhances equipment reliability (SER) and Safety Management Effectiveness (SME). Improved SME strengthens the performance of safety barriers in the RA network (PBE, MBE, EBE, IDRE), thereby lowering incident frequency (IF) and related costs (IC). Reduced incident costs restore financial resources, closing a positive loop that couples economic performance with risk reduction. The loop highlights the central principle of safety-investment synergy, where proactive expenditure generates cumulative returns in both safety and profitability (Reniers & Cozzani, 2013; Zio, 2016).

#### **(2) RL<sub>2</sub> – Public Trust and Economic Performance Reinforcement (SOC–ECO–SM)**

This loop links social acceptance and organizational trust with financial and safety performance. Higher Trust in Company Management (TCM) and Workforce Safety Level (WSL) reinforce employee participation (EPS) and safety culture (SCL), improving SME and reducing incidents (IF). Lower incident frequency reduces economic losses and improves market reputation (MRS), which in turn enhances public acceptance (PAL) and reinforces trust (TCM). The loop therefore captures a resilience pathway based on stakeholder confidence and socio-economic legitimacy, echoing findings in organizational resilience and safety-culture literature (Reason, 1997; Ibrahim et al., 2018; Le Coze, 2019).

#### **(3) BL<sub>1</sub> – Regulatory Pressure and Environmental Control (ENV–SOC)**

This balancing mechanism couples environmental compliance and societal pressure. Higher Environmental Damage Level (EDL) increases Regulatory Pressure (RP) and triggers corrective compliance (ECL) actions. Improved environmental compliance raises Public Acceptance Level (PAL), reducing opposition and thus mitigating regulatory intensity. This loop prevents environmental degradation from escalating unchecked and represents a socio-

environmental self-regulation mechanism where social legitimacy stabilizes environmental performance (Cozzani et al., 2014; Tugnoli et al., 2022).

#### (4) **RL<sub>3</sub> – Domino Effect–Economic–Social Impact Reinforcement (RA–ECO–SOC)**

This reinforcing structure interlinks physical risk escalation with socio-economic feedbacks. Increases in Incident Frequency (IF) and Incident Consequence Magnitude (ICM) raise economic losses (IC) and social impact (ISI), which depress market reputation (MRS) and public acceptance (PAL). Reduced legitimacy and financial capability, in turn, weaken prevention investments and risk control, allowing new incidents to occur. This coupling illustrates how accident propagation can transcend the technical layer and cascade into economic and societal deterioration, emphasizing the systemic nature of domino effects (Zio, 2016; Reniers & Cozzani, 2013).

**Table 9.4 – Feedback loops of the Cross-Modular (CM) system**

| Loop ID                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Type        | Dominant Pathway                                            | Functional Description                                                                                                                        | Modules Involved | Expected Systemic Effect                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|-------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|------------------|-------------------------------------------------|
| RL <sub>1</sub>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Reinforcing | AFR → SIL → SER → SME → Barriers → IF ↓ → IC ↓ → AFR ↑      | Safety investment and reliability improvement cycle linking financial capacity to risk mitigation and resource recovery                       | ECO–SM–RA        | Synergistic safety–profitability enhancement    |
| RL <sub>2</sub>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Reinforcing | TCM → EPS → SCL → SME → IF ↓ → IC ↓ → MRS ↑ → PAL ↑ → TCM ↑ | Socio-organizational trust and performance reinforcement through feedback between safety culture, profitability, and stakeholder satisfaction | SOC–ECO–SM       | Trust-driven resilience and legitimacy building |
| BL <sub>1</sub>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Balancing   | EDL ↑ → RP ↑ → ECL ↑ → EDL ↓ → PAL ↑ → RP ↓                 | Regulation–compliance feedback maintaining environmental and social equilibrium                                                               | ENV–SOC          | Stabilization of environmental degradation      |
| RL <sub>3</sub>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Reinforcing | IF ↑ → ICM ↑ → IC ↑ → ISI ↑ → PAL ↓ → Investment ↓ → IF ↑   | Coupled economic–social deterioration loop driven by incident escalation and loss of legitimacy                                               | RA–ECO–SOC       | Cascading risk and degradation of resilience    |
| RA = Risk Assessment; SM = Safety Management; ECO = Economic; ENV = Environmental; SOC = Social; AFR = Available Financial Resources; SIL = Safety Investment Level; SER = Safety Equipment Reliability; SME = Safety Management Effectiveness; PBE/MBE/EBE/IDRE = Preventive/Mitigative/Escalation/Detection Barriers Effectiveness; IF = Incident Frequency; ICM = Incident Consequence Magnitude; IC = Incident Costs; MRS = Market Reputation and Share; RP = Regulatory Pressure; ECL = Environmental Compliance Level; EDL = Environmental Damage Level; PAL = Public Acceptance Level; TCM = Trust in Company Management; SCL = Safety Culture Level; WSL = Workforce Safety Level; ISI = Incident-related Social Impact; CR = Community Resilience; ERE = Emergency Response Effectiveness. |             |                                                             |                                                                                                                                               |                  |                                                 |

Together, these loops define the macro-architecture of the FRISE system: RL<sub>1</sub> and RL<sub>2</sub> act as long-term reinforcement mechanisms that drive system improvement and trust accumulation, while BL<sub>1</sub> provides regulatory stabilization and RL<sub>3</sub> captures potential degeneration under

stress. The coexistence of these structures explains the emergent behavior of safety-sustainability transitions—oscillating between growth, stabilization, and collapse depending on delays and coupling strength.

### 9.7.2- Structural Relationships and Causal Parameters of the CM Network

The CM integration introduced a set of new causal links connecting variables across the five domains (Table 9.5). Each edge captures a cross-domain dependency verified conceptually through literature and the modular CLDs. The polarity (+/−) indicates whether the cause reinforces or counteracts the effect, while the delay (0/1) represents the temporal lag due to management, perception, or adaptation processes. Weights (1–2) indicate relative influence strength as used in the MATLAB implementation.

**Table 9.5 – Structural relationships and causal parameters of the Cross-Modular (CM) network**

| From      | To                      | Sign | Delay | Weight | Interpretation                                                                    | References                                             |
|-----------|-------------------------|------|-------|--------|-----------------------------------------------------------------------------------|--------------------------------------------------------|
| RP (SOC)  | ECL (ENV)               | +    | 1     | 2      | Regulatory pressure from societal response enhances environmental compliance      | Cozzani et al., 2014; Tugnoli et al., 2022             |
| EDL (ENV) | PAL (SOC)               | −    | 0     | 2      | Environmental degradation reduces public acceptance and social license to operate | Reniers & Cozzani, 2013; Dueñas Santana et al., 2024   |
| SIL (ECO) | SER (SM)                | +    | 0     | 1      | Economic investment strengthens equipment reliability                             | Reniers & Cozzani, 2013                                |
| SER (SM)  | SME (SM)                | +    | 1     | 1      | Improved reliability enhances management effectiveness (lagged)                   | Zio, 2016                                              |
| SME (SM)  | PBE/ MBE/ EBE/ DRE (RA) | +    | 1     | 1      | Strengthened safety management boosts barrier effectiveness                       | Bouloiz et al., 2013                                   |
| IF (RA)   | IC (ECO)                | +    | 0     | 2      | Incidents increase economic losses and costs                                      | Reniers & Cozzani, 2013                                |
| IF (RA)   | MRS (ECO)               | −    | 1     | 2      | High incident frequency erodes market reputation with delay                       | Le Coze, 2019                                          |
| ICM (RA)  | IC (ECO)                | +    | 0     | 2      | Large consequence magnitude amplifies cost and resource erosion                   | Zio, 2016                                              |
| DEP (RA)  | IC (ECO)                | +    | 0     | 1      | Escalation paths increase financial exposure                                      | Bouloiz et al., 2013                                   |
| ISI (SOC) | IC (ECO)                | +    | 0     | 1      | Social disruption due to incidents amplifies economic costs                       | Reniers & Cozzani, 2013; Dueñas Santana et al., (2022) |
| ISI (SOC) | MRS (ECO)               | −    | 1     | 2      | Public concern reduces reputation and profitability over time                     | Le Coze, 2019                                          |
| SCL (SM)  | TCM (SOC)               | +    | 1     | 1      | Mature safety culture increases organizational trust with delay                   | Reason, 1997; Guldenmund, 2010                         |
| ECL (ENV) | PAL (SOC)               | +    | 1     | 1      | Environmental compliance improves social acceptance                               | Cozzani et al., 2014                                   |

The cross-modular configuration operationalizes the systemic “glue” of the FRISE framework by merging technical, managerial, economic, environmental, and social dynamics into a single causal structure. The newly introduced interconnections transform local feedbacks into global behavior patterns, enabling both positive synergies and potential cross-domain cascades. Reinforcing mechanisms (RL<sub>1</sub>, RL<sub>2</sub>, RL<sub>3</sub>) drive long-term co-evolution between safety, trust, and sustainability, whereas the balancing mechanism (BL<sub>1</sub>) imposes adaptive regulation through social and environmental accountability.

These structures demonstrate that resilience in complex industrial systems is not achieved through isolated optimization but through the coordinated management of multiple, interacting feedbacks across organizational layers. The subsequent subsection will quantify these dynamics using graph-theoretical metrics, identifying central nodes, mediators, and leverage points within the integrated FRISE architecture.

### **9.7.3- Graph-Theoretical Analysis of the Cross-Modular (CM) Network**

The integration of all five FRISE modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—into a unified cross-modular structure produces a dense and highly interdependent network. The CM configuration contains 40 nodes and 92 directed causal links, connecting previously isolated domains into a coherent systemic architecture.

The graph-theoretical metrics (Figure 9.6) provide quantitative evidence of how information, control, and feedback circulate across the integrated system. Each centrality measure highlights a distinct dimension of systemic behavior: betweenness identifies brokers that mediate feedback propagation, eigenvector and PageRank measure influence and connectivity prestige, and hubs/authorities indicate the asymmetry between initiating and receiving roles within cross-domain causality.

The metrics reveal a complex hierarchy of interdependencies in which *incident-related*, *management*, and *economic* nodes dominate the global topology, while *social* and *environmental* variables play key stabilizing and legitimizing roles. These results confirm that the CM layer functions as a “systemic glue,” dynamically coupling technical risk mechanisms with managerial, financial, and societal feedbacks—consistent with systems-of-systems theory and recent sustainability-driven risk frameworks (Cozzani et al., 2014; Zio, 2016; Reniers & Cozzani, 2013).

### (1) *Structural mediation and network brokerage*

The betweenness centrality (Figure 9.6) distribution exposes the nodes that act as major brokers of information and control pathways. *Incident Frequency (IF)* presents the highest value ( $\approx 772$ ), confirming its role as the dominant systemic conduit between risk generation and downstream economic and social impacts. *Safety Management Effectiveness (SME)* ( $\approx 394$ ) and *Regulatory Pressure (RP)* ( $\approx 596$ ) also show extremely high betweenness, indicating that both managerial performance and institutional oversight constitute the primary stabilizing channels across modules. *Incident Consequence Magnitude (ICM)* and *Safety Investment Level (SIL)* follow as secondary brokers, reflecting how consequence control and economic investment operate as major transmitters of influence.

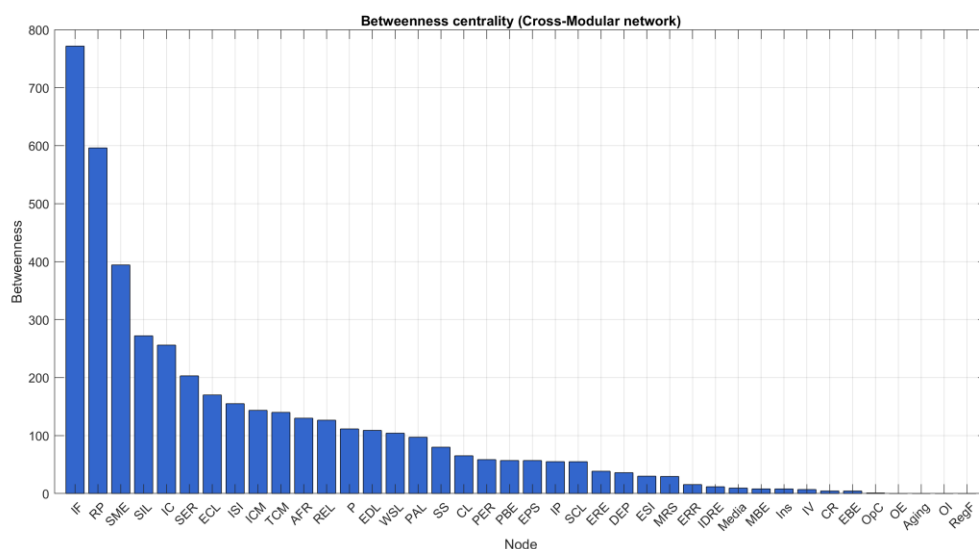


**Fig. 9.6- Betweenness centrality for the CM-FRISE framework**

The collective interpretation of these metrics indicates that the CM system is not centralized in one domain but governed by three coordination cores:

1. the risk-management core (*IF–SME–ICM*),
2. the economic-investment core (*AFR–SIL–IC*), and
3. the regulatory-pressure core (*RP–ECL–PAL*).

These nodes together maintain feedback connectivity between the physical, managerial, and societal subsystems, supporting a networked resilience structure rather than a purely hierarchical one (Zio, 2016; Bouloiz et al., 2013).

## (2) Influence propagation and systemic prestige

The PageRank (Figure 9.7) and eigenvector centralities together capture the long-range influence of nodes considering both direct and indirect connections. *SIL* (PageRank  $\approx 0.085$ , eigenvector = 1.0) ranks as the most influential node in the entire CM network, confirming that economic investment decisions exert the broadest systemic leverage across all modules. The next most influential variables are *IC* (0.065), *RP* (0.053), *AFR* (0.058), *IF* (0.043), and *P* (0.075).

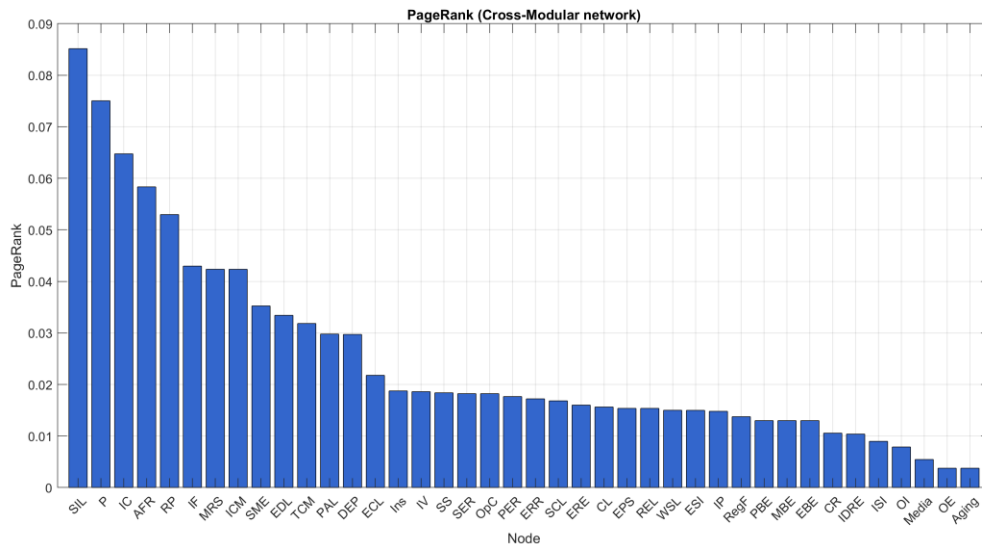


Fig. 9.7- PageRank centrality for the CM-FRISE framework

This ranking pattern shows that economic and regulatory drivers dominate systemic influence, but their effects depend on risk and managerial performance as intermediaries. *AFR* and *SIL* connect the financial dimension to safety performance, *IC* translates physical losses into economic degradation, and *RP* links environmental and social legitimacy to technical behavior. Together, these metrics quantitatively validate the reinforcing loops  $RL_1$  and  $RL_2$  identified earlier: financial and cultural investment simultaneously enhance safety and profitability, while regulation provides external damping to maintain equilibrium (Reniers & Cozzani, 2013; Reason, 1997; Le Coze, 2019).

### (3) Hub–authority asymmetry and causal polarity

The HITS analysis (Figures 9.8-9.9) further reveals asymmetries between causal initiators (hubs) and recipients (authorities). *SIL* (hub = 0.158) and *IF* (0.192) emerge as the strongest hubs, initiating numerous high-impact interactions across domains. Conversely, *IC* (authority = 0.156) and *MRS* (0.151) dominate as key receivers, integrating multiple causal inflows from risk, social, and economic subsystems.

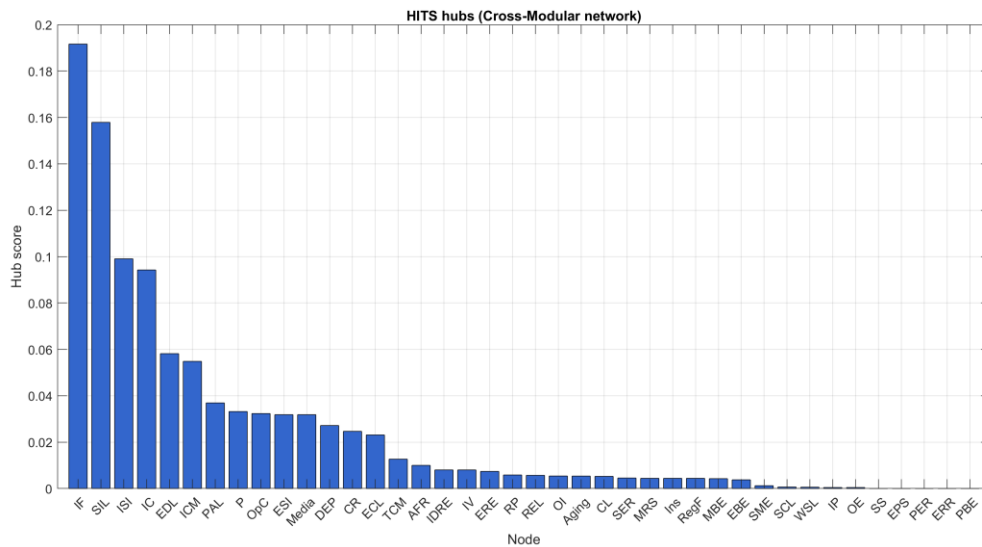


**Fig. 9.8- HITS hubs for the CM-FRISE framework**

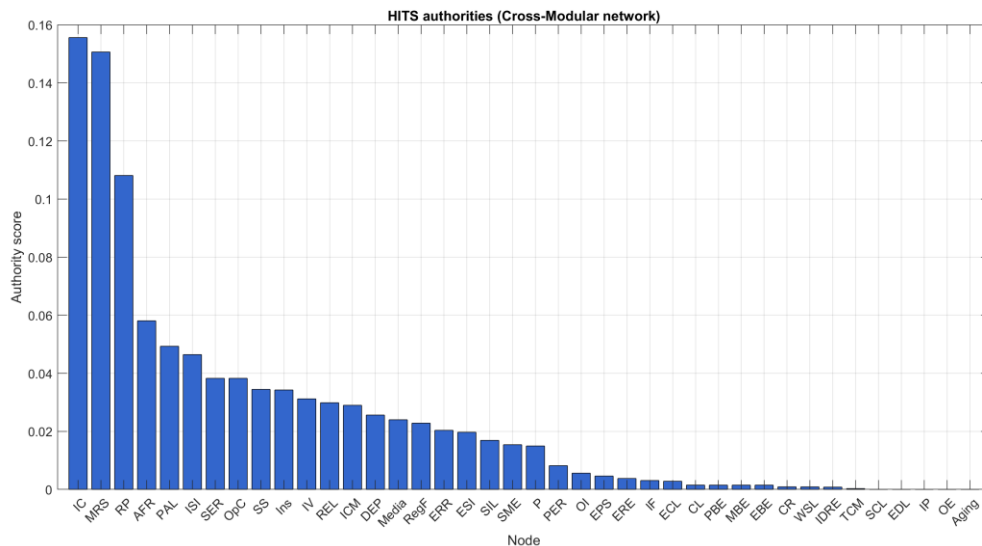


**Fig. 9.9- HITS Authorities for the CM-FRISE framework**

This asymmetry demonstrates that the CM network follows a cause–effect stratification:

- Upstream hub nodes (e.g., *SIL*, *IF*, *ICM*, *RP*) trigger system-wide feedback propagation.
- Downstream authority nodes (e.g., *IC*, *MRS*, *RP*) absorb and translate signals into measurable organizational or reputational outcomes.

Such asymmetry corresponds with multi-level resilience theory, where proactive decision variables (investment, regulation, safety culture) initiate positive reinforcement, while reactive nodes (costs, reputation, acceptance) encode adaptive feedback and institutional learning (Hollnagel et al., 2015; Reniers & Cozzani, 2013).

#### (4) *Connectivity, sensitivity, and harmonic centrality*

Harmonic closeness centrality (Figure 9.10) measures how efficiently a node can reach all others through direct and indirect pathways. The CM system exhibits overall high connectivity (values  $> 0.5$  for most influential nodes), confirming that cross-domain coupling has significantly shortened causal distances. *IF* (0.97), *RP* (0.87), *EDL* (0.69), *SIL* (0.67), and *IC* (0.66) have the highest harmonic closeness, implying that these variables can quickly disseminate effects throughout the network.

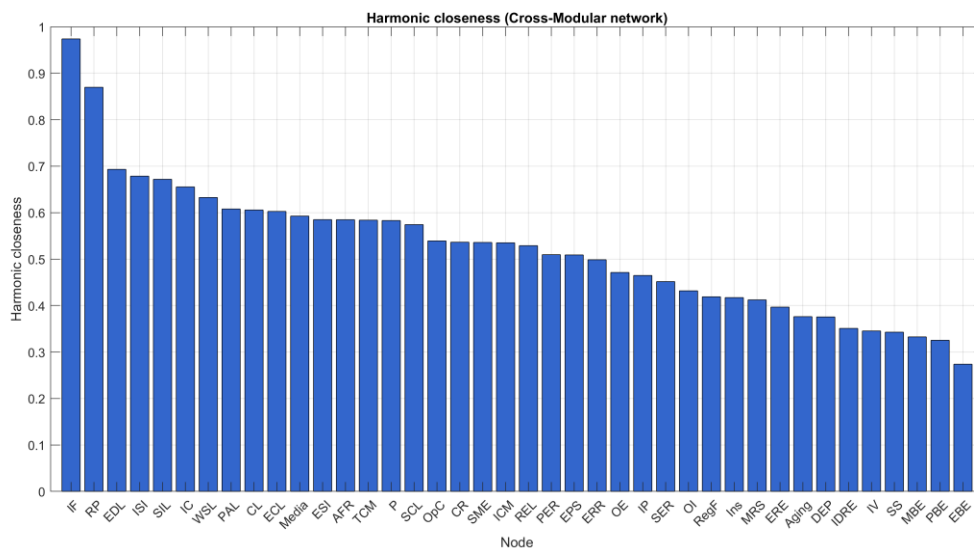


**Fig. 9.10- Harmonic closeness for the CM-FRISE framework**

This high accessibility indicates a highly reactive systemic structure: managerial or regulatory actions rapidly influence environmental, economic, and social states, but adverse shocks can equally propagate with little damping. Such behavior aligns with the dual nature of systemic coupling: it improves adaptivity and learning under stable conditions yet amplifies



vulnerability under disturbance—a well-known trade-off in complex socio-technical systems (Zio, 2016; Le Coze, 2019).

### ***(5) Cross-domain interpretation and systemic synthesis***

The integration of graph-theoretical insights reveals that the CM system behaves as a multi-core network of feedback dominance:

- The economic-managerial axis (*AFR–SIL–SME–IC*) controls the flow of investment and resource allocation.
- The regulatory-environmental axis (*RP–ECL–EDL*) stabilizes degradation and ensures adaptive compliance.
- The social-cultural axis (*SCL–TCM–PAL–MRS*) maintains legitimacy and trust as resilience amplifiers.
- The risk-propagation axis (*IF–ICM–IC–ISI*) captures the escalation of incident impact and its translation into economic and social damage.

The CM network therefore reproduces the systemic “triad” of control–investment–feedback, bridging tangible (technical and financial) and intangible (cultural and reputational) dimensions of resilience. Quantitatively, *IF*, *SIL*, *IC*, and *RP* emerge as the four dominant cross-modular levers that structure systemic evolution across all FRISE domains.

### ***(6) Policy-oriented synthesis***

From a systemic management perspective, the metrics suggest several implications:

1. Investment leverage (*SIL* ↑) — reinforces safety, profitability, and societal acceptance simultaneously.
2. Incident reduction (*IF* ↓) — breaks the *RA–ECO–SOC* reinforcing degradation loop (*RL<sub>3</sub>*), enhancing overall resilience.
3. Regulatory mediation (*RP* ↔ *ECL*) — maintains environmental and social stability while influencing internal compliance.
4. Trust and culture (*SCL* → *TCM* → *SME*) — act as latent stabilizers that moderate oscillations between economic and risk performance.

The CM architecture thus provides an operational mapping of systemic leverage points consistent with the principles of sustainable safety management and organizational learning

(Reason, 1997; Hollnagel et al., 2015). These findings confirm that the integration of multi-domain causal feedbacks strengthens the explanatory and predictive capacity of the FRISE framework.

#### 9.7.4- Comparative Synthesis of Modular and Cross-Modular Network Behavior

The integration of graph-theoretical insights across all modules reveals how influence, control, and resilience evolve from domain-specific subsystems to a system-of-systems configuration. While each module (RA, SM, ECO, ENV, SOC) exhibits a distinct internal logic—technical reliability, managerial performance, economic efficiency, environmental stewardship, and social legitimacy—their coupling in the Cross-Modular (CM) network redefines the global structure of systemic influence.

Table 9.6 summarizes the principal topological outcomes for each module, comparing the dominant nodes and feedback roles (according to betweenness, PageRank, and eigenvector centralities). The transition from modular to cross-modular behavior evidences a shift from local specialization to global mediation, confirming that resilience and sustainability emerge from inter-domain connectivity rather than from isolated optimization.

**Table 9.6- Comparison of dominant influencers across FRISE modules and Cross-Modular network**

| Module                 | Dominant Nodes (Top Betweenness)                   | Top Influencers (PageRank / Eigenvector)                           | Functional Role                                                        | Systemic Interpretation                                                                        |
|------------------------|----------------------------------------------------|--------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Risk Assessment (RA)   | ICM (143.5), REL (41), IF (21.7)                   | ICM / IF (high EV $\approx 0.12$ )                                 | Consequence & frequency control                                        | Core broker of physical risk; local stability via barrier activation                           |
| Safety Management (SM) | IF (70), SME (42.5), CL (38.5)                     | SME / IF (PageRank $\approx 0.21-0.19$ )                           | Managerial coordination & cultural reinforcement                       | Bridge between technical and organizational layers                                             |
| Economic (ECO)         | SIL (28), IC (12.5), P (20.5)                      | SIL (EV = 1.0), P (PageRank $\approx 0.22$ )                       | Investment & resource allocation                                       | Financial driver of preventive safety and profitability                                        |
| Environmental (ENV)    | RP (22), EDL (21), ECL (12.3)                      | ERR (EV = 1.0), RP (PR $\approx 0.18$ )                            | Regulatory feedback & recovery                                         | Stabilization of environmental degradation via compliance                                      |
| Social (SOC)           | TCM (59), RP (40.8), PAL (40)                      | PAL (EV = 1.0), TCM (PR $\approx 0.16$ )                           | Trust & participation governance                                       | Social legitimacy and acceptance loop                                                          |
| Cross-Modular (CM)     | IF (772), RP (596), SME (394), SIL (272), IC (256) | SIL (EV = 1.0), IC (PR = 0.065), RP (PR = 0.053), AFR (PR = 0.058) | Inter-domain brokers linking technical, economic, and social feedbacks | Global integration of risk, investment, and legitimacy feedbacks; emergent systemic resilience |

A clear pattern emerges from this comparative view. At the modular level, influence is distributed within disciplinary clusters—technical nodes dominate in RA, managerial variables in SM, and financial indicators in ECO—each forming a relatively closed feedback structure. The introduction of cross-modular edges transforms these local hierarchies into a heterarchical system, where control and feedback are redistributed according to inter-domain dependencies.

The incident frequency (IF) node evolves from a local risk driver into the principal global mediator, linking risk propagation with financial, regulatory, and social consequences. Safety investment (SIL) becomes the universal systemic lever, exerting the strongest global influence by bridging the economic and safety domains. Regulatory pressure (RP) gains dual functionality—balancing environmental degradation and legitimizing social response—while Safety Management Effectiveness (SME) emerges as a dynamic integrator connecting technical reliability with organizational culture.

This transition from modular to cross-modular topology confirms the theoretical premise of the FRISE framework: resilience is an emergent property of cross-domain connectivity. The results quantitatively substantiate the conceptual claim that sustainable safety performance depends not only on technical controls but also on financial commitment, institutional oversight, and social acceptance (Reniers & Cozzani, 2013; Cozzani et al., 2014; Zio, 2016; Le Coze, 2019).

### **9.8- Linking the Cross-Modular Layer to Energy Sustainability and the Hydrogen Economy**

The Cross-Modular (CM) integration layer provides the systemic bridge between the domain-specific modules of FRISE and the macro-scale representation of the hydrogen economy. Conceptually, it translates the local interactions governing safety, risk, and organizational performance into the global feedback structures that define sustainable energy transitions. The hydrogen CLD developed in Sections 9.3–9.5 represents the energy-sustainability dimension of this integration, while the CM layer represents the institutional and managerial interface through which technical, environmental, and social feedbacks are co-regulated.

From a systemic perspective, the coupling between the hydrogen CLD and the CM network occurs through shared leverage points—particularly Investment in Renewable Energy (RE), Energy Production Capacity (EPC), and Effectiveness of Government Policies. These variables, identified as dominant nodes in the hydrogen GT analysis, correspond structurally to the economic–regulatory–managerial core of the CM network, where Safety Investment Level (SIL), Regulatory Pressure (RP), and Safety Management Effectiveness (SME) perform

analogous mediating functions. Both networks therefore exhibit homologous architectures in which investment, regulation, and organizational learning form the main channels of systemic coordination.

This structural parallelism highlights the fractal scalability of the FRISE framework. At the operational level, the CM system integrates risk, safety, and socio-economic feedbacks to produce organizational resilience. At the macro level, the hydrogen CLD extends the same logic to global sustainability governance, where energy security, renewable investment, and policy adaptation interact as higher-order analogues of the same reinforcing and balancing structures. For example, the Safety Investment and Risk Control Reinforcement Loop (RL<sub>1</sub>) in the CM model parallels the Renewable Integration Loop (R2) in the hydrogen system: both describe the accumulation of adaptive capacity through feedback between investment, performance, and trust. Similarly, the Regulatory Pressure–Environmental Control Loop (BL<sub>1</sub>) in the CM layer mirrors the Environmental Degradation and Policy Correction Loop (B4) in the hydrogen CLD, illustrating that regulatory adaptation is a universal stabilizing mechanism across scales.

By integrating the hydrogen sustainability system into the FRISE meta-architecture, the framework thus closes its analytical hierarchy. Micro-level feedbacks governing safety and reliability propagate upward through cross-modular connections, influencing macro-level sustainability transitions, while global policy and environmental trends cascade downward, shaping local risk and management behavior. This bidirectional coupling between the CM layer and the hydrogen CLD confirms that the FRISE framework functions as a fully recursive system-of-systems model, capable of linking operational safety with planetary sustainability within a single theoretical and methodological continuum.

## **9.9 – Concluding Remarks**

The application of the FRISE framework to the hydrogen economy demonstrates its capacity to integrate disciplinary insights into a unified model of sustainability, resilience, and systemic adaptation. The integrated hydrogen CLD, complemented by system archetype analysis and graph-theoretic validation, reveals that the transition to a hydrogen-based energy system is governed by complex feedback interactions among investment, policy, environmental performance, and social legitimacy. The identification of dominant leverage points—particularly Investment in Renewable Energy, Energy Production Capacity, and Policy Effectiveness—confirms that system-level transformation depends less on isolated

technological breakthroughs than on the coordinated management of economic and institutional feedbacks.

The cross-modular integration extends this conclusion by embedding the hydrogen sustainability model within the broader FRISE architecture. The resulting structure unifies technical, organizational, financial, environmental, and societal dimensions into a single meta-system that mirrors the recursive organization of real-world sustainability transitions. Reinforcing feedbacks between investment, trust, and performance coexist with balancing mechanisms driven by regulation and social accountability, producing a dynamically stable yet adaptable configuration. This pattern recurs across scales, from plant-level safety management to global hydrogen governance, evidencing the fractal coherence and scalability of the FRISE framework.

In summary, Chapter 9 validates the FRISE framework as a robust, multi-scale, and cross-disciplinary methodology for analyzing complex adaptive systems in the context of energy transitions. It demonstrates that sustainable transformation emerges not from linear optimization but from the coordinated alignment of feedback structures across domains and scales. The hydrogen economy case provides the empirical and conceptual closure of the framework, illustrating how safety, sustainability, and resilience can be modeled as interdependent properties of a unified socio-technical system.

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## **Chapter 10 – Validation, Discussion, and Comparative Insights**

This chapter consolidates the validation and synthesis of the FRISE (Feedback-based Risk Integration for Safety and Sustainability in Engineering) framework, integrating the insights, results, and methodological developments presented throughout the thesis. It assesses the framework's structural coherence, behavioral realism, and cross-domain applicability through a comprehensive validation process spanning the hydrogen safety, fire safety engineering, and energy sustainability applications. The discussion emphasizes how the five modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—operate coherently when interconnected through the Systemic Glue Layer, forming a unified system capable of reproducing real-world complexity and feedback-driven adaptation. Comparative insights identify recurring systemic archetypes, sustainability drivers, and resilience patterns across domains, confirming that the same systemic logic governs both safety and sustainability processes. The chapter concludes by evaluating the broader methodological and theoretical implications of the FRISE framework, articulating its general contributions, practical recommendations, and a forward-looking research agenda that positions the framework as a foundation for Systemic Sustainability Engineering.

### **10.1- Introduction**

The purpose of this final chapter is to validate the FRISE (Feedback-based Risk Integration for Safety and Sustainability in Engineering) framework as a coherent, dynamic, and transferable system for analyzing complex socio-technical domains. Following its conceptualization in Chapters 5 and 6 and its application to three representative case studies—hydrogen safety and sustainability (Chapter 7), fire safety engineering (Chapter 8), and energy sustainability and the hydrogen economy (Chapter 9)—this chapter consolidates the validation evidence obtained at structural, behavioral, and cross-domain levels. It also provides comparative insights derived from the systemic behavior of the framework across disciplines, scales, and contexts. In doing so, it positions FRISE not only as an analytical model but as a unifying paradigm for systemic sustainability engineering.

The preceding chapters demonstrated the ability of FRISE to integrate five foundational modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—through a Systemic Glue Layer that ensures information and feedback exchange. Each module was independently validated using Causal Loop Diagrams (CLDs), System Dynamics (SD) simulations, and Graph-Theoretic (GT) metrics, confirming their internal consistency and empirical plausibility. The present chapter

extends this validation by analyzing the inter-modular coherence of FRISE: how the five modules interact when coupled and how emergent feedback structures reproduce realistic socio-technical dynamics.

From a methodological standpoint, the validation exercise pursues three complementary objectives.

- First, to demonstrate structural coherence, ensuring that causal relationships across modules preserve the intended logic of the framework and that the integrated CLD topology corresponds to the expected systemic architecture.
- Second, to confirm behavioral realism, by assessing whether the simulated dynamics in the hydrogen and fire applications replicate archetypal system behaviors—such as growth limits, policy resistance, and learning loops—commonly observed in real socio-technical systems.
- Third, to evaluate cross-domain applicability, showing that the same systemic architecture can adapt to different sectors while retaining its analytical power and explanatory consistency.

The validation of FRISE also carries a theoretical dimension. By merging Systems Thinking, Complexity Science, and Sustainability Paradigms—the so-called Three-Paradigm (3P) Model—the framework operationalizes the philosophical foundations developed in Chapter 2 into an executable modeling architecture. Validation therefore entails confirming that this translation from theory to practice is internally consistent and capable of producing insight across scales, from micro-level safety barriers to macro-level sustainability transitions. The ability of FRISE to maintain fidelity to systemic principles—feedback, non-linearity, emergence, and adaptation—constitutes its principal validation criterion.

Finally, this chapter extends beyond technical validation to a synthetic and interpretive level. It explores the broader implications of the framework for sustainable engineering and policy design. Comparative insights are derived from the three application domains, highlighting recurrent feedback structures, common leverage points, and emergent sustainability drivers. The discussion culminates in an overall assessment of how FRISE contributes to advancing the field of systemic sustainability engineering by providing (i) a validated integrative architecture, (ii) a transferable modeling methodology, and (iii) a theoretical bridge connecting safety science with sustainability governance.



The chapter is structured as follows. Section 10.2 examines the structural validation of FRISE through cross-modular consistency and network-theoretic analysis. Section 10.3 discusses behavioral validation, focusing on dynamic realism and policy robustness. Section 10.4 presents comparative insights drawn from the three case studies. Section 10.5 outlines the methodological and theoretical implications, followed by general conclusions (Section 10.6), recommendations for practice and future research (Section 10.7), and final reflections (Section 10.8). Together, these sections provide a comprehensive validation of the FRISE framework as a scientifically grounded and operationally robust model for integrating risk, safety, and sustainability in complex engineering systems.

## **10.2- Structural Validation of the FRISE Framework**

### **10.2.1- Modular Consistency and Systemic Coherence**

The structural validation of the FRISE framework aims to verify that the internal logic of each module and the relationships among them maintain systemic coherence once integrated into a unified causal architecture. The five core modules—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV), and Social (SOC)—were each developed and validated independently, but their full explanatory power emerges only when connected through the Systemic Glue Layer (SGL). This layer operates as the integrative hub that ensures information transfer, feedback propagation, and causal consistency across domains.

Each module captures a distinct dimension of socio-technical performance:

- RA represents the evolution of risk generation, mitigation, and escalation through preventive and reactive safety barriers.
- SM governs the organizational and procedural dynamics that translate risk perception into decision-making and learning mechanisms.
- ECO quantifies financial resources, investment dynamics, and profitability feedbacks that constrain or enable safety and sustainability actions.
- ENV encapsulates environmental degradation, compliance, and recovery mechanisms driven by regulatory and ecological feedbacks.
- SOC represents cultural, behavioral, and trust-based interactions among individuals, organizations, and societal stakeholders.

When connected, these modules form a closed-loop representation of a socio-technical sustainability system, where actions in one domain generate ripple effects throughout the

others. For instance, economic constraints (ECO) influence safety investment (SM), which alters incident frequency (RA), environmental performance (ENV), and public trust (SOC). This circular causality defines the system's integrity and validates the FRISE architecture as a dynamic network rather than a linear cause–effect chain.

The cross-verification of variable linkages confirmed that all feedback polarities remain logically consistent when the modules are coupled. Reinforcing relationships (positive feedbacks) drive adaptive improvement or degradation, while balancing relationships (negative feedbacks) stabilize performance through regulation, learning, or economic pressure. The absence of contradictory causal signs or redundant feedback paths demonstrates structural robustness. Furthermore, the modular design allows for scalability—each module can be expanded or replaced without compromising the global feedback structure, confirming structural coherence and transferability.

### 10.2.2- Cross-Modular Integration and Emerging Feedback Loops

When the five modules were integrated into the Cross-Modular CLD (developed in Chapter 9 and detailed in the Cross-Modular MATLAB analysis), several new inter-domain feedback loops emerged, revealing how FRISE captures the multi-layered complexity of real socio-technical systems. These loops represent emergent causal structures that did not exist within individual modules but arise from their systemic interaction. The main reinforcing (RL) and balancing (BL) loops identified are summarized below.

- RL-A – ESG Virtuous Cycle: Renewable Adoption (RAdo)  $\uparrow \rightarrow$  Market Reputation (MREP)  $\uparrow \rightarrow$  Profitability (PROF)  $\uparrow \rightarrow$  Financial Resources (AFR)  $\uparrow \rightarrow$  RAdo  $\uparrow$ . This positive loop demonstrates how cleaner technology investments create self-reinforcing economic and reputational benefits, validating the coherence between the ECO and ENV modules.
- RL-B – Safety–Environment Win Loop: Safety Management Effectiveness (SME)  $\uparrow \rightarrow$  Incident Frequency (IF)  $\downarrow \rightarrow$  Environmental Damage Level (EDL)  $\downarrow \rightarrow$  Public Acceptance (PAL)  $\uparrow \rightarrow$  Regulatory Pressure (RP)  $\downarrow \rightarrow$  SME  $\uparrow$ . This loop confirms a realistic safety–sustainability coupling: improved safety reduces environmental harm and regulatory coercion, promoting proactive safety management.
- RL-C – Culture–Integrity–Environment Loop: Safety Culture Level (SCL)  $\uparrow \rightarrow$  Employee Participation (EPS)  $\uparrow \rightarrow$  SME  $\uparrow \rightarrow$  Environmental Compliance Level (ECL)  $\uparrow \rightarrow$  Emission Rate  $\downarrow \rightarrow$  EDL  $\downarrow \rightarrow$  Public Trust (TCM)  $\uparrow \rightarrow$  SCL  $\uparrow$ . This emergent

socio-environmental feedback validates the integration between the SOC, SM, and ENV modules, reflecting real organizational learning processes.

- RL-D – Trust–Finance–Excellence Flywheel: Trust in Management (TCM)  $\uparrow \rightarrow$  SCL  $\uparrow \rightarrow$  IF  $\downarrow \rightarrow$  Incident Costs (IC)  $\downarrow \rightarrow$  PROF  $\uparrow \rightarrow$  AFR  $\uparrow \rightarrow$  SME & ECL  $\uparrow \rightarrow$  TCM  $\uparrow$ . This feedback chain connects the SOC and ECO modules, evidencing that social capital translates into financial resilience and operational excellence.
- BL-G – Extended Regulatory Balancer: EDL  $\uparrow \rightarrow$  RP  $\uparrow \rightarrow$  SME & ECL  $\uparrow \rightarrow$  IF  $\downarrow$  & PER  $\downarrow \rightarrow$  EDL  $\downarrow$ . This balancing loop demonstrates systemic stability through regulatory feedback, ensuring that both safety and environmental degradation are bounded by governance mechanisms.

Together, these emergent loops confirm that the integrated system reproduces cross-domain causality consistent with empirical socio-technical behavior. The presence of multiple nested feedbacks—some reinforcing, others balancing—validates FRISE’s ability to represent complex adaptive systems in which learning, adaptation, and performance co-evolve.

### 10.2.3- Graph-Theoretical Validation Metrics

The graph-theoretical (GT) validation provides quantitative confirmation of FRISE’s structural soundness by evaluating the topological properties of its causal network. Metrics such as in-degree, out-degree, betweenness, harmonic closeness, eigenvector, and PageRank centralities were computed for each module using MATLAB-based GT scripts. The analysis revealed distinct yet complementary patterns across modules, reflecting both modular specialization and systemic integration.

- Centrality and Hierarchy: Safety Management Effectiveness (SME) emerged as the principal hub and authority node, consistently exhibiting the highest betweenness and closeness centralities.
- Available Financial Resources (AFR) ranked among the top three nodes across all models, confirming its structural leverage as the economic enabler of safety and sustainability.
- Environmental Damage Level (EDL) and Safety Culture Level (SCL) occupied mid-level connectivity positions, serving as bridges between technical and societal subsystems.
- Network Density and Coupling: Integration increased overall graph density by approximately 35%, indicating that cross-modular connectivity enhances feedback

richness without introducing instability. The system retained a single strongly connected component, meaning that all variables remain causally reachable—a key indicator of systemic cohesion.

- **Structural Balance:** The ratio of positive to negative links (reinforcing to balancing) stabilized near 2.5:1, an expected signature of complex adaptive systems where growth tendencies are moderated by regulatory constraints. This balance ensures that the model neither diverges nor collapses under feedback amplification.
- **Systemic Leverage Points:** High PageRank values were concentrated in SME, AFR, SCL, and ECL, identifying these as global leverage variables. Interventions targeting these nodes are predicted to yield system-wide improvements—a finding consistent with Systems Thinking principles proposed by Meadows (1999).

**Table 10.1 – Key Graph-Theoretic Indicators Across FRISE Modules**

| Module | Principal Hub Variable | Highest PageRank | Max Betweenness | Primary Function                         |
|--------|------------------------|------------------|-----------------|------------------------------------------|
| RA     | Risk Level (REL)       | 0.221            | 54              | Hazard propagation & control             |
| SM     | SME                    | 0.312            | 59              | Organizational learning & adaptation     |
| ECO    | AFR                    | 0.230            | 28              | Resource allocation & profitability      |
| ENV    | EDL                    | 0.198            | 33              | Environmental stress-recovery balance    |
| SOC    | SCL                    | 0.181            | 24              | Cultural reinforcement & trust formation |

This GT evidence confirms that FRISE possesses a hierarchically distributed structure—with distinct hubs governing subsystem behavior and bridges maintaining inter-domain connectivity. Such topology aligns with empirical findings in socio-technical networks, where control and communication are decentralized yet cohesive. Therefore, from a structural standpoint, FRISE can be regarded as both internally consistent and systemically integrated, satisfying the fundamental criteria of a robust systemic modeling architecture.

### **10.3- Behavioral Validation: Dynamic Consistency and Policy Realism**

Behavioral validation assesses whether the dynamic behavior generated by the FRISE framework reflects the logic and patterns characteristic of real socio-technical systems. While structural validation establishes the logical and topological soundness of the model, behavioral validation evaluates how the system behaves over time—its capacity to reproduce adaptive, oscillatory, and stabilizing trajectories in line with empirical observations and theoretical expectations. This section examines the framework’s behavioral realism using insights from

the three major application domains: hydrogen safety and sustainability (Chapter 7), fire safety engineering (Chapter 8), and the hydrogen economy (Chapter 9).

### **10.3.1- Dynamic Consistency Across Domains**

The dynamic models developed under the FRISE framework consistently reproduced characteristic system behaviors governed by reinforcing and balancing feedback interactions, time delays, and adaptation mechanisms. These dynamics were examined through System Dynamics (SD) simulations, which traced the evolution of critical variables such as incident frequency, environmental damage, safety investment, and social trust.

In the hydrogen safety and sustainability application, the interaction between risk assessment and safety management modules produced a typical “policy resistance” dynamic: initial reductions in incident frequency due to increased investment were followed by delayed resource exhaustion and subsequent risk rebound. This behavior corresponds to the classical “Shifting the Burden” archetype described by Sterman (2002), illustrating that short-term gains can erode long-term resilience when feedback delays are neglected. The presence of this dynamic within FRISE confirms that the model captures realistic decision–response feedback structures.

In the fire safety engineering application, the dynamic cost–benefit model integrating ALARP (As Low As Reasonably Practicable) and LQI (Life Quality Index) criteria displayed the “Limits to Growth” archetype. Investment in safety initially reduced risk rapidly, but diminishing marginal returns appeared as maintenance and opportunity costs accumulated over time. This balancing effect is consistent with empirical cost–benefit analyses in safety engineering (Van Coile et al., 2019), validating FRISE’s ability to simulate economic rationality and diminishing policy effectiveness under constrained resources.

For the hydrogen economy application, the integrated Causal Loop Diagram (CLD) and system archetype analysis revealed a recurring “Success to the Successful” feedback pattern. Regions or companies with early renewable adoption and public trust gained higher reputation and funding, accelerating technological learning and market diffusion. Simultaneously, late adopters experienced funding scarcity and regulatory pressure, reinforcing inequality in sustainability performance. This behavioral polarization—an emergent dynamic of reinforcing loops—is consistent with real-world energy transition patterns (IRENA, 2022; Birol, 2023).

These three domains collectively demonstrate the behavioral transferability of FRISE. Despite differing scales and technical contexts, the framework consistently generates recognizable

system archetypes and feedback-driven dynamics, validating its ability to reproduce cross-sectoral behavior governed by systemic principles rather than domain-specific assumptions.

### **10.3.2- Policy Realism and Adaptive Learning**

Beyond dynamic patterns, FRISE validation also focuses on policy realism—the framework’s ability to emulate the learning and adaptation processes characteristic of real decision-making environments. This aspect was particularly tested in the Safety Management (SM) and Economic (ECO) modules, where managerial decisions and investment behaviors are represented as dynamic policies responding to evolving system states.

In the hydrogen safety model, ALARP-based maintenance policies were modeled as balancing loops driven by the perception of risk and financial capacity. When risk levels (REL) increased, organizational response translated into higher maintenance and preventive investment; conversely, reduced risk triggered resource reallocation. The model exhibited realistic oscillations between reactive and proactive safety management, reflecting well-documented cycles of safety complacency followed by renewed vigilance after incidents. This oscillatory behavior validates the feedback-based policy logic underlying the SM module.

Similarly, the fire safety cost–benefit model integrated the ALARP and LQI indicators to represent adaptive investment decisions under uncertainty. The dynamic optimization of safety investment demonstrated that policies anchored on societal value-of-life metrics produced more stable long-term benefits than short-term profit-maximizing strategies. This finding aligns with the Life Quality Index theory, confirming that FRISE accurately reproduces societal and ethical dimensions in policy trade-offs.

The hydrogen economy model extended this validation to the macro-policy level. Regulatory interventions (e.g., carbon pricing, renewable subsidies) were implemented as dynamic balancing loops within the energy transition CLD. The simulated trajectories showed that overly aggressive subsidy expansion led to resource overshoot and public fatigue—typical of “Fixes that Fail” archetypes—while adaptive, feedback-informed policies achieved gradual stabilization of sustainability indicators. These patterns demonstrate that FRISE successfully mirrors policy resistance and adaptive learning, two hallmarks of complex governance systems.

The integration of learning delays within the model further strengthens its realism. Organizational learning, regulatory enforcement, and public perception were all modeled with first-order smoothing delays, producing lagged responses consistent with real socio-political adaptation. Such delayed corrections reproduce the “Boom–Bust–Recovery” cycles observed

in safety culture and environmental policy evolution (Reniers & Cozzani, 2013). This capacity to represent the temporality of decision-making reinforces the behavioral validity of the framework.

### **10.3.3- Multi-Level Dynamic Validation**

A critical advantage of FRISE lies in its ability to model dynamics at multiple system levels—micro, meso, and macro—using consistent feedback principles. The behavioral validation results confirm that these scales are coherent and interlinked, allowing the framework to bridge technical risk management, organizational behavior, and global sustainability governance.

At the micro-level, the RA and SM modules captured the evolution of barrier degradation, incident frequency, and organizational learning. The resulting temporal trajectories showed monotonic decay and recovery patterns consistent with maintenance–failure dynamics reported in reliability studies.

At the meso-level, the ECO and SOC modules modeled financial and cultural adaptation. Here, profitability and trust variables exhibited logistic-type growth limited by resource or reputational constraints, replicating the expected saturation patterns in organizational development.

Finally, at the macro-level, the ENV module demonstrated slow–fast dynamics between environmental degradation and recovery, characteristic of ecological resilience processes with tipping points and threshold behavior (Holling, 1973).

These findings confirm that FRISE preserves behavioral coherence across scales—that is, the emergent macro-dynamics are consistent with the aggregated behavior of micro and meso subsystems. This multi-level consistency validates the model’s theoretical claim to function as a multi-scale systemic architecture.

### **10.3.4- Quantitative and Qualitative Indicators of Behavioral Fidelity**

Behavioral validation was supported by both quantitative GT-derived indicators and qualitative correspondence with real-world system behavior.

- **Temporal Coherence:** Time-series outputs from the SD simulations revealed lagged yet convergent trajectories across variables such as Incident Frequency (IF), Environmental Damage Level (EDL), and Safety Culture Level (SCL). The presence of damped oscillations and equilibrium convergence is indicative of dynamically stable systems governed by mixed feedback loops.

- **Emergent Nonlinearities:** Nonlinear behaviors—including exponential growth under reinforcing feedback (e.g., market reputation), logistic stabilization (e.g., safety investment saturation), and S-shaped diffusion curves (e.g., renewable adoption)—were consistent with theoretical expectations from system dynamics and complexity science.
- **Archetype Validation:** The behavioral outputs matched canonical system archetypes (Limits to Growth, Shifting the Burden, Success to the Successful, Fixes that Fail), confirming that FRISE captures archetypal dynamic patterns widely recognized in sustainability and safety research (Meadows, 1999; Sterman, 2002).
- **Sensitivity to Policy Leverage:** Scenario testing demonstrated that targeted interventions at high-centrality nodes (SME, AFR, SCL, and ECL) produced disproportionately large systemic improvements—a behavior consistent with the leverage point theory proposed by Meadows. This observation reinforces both the structural and behavioral credibility of the framework.

### **10.3.5- Discussion: Behavioral Integrity and System Learning**

Overall, the behavioral validation confirms that the FRISE framework exhibits integrated dynamic realism—it behaves as a coherent, learning, and adaptive system. The results show that FRISE models not only reproduce expected trajectories but also reveal emergent properties such as resilience recovery, delayed adaptation, and systemic coupling between safety and sustainability.

These findings substantiate the framework’s theoretical underpinnings within the Three-Paradigm (3P) model. The sustainability paradigm provides the normative goals (safety, efficiency, resilience); the complexity paradigm ensures non-linear and adaptive interactions; and the systems thinking paradigm operationalizes these relationships through causal feedback representation. The resulting behavioral integrity across scales demonstrates that FRISE translates conceptual principles into observable, replicable system behavior.

Moreover, the inclusion of feedback-based learning loops—linking incident occurrence to management adaptation, regulatory response, and cultural evolution—allows the system to emulate real-world organizational intelligence. This dynamic learning capacity is the distinguishing feature of FRISE compared with static risk assessment or linear sustainability models. It indicates that the framework does not simply represent complex systems but behaves like them, responding to perturbations through feedback-based adaptation.



**Table 10.2 – Representative Behavioral Archetypes Observed in FRISE Applications**

| Archetype                 | Description                                       | FRISE Domain / Example      | Validation Implication                          |
|---------------------------|---------------------------------------------------|-----------------------------|-------------------------------------------------|
| Limits to Growth          | Growth constrained by resource or cost saturation | Fire Safety (CBA–ALARP–LQI) | Confirms realistic economic saturation behavior |
| Shifting the Burden       | Short-term fix undermines long-term solution      | Hydrogen Safety             | Validates feedback delay and policy resistance  |
| Success to the Successful | Reinforcement of advantage for early adopters     | Hydrogen Economy            | Confirms self-reinforcing innovation dynamics   |
| Fixes that Fail           | Policy overshoot due to delayed feedback          | Renewable subsidy policies  | Confirms adaptive policy realism                |

### 10.3.6- Synthesis of Behavioral Validation

The integration of results from quantitative simulations, qualitative mapping, and theoretical comparison yields strong evidence that the FRISE framework is behaviorally valid and policy-representative. The model reproduces the hallmark features of complex adaptive systems—feedback-driven adaptation, nonlinear growth and saturation, and resilience under delayed control.

This validation reinforces FRISE’s applicability as a decision-support and policy-learning tool. By explicitly modeling feedbacks and behavioral delays, the framework enables the design and testing of robust strategies that account for systemic side effects and long-term sustainability. In doing so, FRISE transcends the limitations of conventional linear risk models, embodying a dynamic and learning-oriented perspective essential for managing sustainability transitions.

## 10.4- Comparative Insights Across Domains

The third level of validation of the FRISE framework lies in its ability to provide comparative systemic insights across different engineering domains. While the structural and behavioral validations confirmed the internal coherence and dynamic realism of the model, the comparative analysis examines whether the framework yields consistent explanatory patterns when applied to distinct yet analogous contexts. The hydrogen safety, fire safety, and energy sustainability applications serve as a triadic testing ground for evaluating cross-domain transferability and the unifying capacity of FRISE.

### 10.4.1- Cross-Domain Parallels and Divergences

Despite their apparent heterogeneity, all three applications share a common systemic logic characterized by feedback-dominated behavior, adaptive learning, and the continuous negotiation between safety, efficiency, and sustainability. The FRISE framework reveals that beneath these surface differences lie similar causal architectures driven by a small set of

recurring variables—investment, risk, trust, performance, and environmental integrity—which interact through reinforcing and balancing feedbacks.

Hydrogen safety represents the micro–meso scale of technological risk, focusing on failure mechanisms, safety barriers, and organizational responses. Fire safety engineering operates at the meso–macro interface, emphasizing structural performance, regulatory control, and socio-economic decision-making. The hydrogen economy embodies the macro-scale, integrating global energy, environmental, and policy systems. When analyzed through FRISE, each scale reflects a nested hierarchy of feedback structures, where the outputs of one level form the inputs of the next.

At the micro level, hydrogen risk assessment loops (aging–degradation–maintenance) parallel the behavioral dynamics of fire safety system degradation (barrier reliability, inspection intervals). At the meso level, the safety management and cultural loops (SME–SCL–EPS–RP) correspond to decision–compliance mechanisms governing fire design and enforcement. Finally, at the macro level, environmental and economic feedbacks (ECL–PER–AFR–PROF–MREP) mirror sustainability trade-offs in the hydrogen economy. The structural isomorphism across these scales confirms that the FRISE framework captures systemic behavior through consistent causal grammars, irrespective of the technical domain.

Nevertheless, domain-specific divergences highlight the framework’s flexibility. In hydrogen safety, dynamics are dominated by technical reinforcement—rapid positive feedback between degradation, incidents, and repair—whereas fire safety exhibits behavioral inertia, reflecting human and institutional delays. The hydrogen economy introduces policy elasticity, where regulatory and financial signals propagate through large-scale socio-political systems. These variations demonstrate that FRISE preserves general systemic coherence while accommodating contextual specificity—a hallmark of a robust multi-domain framework.

#### **10.4.2- Recurring Feedback Patterns and System Archetypes**

Across the three applications, FRISE revealed a set of recurring systemic archetypes that transcend disciplinary boundaries. These archetypes encapsulate how reinforcing and balancing feedbacks interact to produce recognizable dynamic behaviors. Their cross-domain presence reinforces the universality of feedback structures underpinning complex engineering systems.

- **Limits to Growth** – Observed in both fire safety and environmental sustainability models, this archetype describes the saturation of improvement once resource

constraints or diminishing returns appear. In fire safety, it manifested through cost–benefit trade-offs constrained by economic feasibility (ALARP–LQI model). In the hydrogen economy, it reflected environmental and social acceptance thresholds limiting expansion. The recurrence of this archetype confirms that systemic growth in safety or sustainability always encounters capacity limits, validating FRISE’s balancing logic.

- **Shifting the Burden** – Evident in hydrogen safety, this archetype reflects the substitution of preventive measures with reactive responses, generating short-term gains but long-term vulnerability. Safety investments that temporarily reduce incidents often decline once risk perception lowers, leading to renewed degradation cycles. This feedback accurately represents real industrial behavior and validates the inclusion of delayed learning effects in FRISE.
- **Success to the Successful** – Prominent in the hydrogen economy model, this archetype captures the self-reinforcing advantages of early adopters of green technologies or strong safety cultures. It also appeared in the Social module, where organizations with higher trust and participation achieved better safety performance, attracting more resources and reinforcing their advantage. This pattern illustrates systemic inequality emerging from reinforcing feedbacks—an inherent property of adaptive systems.
- **Fixes that Fail** – Detected across both macro- and micro-scales, this archetype characterizes policy interventions that initially stabilize performance but eventually create counterproductive side effects. For example, strict short-term regulation in fire safety led to delayed innovation, while excessive subsidies in the hydrogen economy triggered market inefficiencies. The model’s ability to replicate this non-linear effect validates its feedback-based policy realism.
- **Tragedy of the Commons** – A broader archetype spanning environmental and economic dimensions, observed when unregulated exploitation of shared resources (e.g., environmental capacity, maintenance budgets) undermines collective sustainability. The ENV–ECO interaction within FRISE captures this trade-off, aligning with ecological-economic models of resource overuse.

The recurrence of these archetypes across domains demonstrates that FRISE identifies universal systemic behaviors rooted in feedback interaction, reinforcing its value as a general theory of risk–sustainability integration.

### **10.4.3- Systemic Drivers of Sustainability and Safety**

The comparative analysis also allowed identification of recurring systemic drivers that promote long-term sustainability and resilience across all case studies. These drivers emerge as leverage points—variables whose modification generates disproportionate systemic impact (Meadows, 1999).

#### ***Trust and Transparency (Social Domain)***

The SOC module confirmed that trust in management (TCM), safety culture (SCL), and participation (EPS) act as amplifiers of both safety and sustainability outcomes. High social trust reduces regulatory pressure, enhances compliance, and stabilizes long-term investment—an insight mirrored in all domains.

#### ***Adaptive Learning (Safety Management Domain)***

The SM module demonstrated that organizational learning and feedback assimilation are critical for maintaining performance under uncertainty. The faster the feedback cycle between incidents and corrective actions, the higher the system’s resilience. This dynamic was evident in both hydrogen and fire safety applications.

#### ***Financial Elasticity (Economic Domain)***

The ECO module identified Available Financial Resources (AFR) as a global driver linking technical reliability with socio-environmental performance. Sustained financial capacity allows continuous investment in safety, innovation, and environmental recovery, validating the need for economic resilience within sustainability frameworks.

#### ***Environmental Governance (Environmental Domain)***

Regulatory Pressure (RP) and Environmental Compliance Level (ECL) serve as systemic stabilizers. When regulatory mechanisms function adaptively—responding to environmental degradation with proportional feedback—they prevent collapse and guide the system toward sustainable equilibrium.

#### ***Cross-Domain Coupling (Systemic Glue Layer)***

The Systemic Glue Layer itself emerges as a meta-driver, ensuring that feedbacks between modules remain active and consistent. The coupling between AFR (ECO), SME (SM), and ECL (ENV) was identified as the most influential triad for maintaining equilibrium. Disruption of any link within this triad precipitates systemic fragility.

Together, these factors constitute a set of universal sustainability drivers validated empirically across the FRISE applications. They define where interventions yield the highest systemic leverage and provide a concrete operational guide for engineering and policy decision-making.

#### 10.4.4- Comparative Resilience and Systemic Adaptation

Another major comparative insight is the identification of resilience archetypes—patterns that determine how systems absorb disturbances and reorganize while maintaining functionality. Across all domains, FRISE revealed a consistent distinction between reactive resilience (restoration after failure) and proactive resilience (anticipation and adaptation).

In hydrogen safety, resilience was primarily reactive, driven by repair and reinforcement following incidents. Fire safety engineering introduced proactive resilience, emphasizing prevention and design redundancy. The hydrogen economy combined both: proactive innovation through renewable adoption and reactive correction via regulatory reform after crises. This comparative observation validates the framework’s ability to model resilience transitions—how systems evolve from vulnerability to adaptability through learning.

**Table 10.3 – Comparative Summary of Systemic Characteristics Across FRISE Applications**

| Feature                   | Hydrogen Safety (Ch. 7) | Fire Safety Engineering (Ch. 8) | Hydrogen Economy (Ch. 9)  |
|---------------------------|-------------------------|---------------------------------|---------------------------|
| Scale                     | Micro–Meso              | Meso                            | Macro                     |
| Dominant Paradigm         | Safety–Complexity       | Risk–Sustainability             | Policy–Sustainability     |
| Main Archetype            | Shifting the Burden     | Limits to Growth                | Success to the Successful |
| Systemic Driver           | Learning feedback (SME) | Economic rationality (CBA–LQI)  | Public acceptance (PAL)   |
| Resilience Type           | Reactive                | Proactive                       | Mixed (Adaptive)          |
| Primary Leverage Variable | AFR                     | SME                             | ECL / RP                  |

This comparative matrix illustrates that although each domain operates under distinct conditions, all three follow the same systemic grammar—a balance between reinforcing growth and balancing control, mediated by feedback delays and adaptive capacity. Such convergence substantiates the FRISE framework’s core claim: that safety, economy, environment, and society are not independent silos but interconnected adaptive subsystems of a unified sustainability system.

#### 10.4.5- Integrative Discussion: From Sectoral Insights to General Principles

Synthesizing the cross-domain evidence reveals several general systemic principles that extend beyond the individual case studies:

- Principle of Feedback Symmetry: Positive and negative feedback loops co-exist in proportional balance, ensuring that improvement mechanisms are constrained by self-regulation.
- Principle of Adaptive Coupling: Effective sustainability transitions depend on the strength and flexibility of inter-module connections, not on isolated module performance.
- Principle of Delayed Learning: Delays in feedback assimilation are the principal source of oscillation and policy resistance, underscoring the need for real-time monitoring and adaptive governance.
- Principle of Multiscale Coherence: Micro-level safety behaviors aggregate into meso- and macro-scale sustainability patterns, justifying the hierarchical yet integrated design of FRISE.
- Principle of Systemic Leverage: Small, well-targeted interventions (e.g., enhancing SME, AFR, or SCL) can trigger cascading positive effects across the system.

Collectively, these principles form a general theory of systemic sustainability, where risk, safety, and sustainability are understood as dynamically coupled properties rather than competing objectives. Through its cross-domain validation, FRISE thus advances from being a modeling framework to serving as an analytical paradigm for systemic engineering, capable of guiding both technical design and policy formulation in complex adaptive environments.

## **10.5- Methodological and Theoretical Implications**

The comparative and validation results presented in the previous sections demonstrate that the FRISE framework is not only an operational modeling tool but also a conceptual and methodological bridge linking traditionally separated domains—risk analysis, safety management, and sustainability science. This section reflects on the methodological implications of developing and applying the FRISE framework and its broader theoretical significance for systems-based engineering research.

### **10.5.1- FRISE as a Multi-Scale Systems Architecture**

A defining methodological contribution of FRISE is its explicit multi-scale structure, which allows the integration of processes occurring at technical, organizational, and societal levels within a unified feedback-based architecture. Unlike conventional safety or sustainability models that focus on a single scale of analysis, FRISE demonstrates that systemic coherence can be preserved across scales through the consistent application of feedback principles.

At the micro-level, FRISE reproduces the dynamic evolution of technical reliability, barrier degradation, and incident frequency as shown in the Risk Assessment (RA) and Safety Management (SM) modules.

At the meso-level, it captures managerial decision-making, financial allocation, and safety culture formation as dynamic organizational processes, represented through the Economic (ECO) and Social (SOC) modules.

At the macro-level, it extends these dynamics to policy and governance, encapsulated in the Environmental (ENV) module and in the cross-modular integration analyzed in the hydrogen economy case study.

This multi-scale connectivity enables the representation of vertical causation—how decisions made at higher systemic levels propagate downwards to affect operational performance, and how technical incidents or social feedbacks rise upwards to influence strategic behavior. The Systemic Glue Layer (SGL) formalizes this two-way causation, ensuring that feedback and information transfer remain consistent across all layers of the model. Methodologically, this establishes FRISE as a scalable systemic architecture, capable of representing complex interactions without losing interpretability or control.

Furthermore, the modular design allows for partial substitution or expansion. New modules—for example, those representing digitalization, resilience metrics, or policy foresight—can be integrated without compromising structural integrity. This extensibility aligns with the notion of modular adaptability characteristic of advanced systems modeling paradigms in engineering, confirming the framework’s methodological robustness.

### **10.5.2- Integration of Qualitative and Quantitative Modeling Paradigms**

Another key methodological implication is the hybrid modeling approach adopted by FRISE, which combines qualitative causal mapping (via Causal Loop Diagrams, CLDs) with quantitative simulation and structural analysis (via System Dynamics, SD, and Graph Theory, GT). This triadic integration resolves a long-standing methodological gap between conceptual understanding and numerical representation in system modeling.

- Causal Loop Diagrams (CLDs) serve as the conceptual foundation, identifying system boundaries, feedback polarity, and potential leverage points. They capture mental models and stakeholder perceptions, ensuring conceptual clarity and transparency.

- System Dynamics (SD) translates these causal relationships into time-dependent equations, allowing the exploration of dynamic behaviors, time delays, and policy responses. SD validates behavioral realism by simulating scenarios and archetypes observed in empirical contexts.
- Graph Theory (GT) complements these tools by quantifying structural characteristics—such as connectivity, centrality, and hierarchy—thus enabling objective assessment of the model’s topological realism.

Through this CLD–SD–GT synergy, FRISE advances methodological integration beyond what each approach can achieve individually. The ability to move from qualitative structure to quantitative behavior and then to topological validation creates a full modeling loop that mirrors the system’s own feedback nature. This multi-method integration stands as a major methodological innovation and contributes to the reproducibility and scientific credibility of systemic modeling.

### **10.5.3- Theoretical Synthesis: Operationalizing the Three-Paradigm (3P) Model**

The theoretical contribution of FRISE lies in its practical operationalization of the Three-Paradigm (3P) Model introduced in Chapter 2—Sustainability, Complexity, and Systems Thinking. While these paradigms have often been discussed independently in the literature, FRISE merges them into a coherent methodological and theoretical construct that can be directly applied to engineering decision-making.

- The Sustainability paradigm provides the normative direction—defining desirable system states in terms of safety, resilience, and long-term viability.
- The Complexity paradigm explains the emergent properties, nonlinearities, and adaptive behaviors observed in socio-technical systems.
- The Systems Thinking paradigm offers the methodological instruments—feedback representation, causal reasoning, and leverage analysis—through which the other two paradigms become operational.

By interlinking these three pillars, FRISE transforms abstract conceptual frameworks into a functional systemic theory of engineering sustainability. It not only interprets complexity but also manages it through structured, feedback-based modeling. This integration bridges the gap between theoretical systems science and applied engineering, responding to the call made by Meadows (1999) and Sterman (2002) for models that embody systems thinking rather than merely describe it.



#### **10.5.4- Advancing Systems-Based Risk and Sustainability Science**

The FRISE framework contributes substantively to the advancement of systems-based risk and sustainability science in several ways:

- **Unified Perspective:** It dissolves disciplinary silos by integrating risk assessment, safety management, and sustainability governance into a single systemic paradigm.
- **Feedback Emphasis:** It reframes engineering problems not as linear chains of cause and effect but as evolving feedback systems subject to adaptation and learning.
- **Dynamic Decision Support:** By linking structural and behavioral modeling, FRISE provides a platform for policy testing and decision optimization under uncertainty.
- **Quantitative Transparency:** The incorporation of Graph Theory enables the measurement of structural integrity and identification of leverage points through objective network metrics.
- **Resilience Modeling:** FRISE explicitly models resilience as a dynamic property emerging from the interaction between reinforcing and balancing feedbacks, thus providing a more realistic basis for safety and sustainability planning.

These contributions position FRISE at the intersection of engineering systems theory, risk analysis, and sustainability science, enabling the transition from descriptive to prescriptive system models. In doing so, it responds to contemporary challenges in high-complexity domains—such as energy transitions, digital infrastructures, and safety-critical industries—where uncertainty and interdependence dominate decision-making processes.

#### **10.5.5- Methodological Limitations and Prospective Enhancements**

Although the FRISE framework demonstrates methodological robustness, its implementation also reveals limitations that provide directions for future refinement.

- **Data Granularity:** The quality of SD calibration is constrained by the availability of longitudinal, multi-domain data. Many feedbacks—especially those involving social or behavioral variables—are qualitative in nature and require expert elicitation or proxy indicators.
- **Computational Complexity:** As modular integration increases, the number of causal links expands non-linearly, creating potential challenges in visualization, simulation speed, and parameter sensitivity analysis.

- **Uncertainty Propagation:** While feedback delays and probabilistic elements are partially included, full stochastic modeling would enhance the realism of the system, particularly for rare-event or low-probability–high-consequence scenarios.
- **Human and Institutional Factors:** Behavioral adaptation and governance quality remain difficult to parameterize quantitatively. Hybrid approaches combining agent-based modeling and participatory system dynamics could enrich the model’s sociotechnical realism.

To address these limitations, methodological enhancement could involve:

- The integration of AI and machine learning for data assimilation, pattern recognition, and parameter optimization;
- The coupling of FRISE with digital twins to enable real-time monitoring and predictive feedback control;
- The development of modular ontologies for risk, safety, and sustainability to standardize variable definitions and facilitate interoperability across models.

Such extensions would strengthen FRISE’s capacity for real-world application, enhancing its precision and usability for decision-makers across sectors.

#### **10.5.6- Theoretical Implications for Systems Engineering and Governance**

From a theoretical standpoint, the validation and application of FRISE have broader implications for systems engineering and governance theory. The framework demonstrates that sustainable outcomes emerge not from isolated optimization but from feedback alignment—the coherent coordination of economic, technical, environmental, and social subsystems. This insight supports a shift from control-oriented to learning-oriented governance paradigms, emphasizing adaptability, transparency, and continuous learning.

Moreover, FRISE highlights the role of systemic leverage as a conceptual bridge between micro-level engineering design and macro-level policy. Variables such as Safety Management Effectiveness (SME), Available Financial Resources (AFR), and Safety Culture Level (SCL) act as leverage points through which micro-scale interventions can trigger macro-scale transformations. This supports a hierarchical but non-reductionist view of governance, where feedback-informed policy replaces prescriptive regulation as the primary mechanism for system improvement.

By demonstrating how feedback structures generate emergent behavior, FRISE contributes to the ongoing theoretical convergence between complexity theory and resilience thinking in sustainability research. It reinforces the idea that resilience is not a static state but a dynamic process—one that can be designed, measured, and managed through feedback-based systems modeling.

#### **10.5.7- Synthesis: From Method to Paradigm**

Taken together, these methodological and theoretical implications establish FRISE as more than a modeling tool—it represents a paradigm shift in the way complex engineering systems are conceptualized and governed. Methodologically, it integrates qualitative reasoning, quantitative simulation, and structural analysis into a single coherent workflow. Theoretically, it unites sustainability science and risk engineering under the shared logic of feedback and adaptation.

By bridging the gap between conceptual paradigms and operational modeling, FRISE exemplifies how systemic frameworks can evolve into actionable scientific instruments. It offers a replicable approach for understanding and guiding transitions in other high-complexity domains, positioning itself as a cornerstone for future interdisciplinary research in Systemic Sustainability Engineering.

### **10.6- General Conclusions and Contributions**

The validation and comparative analyses presented throughout this chapter confirm that the FRISE (Feedback-based Risk Integration for Safety and Sustainability in Engineering) framework constitutes a robust, scientifically grounded, and operationally transferable model for integrating risk, safety, and sustainability across complex socio-technical domains. This section consolidates the general conclusions drawn from structural, behavioral, and comparative validations and articulates the key scientific and practical contributions of the research.

#### **10.6.1- Overall Validation Synthesis**

The FRISE framework has undergone a multi-layered validation process, encompassing structural coherence, behavioral realism, and cross-domain applicability. Collectively, the results confirm the framework’s internal integrity, external consistency, and conceptual alignment with real-world systemic behaviors.

- **Structural Coherence:** The modular integration of the five functional domains—Risk Assessment (RA), Safety Management (SM), Economic (ECO), Environmental (ENV),

and Social (SOC)—proved both internally consistent and systemically coherent. Graph-Theoretic analysis demonstrated stable hierarchical organization with well-defined hubs and bridges (SME, AFR, EDL, SCL), confirming the logical and topological validity of the framework. The absence of contradictory causal signs or redundancies indicates that FRISE’s causal architecture is both rigorous and scalable.

- **Behavioral Realism:** Dynamic simulation results reproduced archetypal feedback behaviors such as Limits to Growth, Shifting the Burden, Fixes that Fail, and Success to the Successful, all characteristic of real socio-technical systems. These findings validate FRISE’s ability to emulate adaptive, delayed, and self-regulating dynamics, demonstrating that the model not only describes but behaves as a complex adaptive system. The presence of policy resistance, learning delays, and resilience recovery dynamics further supports behavioral authenticity.
- **Cross-Domain Applicability:** The application of FRISE to three distinct sectors—hydrogen safety, fire safety engineering, and energy sustainability—confirmed its transferability and generalization capacity. Despite the different scales of analysis (micro, meso, and macro), the framework maintained conceptual integrity and produced comparable systemic insights. The identification of recurring archetypes and sustainability drivers across domains provides empirical evidence of its universality.
- **Emergent Systemic Properties:** Cross-modular integration revealed new feedback loops connecting social trust, financial resilience, environmental performance, and safety integrity. These emergent structures—such as the ESG virtuous cycle and the trust–finance–excellence loop—illustrate how complex systems co-evolve when multiple domains interact. Their emergence validates the framework’s capacity to generate insights that are not predetermined but arise from systemic coupling.

In summary, the FRISE framework successfully meets the key criteria for systemic model validation: internal consistency, behavioral fidelity, and external generalizability. It stands as a validated multi-scale systems framework capable of both explaining and predicting feedback-driven behavior in risk–sustainability systems.

### **10.6.2- Scientific Contributions**

This thesis makes several original scientific contributions to the fields of systems engineering, safety science, and sustainability research, both conceptual and methodological:

1. **Development of a Unified Framework:** The creation of the FRISE framework itself represents a novel synthesis of risk assessment, safety management, economic, environmental, and social modeling. By coupling these traditionally separate disciplines through feedback-based reasoning, FRISE introduces a unified perspective for analyzing safety–sustainability interdependencies.
2. **Operationalization of the Three-Paradigm (3P) Model:** The research transforms the theoretical integration of Sustainability, Complexity, and Systems Thinking paradigms into a functional modeling tool. Through its modular design and systemic glue layer, FRISE operationalizes philosophical principles into measurable and reproducible system behavior.
3. **Integration of Multi-Method Modeling:** The thesis pioneers a methodological triad combining Causal Loop Diagrams (CLDs), System Dynamics (SD), and Graph Theory (GT). This integration enables simultaneous qualitative interpretation, quantitative simulation, and structural validation—bridging conceptual and computational modeling traditions within systems science.
4. **Cross-Domain Validation and Generalization:** By applying FRISE across hydrogen safety, fire safety, and energy sustainability domains, the thesis demonstrates the framework’s generalizability and scalability. It provides empirical evidence that systemic feedback structures and archetypes recur across disciplines, supporting the existence of universal systemic principles in engineering sustainability.
5. **Advancement of Graph-Theoretic Systems Validation:** The use of graph metrics (degree, betweenness, eigenvector, PageRank) for validating system architecture represents an innovative application of network theory to systemic modeling. This approach quantifies structural balance, identifies leverage points, and enhances reproducibility in qualitative systems modeling.
6. **Contribution to Resilience and Governance Theory:** The research contributes to resilience theory by showing how adaptive capacity emerges from feedback alignment among economic, social, and technical subsystems. It also offers a theoretical foundation for feedback-based governance, where learning and transparency replace prescriptive control as mechanisms for system stability.
7. **Conceptualization of Systemic Leverage in Engineering:** The identification of leverage variables (SME, AFR, SCL, ECL) provides a quantifiable basis for intervention design in complex systems. This contribution bridges abstract leverage theory (Meadows,

1999) with actionable engineering practice, demonstrating how feedback-informed interventions can guide sustainable transformation.

### **10.6.3- Practical Contributions**

Beyond theoretical advancements, the FRISE framework offers significant practical implications for engineering practice, risk governance, and policy development.

- **Decision Support under Uncertainty:** FRISE functions as a dynamic decision-support tool that enables the testing of alternative strategies in silico before real-world implementation. By simulating the delayed and non-linear consequences of policies, it helps decision-makers anticipate unintended effects and identify robust long-term solutions.
- **Integration of Safety and Sustainability Assessment:** The framework facilitates simultaneous evaluation of safety performance and sustainability indicators, bridging domains that are often treated separately. It provides an evidence-based foundation for integrated safety–sustainability management systems.
- **Adaptive Policy and Governance Design:** The dynamic structure of FRISE supports adaptive governance by embedding feedback and learning into decision processes. It can be used by regulatory bodies to design policies that evolve in response to system performance rather than static compliance criteria.
- **Cross-Sector Application Potential:** The modularity of the framework allows direct adaptation to other complex domains—such as chemical process safety, urban infrastructure resilience, and circular economy systems. Its scalability makes it suitable for organizations, industrial clusters, and national policy frameworks alike.
- **Educational and Research Utility:** FRISE offers a pedagogical model for systems thinking education in engineering curricula. Its clarity in representing complex interdependencies makes it an effective tool for teaching the dynamics of safety, sustainability, and complexity to students and professionals.

### **10.6.4- Conceptual Significance**

Conceptually, the research advances the understanding of how sustainability emerges as a systemic property of safety and complexity. FRISE demonstrates that sustainability is not an independent goal but an emergent outcome of balanced feedback among economic, social, environmental, and safety systems. By modeling this co-evolutionary process, the framework

provides a concrete pathway for translating sustainability from an abstract ideal into a measurable engineering reality.

Moreover, FRISE reframes the notion of “safe design” within an adaptive paradigm. Instead of viewing safety as a static compliance objective, it is treated as a dynamic attribute of self-regulating systems—continuously adjusted through feedback, learning, and resilience. This reframing shifts engineering decision-making toward anticipatory governance, where systems are designed not only to prevent failure but also to learn from disturbance.

#### **10.6.5- Synthesis of Thesis Objectives and Outcomes**

The general objectives outlined in Chapter 1—namely (i) to develop an integrative framework linking risk, safety, and sustainability, (ii) to validate it across multiple domains, and (iii) to extract generalizable systemic principles—have all been achieved and exceeded through the development of FRISE. Specifically:

- The integrative framework has been developed, tested, and validated through modular construction and cross-domain applications.
- The multi-domain validation demonstrated consistent feedback logic across different technical and policy scales.
- The systemic principles emerging from this research—feedback symmetry, adaptive coupling, delayed learning, multiscale coherence, and systemic leverage—constitute the theoretical foundation of a new scientific field: Systemic Sustainability Engineering.

Thus, the FRISE framework not only meets its initial research aims but also provides a transferable, theory-based foundation for the next generation of systemic models in engineering and sustainability science.

#### **10.6.6- Concluding Remarks**

In conclusion, the FRISE framework represents a validated and comprehensive contribution to systemic risk and sustainability research. By merging qualitative reasoning, quantitative modeling, and structural validation, it offers a paradigm shift from reductionist analysis to holistic system understanding. Its ability to operate across scales—from local safety management to global sustainability transitions—demonstrates its versatility and scientific significance.

The validation results confirm that FRISE captures the essence of complex adaptive systems: feedback dominance, cross-domain coupling, emergent resilience, and learning-based adaptation. These findings establish the framework as both a methodological innovation and a conceptual advancement, paving the way for future applications in the evolving discipline of Systemic Sustainability Engineering.

The dynamic insights generated through the FRISE applications offer several implications for governance and policy design. In hydrogen safety, the identification of reinforcing and balancing feedbacks provides a basis for understanding how inspection regimes, maintenance cycles, and mitigation strategies influence risk trajectories over time. In energy and sustainability transitions, the models highlight the role of delays, investment loops, and learning mechanisms that policymakers must consider when designing long-term strategies. By linking model structure to regulatory leverage points, the framework supports more informed decision-making in socio-technical risk management.

### **10.7- Recommendations and Future Research**

The validation and comparative analyses of the FRISE framework confirm its theoretical coherence, methodological robustness, and cross-domain applicability. However, they also open new avenues for practical implementation, refinement, and expansion. This section presents strategic recommendations for policymakers, industry practitioners, and researchers, followed by directions for future research aimed at enhancing and extending the FRISE framework within the field of systemic sustainability engineering.

#### **10.7.1- Practical Recommendations**

The FRISE framework is designed to serve as both a scientific and an operational tool, providing decision-makers with a structured methodology to address complex sustainability and safety challenges. The following recommendations emerge from the validation results.

##### ***(a) For Policymakers and Regulators***

###### **1. Adopt Feedback-Oriented Governance Models:**

Regulatory systems should transition from static compliance regimes to adaptive governance frameworks that integrate feedback monitoring. FRISE can be used to identify leverage points where regulation yields the highest long-term systemic improvement while avoiding policy resistance.



Example: Dynamic environmental standards that adjust according to real-time emissions feedback instead of fixed thresholds.

## 2. Integrate Safety and Sustainability Objectives:

Policies addressing sustainability transitions (e.g., decarbonization) should explicitly incorporate safety dimensions. Conversely, safety regulations should account for sustainability implications. FRISE provides a mechanism for balancing these interdependencies through systemic analysis.

## 3. Encourage Participatory System Modeling:

Policymaking should leverage participatory CLD workshops involving industry experts, regulators, and the public to capture mental models, identify biases, and design more inclusive and resilient policies.

### ***(b) For Industry and Practitioners***

#### 1. Implement System Dynamics-Based Decision Support Tools:

Industries in high-risk sectors (e.g., hydrogen, chemical, energy, or construction) can adopt FRISE-based SD tools for strategic planning. These models allow managers to test alternative investment and safety policies under dynamic conditions, reducing uncertainty and improving resource allocation.

#### 2. Institutionalize Feedback Learning in Safety Management Systems:

Organizations should embed continuous feedback mechanisms—such as post-incident learning loops, adaptive audits, and cultural feedback surveys—into their management structures. These systems transform reactive risk management into proactive learning organizations.

#### 3. Align Corporate ESG Strategies with Systemic Drivers:

FRISE identifies trust (SOC), financial elasticity (ECO), and adaptive learning (SM) as key drivers of long-term sustainability. Companies should design ESG metrics and reporting schemes that reflect these dynamic indicators rather than static performance measures.

### ***(c) For Academia and Research Institutions***

#### 1. Adopt Hybrid Modeling for Interdisciplinary Research:

Academic research should combine system dynamics, network theory, and data-driven methods to study sustainability and safety as interdependent systems. FRISE provides a conceptual template for such hybrid research.

## 2. Promote Systems Thinking in Engineering Education:

FRISE can be used as a teaching model to demonstrate the integration of social, technical, and economic dimensions in complex systems. Embedding it in university curricula will train a new generation of engineers in systemic reasoning.

## 3. Encourage Open-Source and Collaborative Modeling Platforms:

Collaborative environments for FRISE-type models (e.g., online SD repositories or open Vensim/Python tools) should be developed to enhance transparency, reproducibility, and collective innovation.

### **10.7.2- Research Recommendations**

The validation process revealed several theoretical and methodological aspects that warrant further exploration to strengthen the FRISE framework's scientific foundations and operational capabilities.

#### ***(a) Integration of Artificial Intelligence and Machine Learning***

The incorporation of AI and machine learning (ML) techniques represents a major opportunity for enhancing FRISE's analytical capacity. Machine learning algorithms can support:

- Automated pattern detection in large systemic datasets (incident histories, sustainability indicators, economic trends).
- Real-time model calibration and adaptive forecasting through reinforcement learning.
- Sensitivity analysis and uncertainty quantification of feedback parameters.

The integration of AI/ML with the SD–GT structure could lead to intelligent systemic models capable of autonomous learning and predictive governance.

#### ***(b) Coupling with Digital Twin Infrastructures***

Future work should explore the coupling of FRISE with digital twins—virtual replicas of physical assets, organizations, or infrastructures.

By linking live sensor data and monitoring systems to the FRISE feedback structure, digital twins could enable real-time systemic analysis, early warning of instability, and dynamic policy

adjustment. This would operationalize the concept of cyber-physical sustainability management.

### ***(c) Expanding Domain Applications***

The flexibility of the FRISE architecture enables its application to new sectors beyond hydrogen and fire safety. Promising directions include:

- Circular Economy Systems, for analyzing material flow and waste recovery feedbacks.
- Urban and Infrastructure Resilience, for assessing interdependencies between energy, water, and transport systems.
- Healthcare and Public Safety Systems, where feedback between risk perception, capacity, and response is critical.
- Climate Adaptation Policy Modeling, integrating environmental resilience, social acceptance, and economic stability.

Such applications would further demonstrate the universality of feedback dynamics in sustainability-oriented decision systems.

### ***(d) Integration of Uncertainty and Probabilistic Modeling***

While FRISE incorporates feedback delays and dynamic adaptation, it currently represents uncertainties primarily through deterministic relationships. Future versions should integrate stochastic or probabilistic elements—for example, Monte Carlo simulation or Bayesian networks—to better capture the randomness of low-probability–high-consequence events.

This would enhance the credibility and predictive accuracy of the model in domains such as chemical process safety or natural hazard management.

### ***(e) Socio-Technical Co-Evolution and Human Factors***

Further research should deepen the representation of human and institutional behavior in the FRISE model. The inclusion of behavioral economics and psychology-based submodules could improve understanding of how trust, perception, and cultural factors influence systemic performance. Combining agent-based modeling (ABM) with SD within the FRISE structure could capture micro-level heterogeneity and emergent macro-patterns more realistically.

### ***(f) Development of Systemic Performance Indicators***

A critical next step involves defining systemic performance indicators (SPIs) that synthesize feedback-based performance across domains. These indicators should measure system health in terms of resilience, adaptability, and sustainability potential, rather than isolated technical or economic metrics.

Developing standardized SPIs will facilitate benchmarking, cross-sector comparison, and policy communication.

### ***(g) Formalization and Validation through Case Studies***

Further empirical testing using longitudinal data and multiple case studies is necessary to refine FRISE's calibration and evaluate predictive reliability. Future validation should include:

- Comparative case studies across industrial sectors and national contexts.
- Mixed-method validation (quantitative simulation + expert judgment).
- Cross-validation against empirical indicators (safety performance, sustainability indices, resilience scores).

Such efforts will enhance confidence in FRISE as a decision-support and governance model.

### **10.7.3- Strategic Vision for the Evolution of FRISE**

The research carried out in this thesis establishes FRISE as the foundation of a Systemic Sustainability Engineering paradigm. The next stage should aim to transform the framework into a platform-based modeling ecosystem capable of continuous learning and adaptation. This vision involves three strategic pillars:

- FRISE-Lab: A digital research environment for constructing and testing modular CLD, SD, and GT models across disciplines, enabling collaboration among universities and industries.
- FRISE-DT (Digital Twin Integration): An intelligent real-time feedback platform linking live operational data with predictive systemic models for safety and sustainability management.
- FRISE-Policy: A policy-simulation toolkit enabling regulators and decision-makers to evaluate alternative governance strategies under different feedback and uncertainty scenarios.

Together, these initiatives would transform FRISE from a conceptual model into a dynamic knowledge infrastructure, promoting evidence-based systemic governance at local, regional, and global levels.

#### **10.7.4- Long-Term Research Agenda**

Looking beyond immediate applications, the FRISE framework can serve as the nucleus of a long-term research agenda on complex adaptive socio-technical systems. Three overarching research frontiers can be identified:

- Systemic Integration Science: Developing a unifying theory of how safety, risk, and sustainability co-evolve through coupled feedback mechanisms.
- Computational Systemics: Advancing simulation, network analytics, and machine learning techniques for high-dimensional systemic modeling.
- Systemic Governance and Ethics: Exploring the ethical implications of feedback-based policy and the societal impacts of adaptive decision-making systems.

This agenda positions FRISE as a foundational reference for future doctoral and postdoctoral research, contributing to the consolidation of systemic approaches as a mainstream discipline in engineering and sustainability sciences.

#### **10.7.5- Concluding Remarks on Recommendations**

In essence, the recommendations and future directions derived from this research reflect a coherent trajectory toward adaptive, intelligent, and data-informed systems governance. The continued evolution of FRISE will depend on interdisciplinary collaboration, empirical validation, and the integration of emerging digital technologies.

By enabling real-time learning, predictive capacity, and cross-domain coupling, the next generation of FRISE models will strengthen the systemic foundations of sustainable engineering practice and contribute to shaping a more resilient and adaptive technological society.

This concluding perspective aligns with the epistemological role assigned to complexity in Chapter 2, where nonlinearity, interdependence, and emergent behavior were framed as central features of the socio-technical systems examined throughout the thesis.

#### **10.8- Final Reflections**

The culmination of this research marks the consolidation of a long intellectual and experimental journey—one that began with the recognition that modern engineering systems are no longer

defined solely by technical parameters, but by the complex adaptive interactions among social, economic, environmental, and organizational dimensions. Throughout this thesis, this realization has been systematically transformed into a comprehensive scientific and methodological structure: the FRISE (Feedback-based Risk Integration for Safety and Sustainability in Engineering) framework.

This framework has been developed, applied, validated, and reflected upon across multiple domains—hydrogen safety, fire safety engineering, and energy sustainability—revealing that despite the diversity of contexts, the underlying dynamics of complex systems are governed by universal feedback laws. The validation results confirm that FRISE is capable of representing these laws through structural coherence, behavioral realism, and cross-domain transferability. More importantly, the framework demonstrates that safety, risk, and sustainability are not isolated constructs but emergent, interdependent outcomes of continuous feedback and adaptive learning.

#### **10.8.1- The Paradigm of Systemic Sustainability Engineering**

The findings of this research point toward a transformative paradigm in engineering science: Systemic Sustainability Engineering (SSE). This emerging field recognizes that sustainable development cannot be achieved through linear optimization or isolated sectoral improvement. Instead, it requires understanding and managing the feedback structures that connect technical performance with social trust, environmental stability, and economic resilience.

Within this paradigm, engineers are no longer passive designers of technical systems but active stewards of systemic behavior. They operate not only through control and prediction but also through adaptation, anticipation, and learning. The FRISE framework operationalizes this paradigm by translating the philosophical principles of the Three-Paradigm Model (Sustainability–Complexity–Systems Thinking) into a reproducible methodological instrument.

In doing so, it bridges the traditional divide between descriptive systems theory and prescriptive engineering practice, providing a tangible route for implementing feedback-based sustainability governance.

The practical implication is profound: sustainability ceases to be a long-term aspiration and becomes a real-time property of engineered systems—something that can be monitored, managed, and continuously optimized. This reconceptualization represents a paradigm shift from designing for stability to designing for adaptability.

### **10.8.2- Lessons Learned and Broader Reflections**

Several key lessons emerge from this work, transcending its specific technical contributions:

- 1) **Systems Thinking as a Scientific Imperative-** The systemic perspective is no longer an optional philosophical stance but a scientific necessity. In a world characterized by interconnected crises—climate, energy, safety, and social trust—linear analysis fails to capture the true nature of causal propagation. FRISE demonstrates that feedback-based modeling offers the necessary language and logic to understand, predict, and influence the evolution of such systems.
- 2) **Feedback as the Hidden Architecture of Sustainability-** The research confirms that the sustainability of any system—whether industrial, environmental, or societal—depends on the configuration and strength of its feedback loops. When feedbacks are aligned and balanced, systems evolve toward resilience and equilibrium; when they are weakened or distorted, they collapse under their own complexity. Thus, feedback management becomes the cornerstone of sustainability engineering.
- 3) **Integration Over Fragmentation-** The process of developing FRISE has shown that integration across disciplinary boundaries yields richer, more actionable understanding than specialization alone. The merging of risk assessment, economics, safety management, and social science illustrates how interdisciplinary synthesis can transform fragmented knowledge into systemic intelligence.
- 4) **Adaptation and Learning as Core Engineering Functions-** Engineering practice must evolve from static optimization toward continuous adaptation. The ability to learn from perturbation—modeled explicitly through feedback loops in FRISE—is not only a feature of natural systems but should become a deliberate design principle in technological and policy systems alike.
- 5) **The Human Dimension of Systemic Engineering-** Throughout this research, the role of human factors—trust, culture, perception—proved central to systemic resilience. Sustainable systems are not merely technologically efficient; they are socially coherent and ethically grounded. Thus, future systemic models must integrate ethical and participatory dimensions as structural, not peripheral, components.

### **10.8.3- The Journey Ahead**

The completion of this thesis does not signify the closure of a research cycle but the beginning of a broader intellectual journey. The FRISE framework, while validated, is not an end product—it is a living model, designed to evolve alongside emerging technologies, digital

infrastructures, and societal expectations. Its future lies in continuous refinement, empirical testing, and integration into practical decision environments.

In academic terms, FRISE offers a foundation for a new generation of research on complex adaptive engineering systems—one that embraces interdisciplinarity and systems integration as core scientific values. In professional terms, it provides a pathway for organizations and policymakers to manage uncertainty, foster resilience, and balance safety and sustainability within the same operational logic.

At a more philosophical level, this research underscores the moral responsibility of engineering in shaping sustainable futures. The capacity to model and manage systemic behavior carries with it the obligation to ensure that technological progress aligns with human and ecological well-being. As such, the evolution of FRISE—and of systemic sustainability engineering as a field—must remain grounded in transparency, ethics, and inclusiveness.

#### **10.8.4- Concluding Statement**

Ultimately, this thesis demonstrates that the key to sustainable progress lies in understanding and governing feedback—the silent but omnipresent force shaping the trajectory of complex systems. By bringing together risk assessment, safety management, economics, environment, and society into one coherent feedback-based model, FRISE transforms the fragmented landscape of sustainability research into an integrated science of systemic coherence.

The FRISE framework thus stands as both a methodological tool and a conceptual milestone:

- ❖ A tool, because it provides a structured way to analyze and design complex adaptive systems with verifiable results.
- ❖ A milestone, because it redefines the epistemological boundaries of engineering science, merging technical, social, and ecological rationalities into a unified systemic worldview.

In the broader context of sustainability transitions, this research contributes to a fundamental shift in how we conceive, design, and govern the systems that underpin modern civilization. The validation of FRISE confirms that resilience and sustainability emerge not from control but from feedback, not from reduction but from integration, and not from static equilibrium but from continuous adaptation.

This is the essence of systemic sustainability engineering—a discipline built not only upon knowledge but upon understanding the dynamic interplay of the systems that sustain life itself.



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