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# Building Information Modelling to support facilities management

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# Abstract.

**Background:** Facility Management (FM) regards a variety of competencies and activities aimed at improving people's quality life and the productivity of the core business of an enterprise. Those practices can be improved by using new information technologies. Building Information Modelling (BIM) plays a key role in this sense, integrating different disciplines in a single platform. Although recent research trends reveal that the interest in FM aided by BIM is increasing, the achievement of an integrated model is still a challenge.

**Purpose:** The thesis aims at developing a methodology to integrate Building Information Models and Facilities Management systems, proposing a so-called Performance Information Model (PIM).

**Methods:** The Performance Information Model implementation process involves an adequate knowledge of the asset and related facilities policies, the definition of asset information requirements and performance assessment methods. The implemented methodology relies on the use of Key Performance Indicators (KPIs) as tools for capturing and quantifying relevant information about the asset condition. The Performance Information Model implementation considers the Industry Foundation Classes (IFC) data schema to address interoperability issues. IFC schema serves also as a reference to design a customised database to keep track of maintenance and monitoring activities and performances evaluation. A framework for a Performance Information Model based on IFC schema has been proposed and validated through international case-studies with regards to healthcare buildings. The integration between Facility Management systems and digital models has been achieved by using customised database and applications based on visual programming language.

**Results:** Three main knowledge domains have been integrated: Facility Management, Performance Assessment and BIM. The proposal supports the achievement of organisational, environmental, and technical requirements. An Environmental Condition Index has been defined ex-novo to quantify environmental quality of surgery rooms, its applicability has been proved by real use cases. Performance Information Models for healthcare facilities have been created to deliver the methodology proof of concept.

**Practical implications:** Using a Performance Information Model allows to manage building conditions in forms of KPIs, facilitating the model updating during the building life-cycle operational phase. It is a client-oriented and integrated analysis support tool which can improve technological and environmental performances assessment, visualisation of building condition, decision-making processes, maintenance tasks planning and maintenance records management.

**Originality:** The research is novel as it addresses a relevant research gap which is moving from a building information model to a facility management model. The methodological approach to the facility management is original as it has pioneered a Performance Information Model for managing and visualizing asset conditions and performances to support decision making. Furthermore, a new Key Performance Indicator has been defined for surgery rooms environmental quality assessment. Eventually, the customised database based on IFC schema can be referred to as an extension of the FM handover Model View Definition.

**Keywords:** building information modelling (BIM); building performance assessment (BPA); facility management (FM); key performance indicators (KPIs); operation and maintenance (O&M); industry foundation classes (IFC); model view definition (MVD); relational database; procedural modelling; visual programming language (VPL); surgery room; healthcare facilities.

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# 1. Introduction

Facility Management (FM) has been defined as the *'organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business'* (International Organization for Standardization, 2017).

Facility Management has to support a wide range of activities (commonly referred to as non-core business) which enhance the work environment and well-being of people; enable the organisation to deliver effective and responsive services; make the physical assets highly cost-effective, allowing also future changes; enhance the organisation's image and culture (Atkin and Brooks, 2015).

It is possible to identify different clusters of services and competencies within the FM domain. These tasks are carried out through different strategies (insourcing, total FM, public private partnership, etc.) but mostly through outsourcing (Ancarani & Capaldo, 2005).

Among the competency areas, the Operation and Maintenance (O&M) service plays a key role. It ensures the facility to function efficiently, reliably, safely, securely in a manner consistent with existing regulations and standards (IFMA, 2018).

Building maintenance activities require a comprehensive information system to capture and retrieve data related to building equipment. The current FM practice relies on different systems (i.e., Building Energy Management Systems (BEMS), Building Automation Systems (BAS), Computerized Maintenance Management System (CMMS) (Shalabi & Turkan, 2016), Computer Aided Facilities Management (CAFM), Document Management System (DMS)), which utilize new technologies to integrate and manage information easier. Studies on maintenance issues reveal that the most frequent problem is the information accessibility (Liu & Issa, 2015).

Building Information Modelling (BIM) can be considered as a tool or a method to face information management challenges throughout a building lifecycle. It has been defined as the "*use of a shared digital representation of a built asset to facilitate the design, construction and operation processes to form a reliable basis for decisions*" (International Organization for Standardization, 2018). BIM is semantically-based and object-oriented; it has 3D modelling capabilities and allows users to retrieve comprehensive information represented by objects and their attributes (Jeong & Kim, 2016). BIM provides a unified platform for various data sources (**Figure 1**) needed for daily O&M activities (Gao & Pishdad-Bozorgi, 2019; Matarneh et al., 2019; Motawa & Almarshad, 2019; Becerik-Gerber et al., 2012), so that data regarding technical specification, planned activities and building performances (simulated or monitored) can be integrated to facilitate the decision-making process.

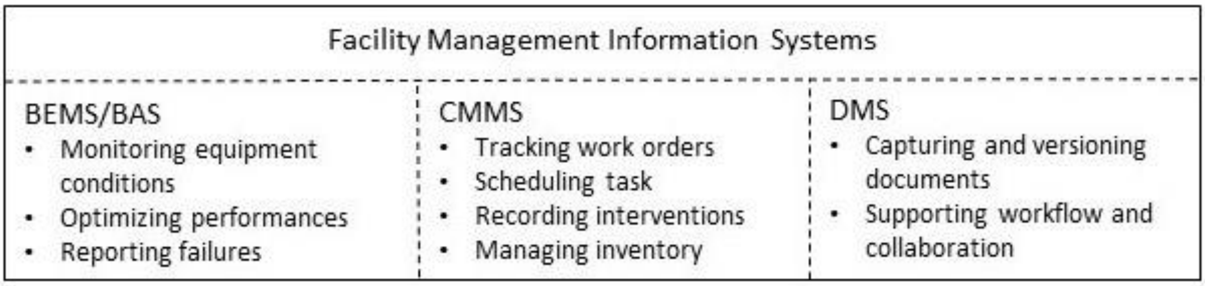



***Figure 1.*** *FM Information Systems.*

The Architecture, Engineering and Construction (AEC) sector is involved in the "Industry 4.0" era and it is being innovating starting from the digitalisation processes.

In this context the Building Information Modelling is a relevant actor for the overall sector transformation, aiming at improving its collaboration, efficiency, and productivity.

The 'Making BIM a global success' manifesto, published by the European Construction Industry Federation, declares that to improve the construction sector productivity and competitiveness two approaches are necessary: (1) top down digital transformation, facilitated by the EU and national governments through policy and investment/EU funding; and (2) bottom up digital transformation driven by the construction industry itself (FIEC, 2017).

The use of electronic tools such as BIM has been encouraged by the European Parliament for public works contracts through the adoption of the 2014 European Union Public Procurement Directive (EUPPD) (European Parliament, 2014). In accordance with these European policies, several Countries adopted legislative provisions and strategies to lead the construction sector innovation. In Italy, the New Procurement Code is the first legislation including this topic (President of Italian Republic, 2016). The Ministerial Decree n. 560/2016 settled the BIM adoption schedule for the Italian public works, which will involve the entire public construction sector by the year 2025.

The AEC industry transformation has been focused on optimizing the design and the construction phases so far, while BIM benefits during the operational phase are not well documented (Pärn et al., 2017). In fact, a lack of real-life examples of BIM-FM integration is one of the major challenges to be faced in order to spread the adoption of BIM during the overall construction lifecycle (Codinhoto & Kiviniemi, 2014; Becerik-Gerber et al., 2012). In addition, a seamless information process between BIM and FM systems does not exist yet (Pärn et al., 2017) and data exchange and interoperability remain problematic topics (Matarneh et al., 2019).

Anyway, current research trends reveal that there is a continuously growing interest in facilities information management using BIM (Gao & Pishdad-Bozorgi, 2019; Edirisinghe et al., 2017; Iltern & Ergen, 2015). Recent studies indicate that energy management has been relatively analysed by researchers, followed by emergency management and maintenance and repair (Gao & Pishdad-Bozorgi, 2019).

A parametric model can establish a knowledge system that can be queried in different ways according to the specific needs, allowing FM managers to make better and faster maintenance decisions and provide higher-quality building performances. The model can support the building modification over its life and it can be the starting point for simulations and interventions evaluations. If the BIM-FM system is kept up to date by operators, it can give an accurate record of current conditions of the facility. The BIM-FM integration is expected to lead to a systematic generation of information, such as Key Performance Indicators (Kiviniemi, A., & Codinhoto, 2014). Developing an FM benchmarking framework enables organisations to identify best practices and strategies improvement.

Within the condition-based maintenance, monitoring of physical variables related to symptoms of failures is needed. Building Performance Assessment (BPA) provides for a better knowledge of an asset, so to make correct decisions at the right time. The performance assessment enriches BIM models with the purpose of evaluating the residual performances, so that coherent interventions can be selected. For example, when certain spaces are performing under a certain threshold the integrated model can make suggestions regarding maintenance planning.

Particularly in the healthcare facilities sector, a facility manager has to consider many factors when making a strategic decision. The identification of a set of specific Key Performance Indicators (KPIs) helps the performance assessment and strategic planning. An Integrated Healthcare Facility Management Model has been proposed (Lavy & Shohet, 2007) to hierarchically analyse healthcare FM core parameters, showing that an analytical quantitative model may significantly contribute to a better understanding of facility management performance. In this sense, qualitative features can be translated into quantitative analysis. Both technological and financial aspects can be included in an integrated model for FM.

## 1.1 Objectives and research questions

The aim of the thesis is to propose a methodological approach for integrating FM systems, BIM and BPA, to support organisational requirements achievement.

The adoption of such a methodology results into the definition of a tool to facilitate performance assessment activities, maintenance management and, as a consequence, the facility managers decision-making. This tool relies on the use of KPIs as a method to evaluate residual building performances and an opportunity to integrate relevant and concise information in a BIM model in order to deliver a proper asset digital twin.

Therefore, the following research objectives are defined:

- Understanding FM and BPA processes and requirements;
- Investigating positive and negative impacts of the BIM adoption into the FM domain;
- Identifying a set of performance (measurable) parameters;
- Defining Key Performance Indicators based on those parameters;
- Designing a standardised tool to keep track of those information;
- Developing a framework for BIM-FM-BPA integration based on the above-mentioned information.

The arising research questions are:

- Which data are required by FM professionals in the operation and maintenance phase?
- To what extend FM and BPA domain can benefit from BIM application?
- What are the gaps which characterize the transition to a BIM-based Facility Management?
- How can the BIM-FM integration process be achieved?

The research meets the latest European Union directives and other international guidelines in the field of digitalization of the AEC sector, and contributes to extend the BIM adoption into the FM domain.

## 1.2 Research design

The thesis development required an overview of FM policies and BPA methods as well as Building Information Modelling and FM information technologies in general.

Then, BIM-FM integration impacts, in terms of benefits to be expected, issues to be faced and ways to address them, are identified by analysing relevant case-studies published in literature.

A novel methodological approach is proposed, stemming from the existing literature, with the aim of facilitating the analysis of current building performances and the integration of such an information within the BIM environment. In this way the FM efficiency can be improved, corrective maintenance and emergency repairs can be reduced, and the maintenance activities record becomes easier.

The healthcare facilities sector has been carefully analysed as first pilot implementation field. For hospitals, laws and regulations provide technological and environmental requirements which can be transposed into performances to be assessed. Furthermore, healthcare buildings are among the most technologically developed building systems which need to be monitored to maintain the quality and the efficiency of their core business high. Hence, the methodological approach has been developed and detailed with regards to this particular application field first.

The identification of FM and BPA information requirements for healthcare facilities started from reviewing guidelines and existing laws. Data gathering involved focus groups, interviews and a Delphi with a panel of experts. This phase led to the identification of a list of measurable parameters which can be transposed into KPIs.

The analysis of collected data included statistical and multi-criteria analysis methods in order to define an Environmental Condition Index for surgery units. Expert opinion was used to interpret KPI results and led to the definition of correlations between environmental and technological systems performances so that recommendable preventive maintenance activities can be identified according to KPIs results.

The feasibility evaluation of the performance-based model has been tested through case studies development. Operating units of three international hospitals have been analysed and modelled and they served as a proof of concept of the methodological approach. Case studies development required the collection of monitoring data and their quantitative analysis.

The BIM-based approach for FM results into a Performance Information Model (PIM), which links facility management information systems, FM workflow repository and BIM Common Data Environment (CDE) (**Figure 2**).

The interoperability issue is addressed by the latest IFC 4x2 specification. This open standard data schema represented the basis for the design of a relational database for maintenance management, monitoring activities record and performance assessment results. Those information, gathered from the so called openPIM database, inform the digital model through customised applications in order to keep the FM-oriented PIM updated.

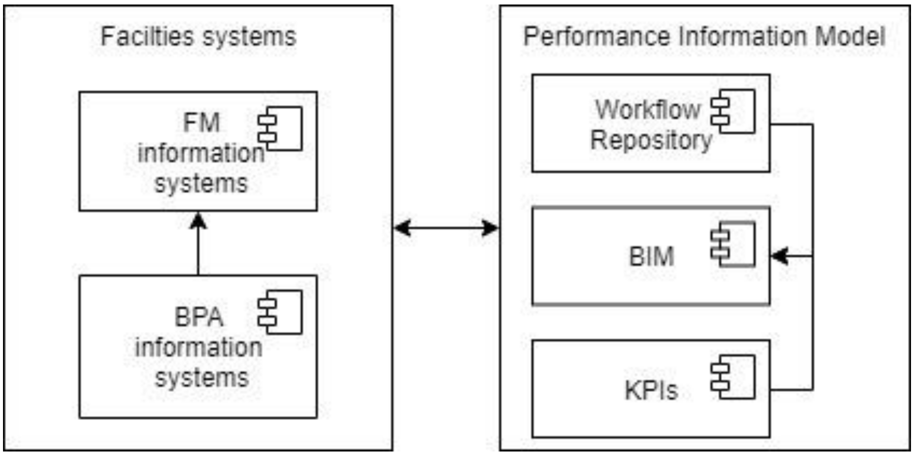



***Figure 2.*** *Organisation of PIM elements.*

## 1.3 Structure of the thesis

We provide here a brief description of the contents so as to guide the reader throughout the entire work.

- **Chapter 1** introduces the problem statement, lists the objectives of the thesis and summarizes the approach proposed;
- **Chapter 2** provides for a comprehensive analysis of the state of the art regarding main topics held in this thesis with references and examples;
- **Chapter 3** introduces specific problems addressed in the research and describes the developed methodology starting from the analysis of healthcare facilities;
- **Chapters 4** contains specification about the framework for integrating a performance information model with facility management information systems;
- **Chapter 5** describes the implemented case studies and related results;
- **Chapter 6** summarises the research findings and discusses future research developments.

# 2. State of the art

A resume of latest and major researches about topics held in this thesis is presented in this chapter. This thesis has been inspired by works regarding the use of KPIs for facilities performance assessment (Lavy et al., 2014; Maltese, 2015), by others regarding the use of BIM for existing buildings (Bruno et al., 2018), and by publications focused on the value of BIM for Facilities Management (Eastman et al., 2008; Teicholz, 2013).

Therefore, Facility Management, Building Performance Assessment, Operations & Maintenance and Building Information Modelling are the main topics discussed here, emphasizing their connection and integration. According to the scope of the thesis, relevant terms definitions are provided as well as methodological and practical features of each topic.

## 2.1 Facility Management

It could be claimed that the 1960s were the beginning of Facility Management (Wiggins, 2010). This was the time when the term 'Facilities Management' was first coined in the USA. At that time, it was associated with trends affecting the management of Information Technologies systems and networks. However, the scope of FM has spread.

During the 1970s, the office furniture sector was evolving fast and the need for strategical space planning was recognized. So, in 1980, the International Facilities Management Association was formally founded in the United States (Wiggins, 2014). Since then, the Facility Management has gradually been recognised as a discipline and a profession within the property and construction industry (Tay & Ooi, 2001).

Several definitions of Facility Management are proposed by the literature, this term had undergone evolution during the last decades as shown in **Table 1**.

***Table 1.*** *List of definitions of Facility Management*

| Author | Definition of FM |
|---|---|
| Becker & Steele (1990) | FM is responsible for co-ordinating all efforts related to planning, designing and managing buildings and their systems, equipment and furniture to enhance the organisation's ability to compete successfully in a rapidly changing world |
| U.S. Library of Congress, in Rondeau (1995) | The practice of coordinating the physical workplace with the people and the work of the organisation; it integrates principles of business administration, architecture and the behavioural and engineering sciences |
| Barret & Baldry (1995) | An integrated approach to maintaining, improving and adapting the buildings of an organisation in order to create an environment that strongly supports the primary objectives of that organisation |
| Alexander (1996) | The scope of the discipline covers all aspects of property, space, environmental control, health and safety, and support services |
| Then (1999) | The practice of FM is concerned with the delivery of the enabling workplace environment the optimum functional space that supports the business processes and human resources |
| Curcio (2003) | The integrated management of all no-core business services (for buildings, space and persons) in order to run and maintain the real estate |

| | |
|---|---|
| UNI EN ISO 41011:2018 | Organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business |

Traditionally, the FM function was described as involving a cost factor for non-value adding activities such as the maintenance and cleaning of a building (Codinhoto & Kiviniemi, 2014).

At its beginning, the FM covered the integration of hard services, such as buildings, furniture and equipment (Tay, 2001), even though in Becker's definition FM seems to be able to make a positive contribution by enhancing the firm's ability to compete successfully. Later definitions included soft services such as people, process, environment, health and safety (Alexander, 1999; Then, 1999).

While the definitions in Table 1 may appear diverse, a closer examination suggests that there are some common recurring themes that give FM its identity. First of all, the focus on the workplace; second, the wide applicability of FM at any organisation; third, FM enhances the performance of the firm (Tay, 2001).

The concept of no-core business was recently advanced. Curcio (Curcio, 2003) introduces the focus on the no-core customer activities "*for buildings, space and persons, in order to run and maintain the real estate*."

The EN ISO 41011:2018 provides for the latest definition of facility management (or facilities management) as the "*organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business".*

Facilities represent substantial investments for their organisation and have to accommodate and support a range of activities, including the core business, for which an appropriate environment must be created, through non-core business. These services are subject of interest for the FM sector (**Figure 3**).

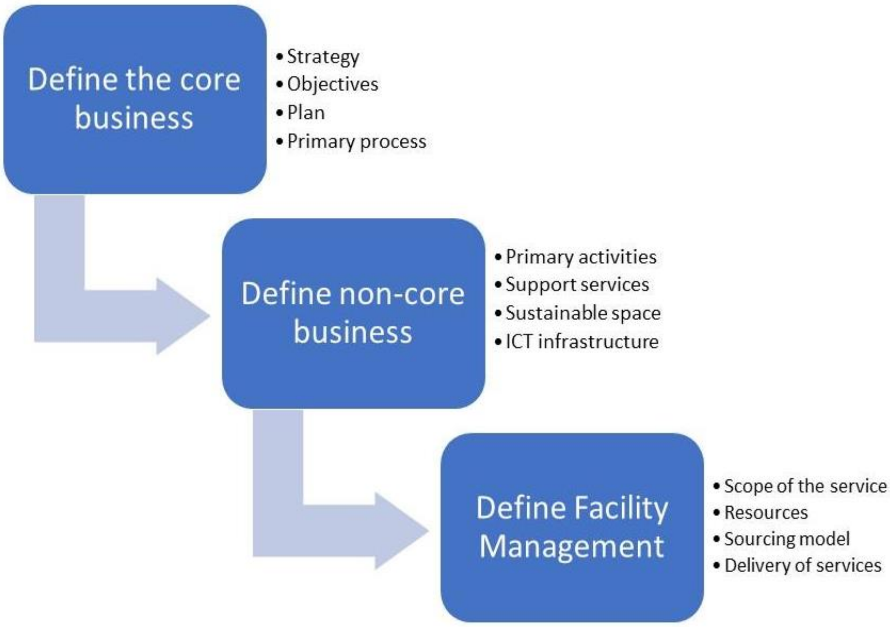



***Figure 3.*** *Relationships between core business, non-core business and FM (based on Atkin & Brooks, 2015).*

Facility Management can thus be regarded to as (Atkin & Brooks, 2015):

- Supporting people in their work and in their activities;
- Enhancing individual well-being;

- Enabling the organisation to deliver effective and responsive services;
- Making the physical assets highly cost-effective;
- Allowing future changes;
- Providing competitive advantages to the core business;
- Enhancing the organisation’s image and culture.

### 2.1.1 Standards for Facility Management

A standard is a document that sets out requirements for a specific item, system or service, or describes in detail a method or procedure (CENCENELEC, 2020). Standards are developed and defined through a process of sharing knowledge and building consensus among technical experts nominated by interested parties and other stakeholders. European Standards (norms) ENs are documents that have been ratified by one of the three European Standardization Organizations, CEN/CENEC/ETSI, recognized as competent in the area of voluntary technical standardization as for the EU Regulation 1025/2012.

A European Standard automatically becomes a national standard in each of the 34 CEN-CENELEC member countries. Standards are voluntary which means that there is no automatic legal obligation to apply them. However, laws and regulations may refer to standards and even make compliance with them compulsory.

The latest European standard on FM is the **UNI EN ISO 41011:2018, Facility Management- Vocabulary** which defines the relevant terms in the Facility Management field and it is intended to be applied in both public and private sectors. This document supersedes the EN 15221:1-2006.

Similarly, **UNI EN ISO 41001:2018, Facility Management – Management systems – Requirements with guidance for use** provides the basis for a common interpretation and understanding of FM and the ways in which it can benefit organisations. It specifies the requirements for a FM system and introduce the concept of “process approach” as the application of a system of processes within an organisation, together with the identification of their combination and interaction.

As illustrated in **Figure 4** the FM team and the demand organisation[1] need to work together to clearly define needs of FM policies to meet the core business strategy. The process approach methodology is known as “Plan-Do-Check-Act” (PDCA), that means:

- *Plan*: establish objectives and processes necessary to deliver results in accordance with customer requirements and the organisation’s policies;
- *Do*: implement the processes;
- *Check*: monitor and measure processes and product against policies, objectives and requirements and report the results;
- *Act*: take actions to continually improve process performances.

[1] A demand organisation is an entity which has a need and the authority to incur costs or have requirements met. It is typically an authorized representative within a functional unit (EN ISO 41001:2018).

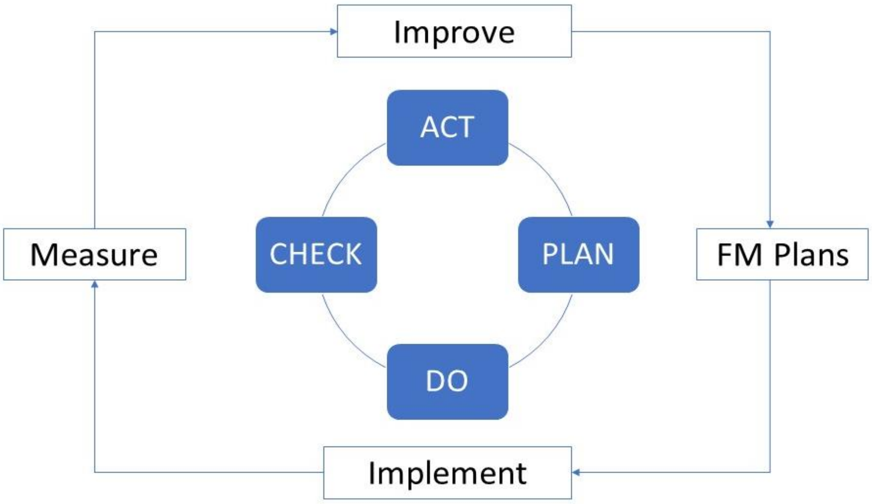



***Figure 4.*** *Process approach methodology in FM (based on EN ISO 41001:2018).*

**UNI EN ISO 41012:2018, Facility management - Guidance on strategic sourcing and the development of agreements** provides guidance on sourcing and development of agreements in facility management. It highlights:

- essential elements in FM sourcing processes;
- FM roles and responsibilities in sourcing processes;
- development processes and structures of typical agreement models.

This document supersedes the EN 15221:2-2007.

FM should be in close synchronization with the mission and the vision of the organisation and its objectives. It is the role of FM to provide a strategic guidance to the core business, interpreting needs and translating them into explicit service demand and requirements. FM acts on three levels:

- at the *strategic level* the organisation's objectives are achieved, in the long term, by defining the FM strategy and related implications;
- at the *tactical level* the strategic objectives are implemented, in the medium term, through implementing guidelines for strategies, translating FM objectives into operational level requirements, defining Service Level Agreements (SLAs), defining Key Performance Indicators (KPIs), etc.;
- at the *operational level* the required environment to the end users is created through delivering services according to SLAs, monitoring the services delivery processes and the services providers, receiving requests for service, collecting data for performance evaluations, communicating with internal or external service providers.

The set of standards for Facility Management, reported below, was provided by the Technical Committee CEN/TC 348 "Facility Management".

**EN 15221-1:2006, Facility Management- Part 1: Terms and definition** (replaced by the UNI EN ISO 41011:2018) gives relevant terms and definitions in the area of Facility Management and provides insight into the scope of FM. The FM model proposed in this standard provides a framework describing how FM supports the primary activities of an organisation (**Figure 5**).

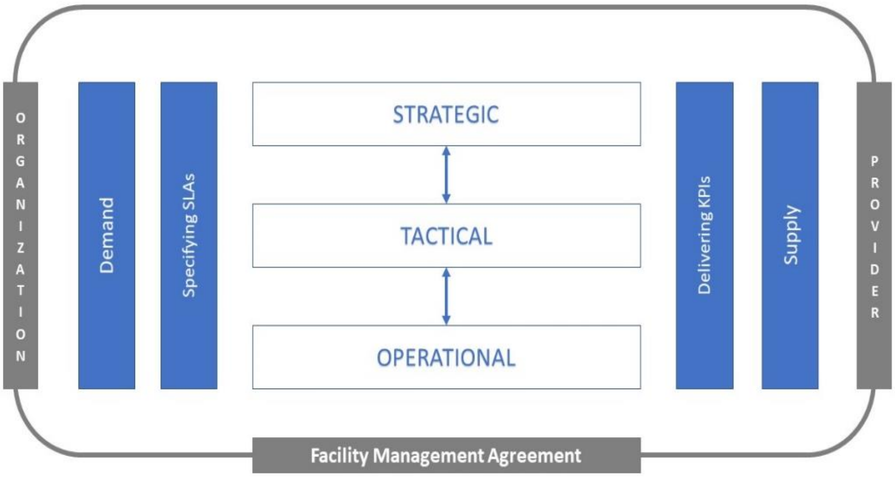



***Figure 5.*** *Facility Management Model (based on UNI EN 15221-1:2006).*

**UNI EN 15221-2:2007, Facility Management – Part 2: Guidance on how to prepare Facility Management agreements** (replaced by UNI EN ISO 41012:2018) aims at providing a guidance for an effective FM agreement. Such an agreement, by nature, defines the relationships between the client and the FM service provider.

**UNI EN 15221-3:2011, Facility Management – Part 3: Guidance on quality in Facility Management** provides a guideline how to measure, achieve and improve quality in FM. It gives complementary guidelines to EN ISO 9000, EN ISO 9001 and EN 15221-2 within the framework of EN 15221-1. The standard provides a link into management methods and management theories. For the client organization the quality of services delivered is fundamental, since it may influence the quality of the primary activity of the organisation. According to this standard, quality is the "*degree to which a set of inherent characteristics of an object fulfils requirements*". In order to define the quality of a product, indicators for appropriate characteristics shall be used. They may be defined as objective (hard) and subjective (soft). The interactions of elements and influences on quality in Facility Management is depicted in **Figure 6**.

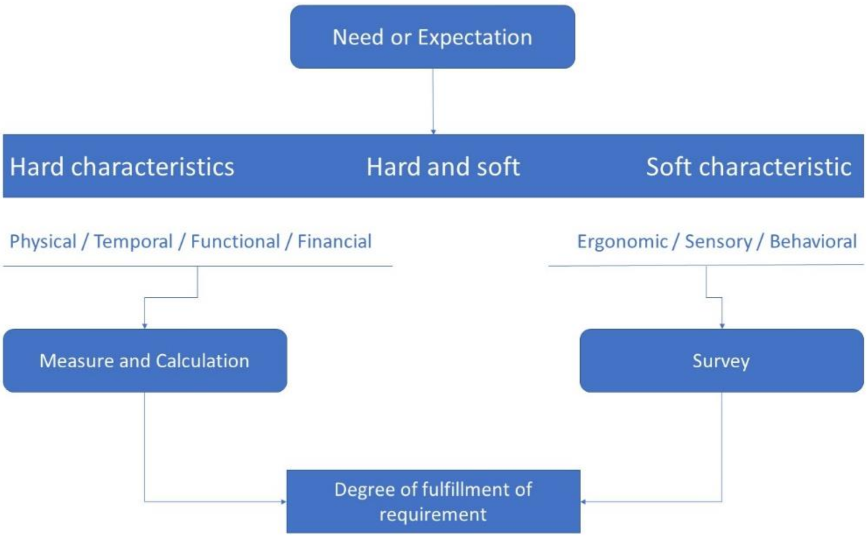



***Figure 6.*** *Elements and influences on quality in FM (based on UNI EN 15221-3:2011)*

**UNI EN 15221-4:2011, Facility Management – Part 4: Taxonomy, Classification and Structures in Facility Management** provides a taxonomy with a relationship model which integrates FM-model, the process matrix, the product structure and a classification system. The approach of this standard is to consider the added value provided to the primary activities by adopting a product perspective. This standard therefore introduces the concept of standardised (classified) facility products.

**UNI EN 15221-5:2011, Facility Management - Part 5: Guidance on Facility Management processes** provides guidance to FM organizations on the development and improvement of their processes to support the primary processes. Processes may be divided into sub-processes, each of which have inputs, workflow and outputs (**Figure 7**).

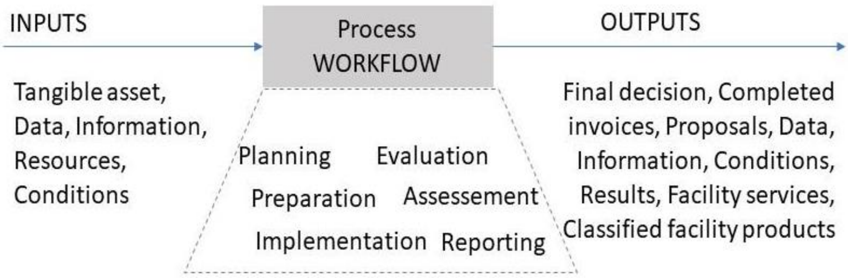



***Figure 7.*** *Process principle and workflow (based on UNI EN 15221-5:2001).*

**UNI EN 15221-6:2011, Facility Management - Part 6: Area and Space Measurement in Facility Management** establishes a common basis for planning and design, area and space management, financial assessment, as well as a tool for benchmarking in the field of Facility Management. It presents a framework for measuring floor areas within buildings and areas outside of buildings.

**UNI EN 15221-7:2012, Facility Management - Part 7: Guidelines for Performance Benchmarking** gives guidelines for performance benchmarking and contains clear terms and definitions as well as methods for benchmarking facility management products, services and organisations. Benchmarking can regard a strategy, a process or a performance. Depending on the purpose of benchmarking, the scope (i.e., content, measure, comparator, domain, frequency) will differ (**Figure 8**).

| | content | | | measure quantitative / qualitative | | | | | | comparator | | | domain | | | frequency | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| purpose | strategy | process | performance | finance | space | environment | service quality | satisfaction | productivity | internal | competitor | cross-sector | local | national | international | one-off | periodic | continuous |
| Identification of improvement options | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Resource-allocation decisions | ✓ | | | ✓ | | | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | |
| Prioritisation of problem areas | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | ✓ | | |
| Verification legal compliance | | ✓ | | | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | |
| Identification of best practices | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | |
| Budget review and planning | ✓ | | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Alignment with corporate objectives | ✓ | | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Improvementof process effectiveness | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | |
| Assessment of property performance | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *- Assessment of cost effectiveness* | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *- Evaluation of floor space usage* | | | ✓ | | ✓ | | | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | |
| *- Appraisal of environmental impacts* | | | ✓ | | | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | |
| *- Assessment of service quality shortfalls* | | | ✓ | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *- Evaluation of end-user satisfaction* | | | ✓ | | | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | |
| *- Appraisal of individual productivity* | | | ✓ | | | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | |

***Figure 8.*** *Examples of benchmarking purposes and scopes (UNI EN 15221-7:2012)*

Finally, the standard **UNI 11447:2012, Urban Facility Management Services - Guidelines to set and program contracts** contains guidelines to customers for setting and programming processes of a service contract for urban Facility Management, in order to unify the approach with a common methodological-operational reference.

### 2.1.2 Functions and competencies

Facility Management embraces a wide range of functions as shown in **Table 2.** These key priority areas have blurred borders, so long that a specific subdivision is hard to obtain.

***Table 2.*** *Common cluster of services within the Facility Management (Chotipanich, 2004; Roper & Payant, 2014; Kiviniemi & Codinhoto, 2014; Atkin & Brooks, 2015).*

| | |
|---|---|
| **Management of the Organisation** | Personnel management, training, work scheduling, standards establishment, contractor evaluation, annual resources planning, etc. |
| **Real Estate and Property Management** | Property strategy, lease administration, landlord activities and rent review, site selection and acquisition, space renting, etc. |
| **Space Planning and Management** | Space allocation, space inventory, space forecasting, space configuration, etc. |
| **Architectural/Engineering Planning and Design** | Building planning, architectural design, as-built maintenance, disaster recovery planning, design document preparation, etc. |
| **Operations, Maintenance and Repairs** | Facility refurbishment, fabric maintenance, equipment and system maintenance, exterior maintenance, hazardous waste management, energy management, inventory of systems and equipment, maintenance projects, cleaning, etc. |

| | |
|---|---|
| **Security, health and Safety Management** | Code compliance, occupational safety, industrial hygiene, risk assessment, safety rules for subcontractors, access control, electronic security, vulnerability assessment, fire protection and safety, etc. |
| **Administration Management** | Budget and cost control, contract control and negotiation, work plan preparation, economic justification, financial forecasting, etc. |
| **Sustainability** | Normally it is done concurrently with other functions. The organisation might have as objective the requirement of optimize the costs and the energy consumption over the life-cycle. |
| **Technologies Management** | Hardware maintenance, software maintenance, system management, licence control, network management, etc. |
| **Employee support** | Help desk, reception, photocopying, food services, child nursery provision, etc. |

IFMA has organized these functions in desirable ‘competencies’ of a facility manager. According to the Competency Guide (IFMA, 2018) a facility manager is expected to be competent in:

- <u>Occupancy and human factors</u>. It regards the workplace environment, occupant services, occupant health, safety and security to protect the environment and the people who use the facility while supporting organizational effectiveness and minimizing risks and liabilities;
- <u>Operations and Maintenance</u>. It means to oversee the operation of the facility and it involves building systems, furniture, physical safety and security, maintenance processes, work management support systems, renewals and renovations;
- <u>Sustainability.</u> Facilities play a key role in the social responsibilities and laws/regulations compliance of the organisation. Sustainability regards energy and water management, materials management, waste management, workplace and site management;
- <u>Facility Information Management and Technology Management</u>. The facility manager is responsible for technology needs assessment and implementation, data collection and information management, maintenance and upgrade of technology systems, cyber-security;
- <u>Risk management</u>. It includes risk management planning, emergency preparedness, response and recovery, facility resilience and business continuity;
- <u>Communication.</u> It regards the stakeholders’ involvement and relationship;
- <u>Performance and quality</u>. It is required to measure the performance of the facility organization and service providers to make continual improvements;
- <u>Leadership and strategy</u>. It is important to align the facility portfolio to the organisation’s demand and to provide guidance to staff and service providers;
- <u>Finance and business</u>. Significant financial investment and considerable operational expense are involved in the facility management process;
- <u>Real estate</u>. Facility managers are expected to deal with real estate strategies, real estate assessment, acquisition and disposal, real estate asset management, space management; major projects and new construction;
- <u>Project Management</u>. Project management is a core skill in facility management and is particularly important because of the wide range of projects assigned to the facility organization.

FM importance grew up together with the complexity of the real estate, including more and more activities and demanding professionals with more skills and wider expertise; from these emerging needs the externalisation of many activities is born, with its benefits and costs. In general organisational models for non-core business management depend on the company's strategies and long-term values analysis, as discussed in the section below.

### 2.1.3 Strategies for non-core processes management

Facility management deals with the optimization of non-core support services management through vertical integration (or insourcing) and outsourcing. Vertical integration and outsourcing are the extremes of a range of potential business configurations (De Toni et al., 2012).

**Outsourcing** is defined as an "*act of moving some of a firm's internal activities and decision responsibilities to outside providers*" (Chase et al., 2004). Outsourcing involves allocating or reallocating business activities from an internal source to an external source.

**Insourcing** can be defined as internal sourcing of business activities even if the allocation is in different geographic locations (Schniederjans et al., 2015).

Today's modern organisations have to balance the potential benefits of outsourcing with its potential costs and challenges.

Vertically integrated companies have direct control over both core and non-core service provision for enhancing processes and product quality. The reasons for this configuration have to be found in the need for keeping under control the uncertainty affecting the relationship with suppliers (De Toni et al., 2012). Indeed, companies have two major motives in using outsourcing: increased efficiency and cost reduction.

Externalisation could be a good solution if properly planned, but it could lead to problems like the loss of important data and the ability to control the asset (having a huge amount of data without the ability to read, check and update them is like not having them) (Maltese, 2015).

From the literature review the benefits and the challenges of each FM configuration have been deduced, as shown in **Table 3.**

***Table 3.*** *Balancing outsourcing and insourcing features (Kurdi et al., 2011; De Toni et al., 2012; Schniederjans, 2015).*

| | OUTSOURCING | INSOURCING |
|---|---|---|
| Possible benefits | - Reduces costs<br>- Increase efficiency, concentrating on the core business<br>- Increase services quality<br>- Reduces risk in operation<br>- Greater diversification of activities and flexibility | - Control of production activity<br>- Loyal and interested workforce<br>- Opportunity to grow people and to provide careers prospects |
| Possible challenges | - Inability to control the asset<br>- Loss of know-how<br>- Increase the need of coordination<br>- Dependency on unique supplier<br>- Bad external supplier<br>- Poor quality of service | - Uncompetitive<br>- Increased labour costs<br>- Management problems<br>- Difficulty in measuring the in-house performances |

| | | |
|---|---|---|
| | - Employee resentment | |

Usually, large enterprises have a facility management division. This functional division is administered by a so-called *facility manager* who is in charge of managing and coordinating the execution of all non-core internal operations. The facility manager can be a manager of the organisation or a consultant. When a facility manager belongs to the organization, an *in house management* strategy is adopted while the engagement of a consultant refers to *managing agent* strategy (Alexander, 1996).

Increasingly, small and large companies alike outsource to companies which are specialized in facility management and can, therefore, ensure the efficient provision of required services. Outsourcing can refer to only a few processes or to many of them, and it can involve one or more service suppliers.

In the literature, different typologies of services providers can be identified, commonly categorised into *general contractor* and sub-contractors. As a result, service providers can belong to two different typologies:

- *Specialized providers*, who focus on a single process/service. The customer needs to turn to diversified providers to obtain the required services;
- *Integrated providers*, who supply different processes/services in an integrated manner through specialised provision business units (Nonino & Panizzolo, 2007).

When a company decides to outsource and manage different specialised providers, they adopt a *direct outsourcing* strategy, which has two major advantages: (1) supply risks are distributed among different individuals and (2) the suppliers' bargaining power is reduced. Relying on a single integrated supplier is called *managing contractor* strategy (De Toni et al., 2012).

Providers can also be divided in three typologies, according to their specialisation (De Toni et al., 2012; Tronconi & Ciaramella, 2014):

- <u>Partial management operators</u>, which experience is limited to some specific activities. They provide operational services more than managerial services;
- <u>Sectorial management operators</u>, which have a deep knowledge of their business fields and many resources. These operators generally provide energy management, maintenance and operations, employee support services and similar;
- <u>Facility Management operators</u>, which provide an extremely wide range of coordinated and integrated services. These organisations usually rely on a structured contract, called **Global Service**, flexible and adaptable though. A Global Service is a particular form of outsourcing based on the results, by which the client relies on a single supplier for several services (UNI 11136:2004). When a company outsources all non-core processes/services to a large facility management operator, it adopts an *integrated facility management strategy*.

It is possible to describe the FM supply with a tripartite pyramid (**Figure 9**).

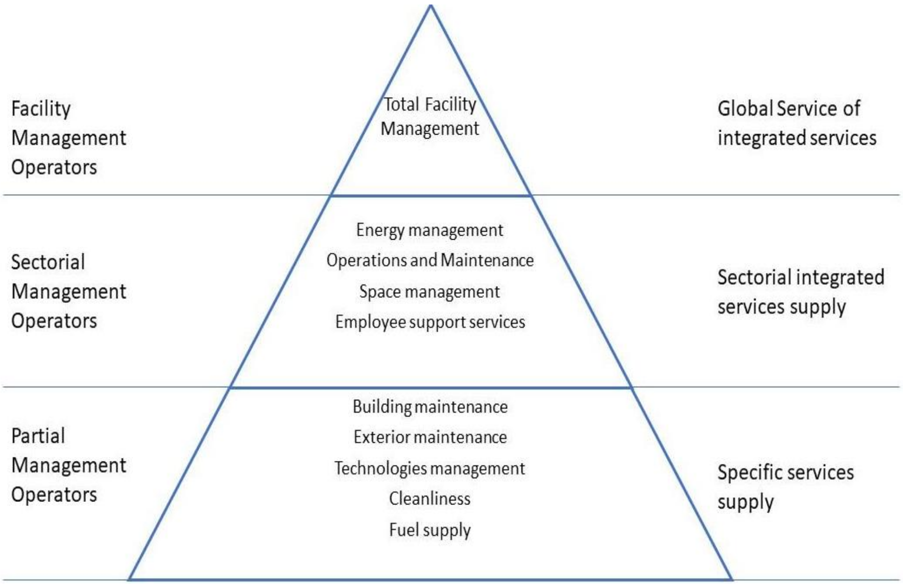



***Figure 9.*** *FM pyramid (based on Tronconi & Ciammarella, 2014).*

Some researches (De Toni et al., 2012) identified business strategies for non-core activities management (**Table 4**). 11 models were identified and classified according to the typology of non-core service providers and the facility manager's organisational role.

***Table 4.*** *Organisational model for non-core activities management (DeToni et al., 2012).*

| **Business strategies** | **Organisational model** |
|---|---|
| ***In-house management*** (internal non-core service management) | 1. Inner functional units are able to provide non-core processes without the help of a facility manager. A typical example of this model is when the cleaning activities in the manufacturing unit are assigned to single operators.<br>2. The organization has their own employees dedicated to non-core processes and a coordinator is usually envisaged within the organization - the so-called 'facility manager'.<br><br>This situation is typical of small-medium enterprises (SMEs).<br>3. A special business unit is created within the company to perform such activities The business unit is administrated by a facility manager who has the authority to manage and coordinate the unit. |
| ***Management by an agent*** (an external consultant performs facility management activities) | 4. If the company does not prove to have the necessary abilities or know-how to manage and coordinate non-core processes autonomously and in an efficient and effective manner, it can choose to appoint an external managing agent, who is employed by the company with a medium- or long-term agreement and acts as a consultant. |
| ***Direct outsourcing*** (the customer decides to contract-out specific services) | 5. The facility manager is an external consultant.<br>6. The facility manager is a customer's employee. |
| ***Managing contractor*** (the services are managed by a single provider called *contract manager*) | 7. Service provider is an external consultant.<br>8. Service provider is employed by the contractor's company. |
| ***Integrated facility management*** (or *total facilities management*, refers | 9. The internal facility manager who works for the customer acts as an interface between the customer and the service provider's facility manager. According to this model, the service provider manager |

| | |
|---|---|
| to the situation in which the customer company assigns service management to companies which can provide services in a coordinated, integrated and autonomous manner) | plays the role of an account manager and he is in charge of external relationships to the customer.<br>10. The outsourced facility manager does not work for the customer and neither for the service provider.<br>11. The service provider is fully in charge of the management and coordination of non-core services. |

Four components can be identified as major features of an ***integrated facility management***: *operational activities*, *management roles*, *facility knowledge and management knowledge* (**Figure 10**). The integration of facility management, as an effective function for an organisation, can be achieved by recognizing three key characteristics: (1) facility management is a *support role* within an organisation, or a support service to an organisation; (2) facility management must *link* strategically, tactically and operationally support activities and primary activities to create value; (3) within the facility management, managers must be *equipped with knowledge* of facilities and management to carry out their integrated support role (Kincaid, 1994).

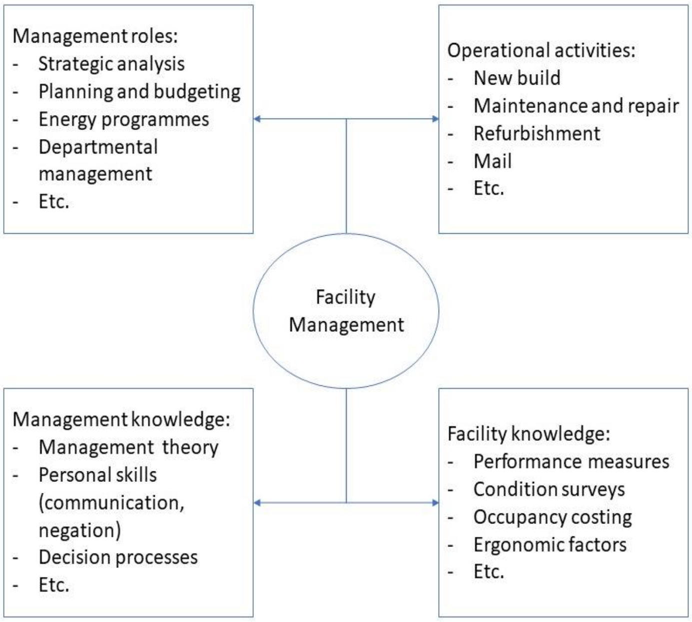



***Figure 10.*** *Integrated Facility Management (based on Kindaid, 1994).*

### 2.1.4 Information Management

An efficient information and data management is necessary for the organisation in order to comply with various obligations and duties, as well as to be able to derive optimal uses and benefits from the facility.

Knowledge about the facility has a real value, as the delivery of a service is also the delivery of an information. In managing a facility it is relevant to know about the spaces to be serviced, the services to be performed and the actual performance of those services (Atkin & Brooks, 2015).

Information should be accurate, reliable, up-to-date and complete. This is not a simple matter of technologies, but it depends on people and finances, guided by standards and policies.

Different types of information are managed in daily FM operation: (1) *commercial information* such as valuations of the real estate, insurance policies and market data; (2) *financial information* such as the cost of operating of the facility, performance of services and related work items; (3) *technical information* related to the safe and correct operation of the facility; (4) *managerial information* include the former, additionally human resources should be considered; (5) *as-built information*, as part of the technical information, include information prepared before the handover phase and those produced during the operational phase (i.e., details of defects, maintenance, alterations, etc.). As-built information are made by drawings, specifications and schedules (Atkin & Brooks, 2015).

FM information management is supported by a series of tools and software, more or less detailed and tailored on the asset/portfolio, depending on some factors: type and extension of the portfolio, abilities of the dedicated personnel, externalisation of the FM activities (Maltese, 2015).

For the scope of this thesis the more relevant information systems are those regarding the Operation and Maintenance (O&M) information management.

Information Communication Technologies (ICT) are increasingly providing the tools for the information management. Ranging from email documents to BIM, including Computerized Maintenance Management System (CMMS), Computer Aided Facilities Management (CAFM) and BAS/BEMS, different tools have supported FM activities during the past decades (Aziz et al., 2016).

The CMMS includes the creation and the management of asset records, bill of materials and work orders; inventory control, etc. (Marquez et al., 2009), thus they support maintenance scheduling, facilities monitoring and preventive maintenance (Mohanta & Das, 2015).

The CAFM is a collection of tools used for organizing and managing various activities within the facilities (Mohanta, 2015) to support the planning and the monitoring of physical space. Typically, CAFM software are based on a CAD front-end linked to a relational database back-end (Atkin & Brooks, 2015).

Both CMMS and CAFM have limited visualization capabilities, as traditionally they utilize paper based or digital 2D plans, which limit the facility manager to identify the exact maintenance location context and the history of modifications (Aziz et al., 2016).

The BEMS are regularly applied to the control of active systems, i.e., heating, ventilation, and air-conditioning (HVAC) system, determining their operating times. While sensors send feedback and alarms to these controlling systems, facility managers can monitor and change any benchmark or override the information (Shalabi & Turkan, 2016). The complexity of BEMS can be integrated to CAFM and BIM to control the operating equipment (Mohanta & Das, 2015).

In order to guarantee the required building operational performance, facility managers must check technical and environmental conditions. In this sense, building sensors and controllers can inform maintenance activities.

BIM might interact with the described systems, as a source for data input, providing material/spatial data, reports or technical analyses, or as an interface for a repository, providing data capture, monitoring, processing and transformation (McArthur, 2015; Volk et al., 2014).

BIM offers many advantages due to the integration of information and data across the facility life-cycle phases. Spatial information and component details, among others information, are essential for operations and maintenance, moreover a digital version of the facility is both dynamic and easy to update.

BuildingSMART is the international body responsible to provide the Industry Foundation Classes (IFC) specification that includes also support for asset and facility management functions. IFC Model View Definition (MVD), together with the Construction Operation Building information exchange (COBie), define a standard structure and minimum data fields needed to support facility management. The scope of the use of MVD and COBie is to define IFC content for exchange between Architectural, Engineering and Construction (AEC) applications and CAFM or CMMS applications (**Figure 11**).

Further information about the use of BIM for FM and related interoperability issues are provided in the subsection 2.4.

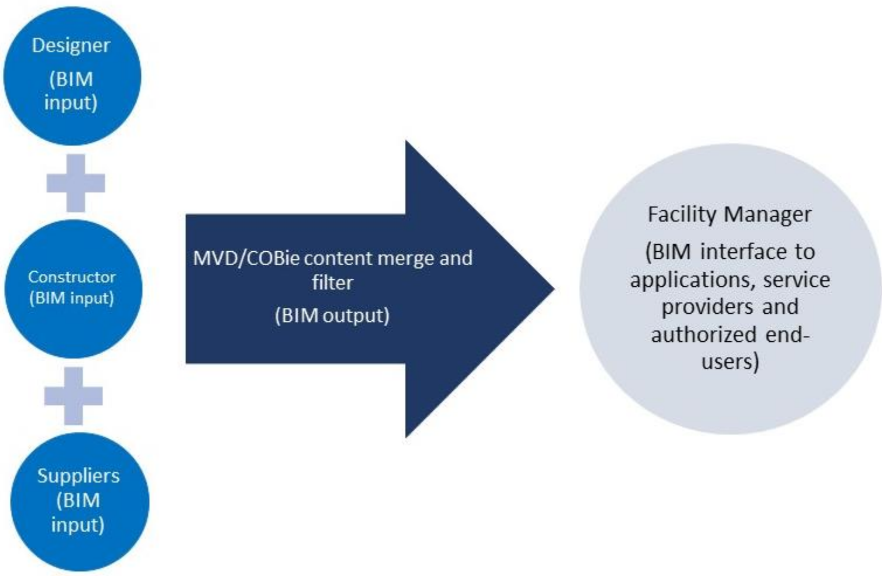



***Figure 11.*** *BIM information and data exchange (based on Atkin & Brooks, 2015).*

## 2.1.5 Future Trends

Outsourcing has become more and more popular, at the same time the focus on sustainability and emergency planning has increased (Roper & Payant, 2014).

Sustainability will become an integral part of FM operations because of the cost reduction implications and because it is desired by employers and customers.

Emergency planning should become second nature for facility managers and can be helped by web-based software.

According to the Global FM Market Report 2018 (Global FM, 2018) North America and Europe are the most mature markets for FM outsourcing and Integrated Facility Management adoption, with many global service providers originating from these regions. The most impacting trends on FM markets are expected to be, among others, business productivity; anything-as-a-service (XaaS), sustainability, energy management, performance contracting. Future workplaces will integrate various mobile infrastructures and devices which allow employees to function with a higher degree of flexibility. New workforce, based on Millennials, Generation X, female and immigrants, and new technologies will facilitate the grown of new employment models. Technological innovations will regard data-enabled decision making; virtual enterprises; human-robot collaboration. The growing ageing population will drive the demand for aged care facilities, retirement villages and support living services.

## 2.2 Building Performance Assessment

A performance is a "*measurable result*" (UNI EN ISO 41011:2018). Performances can be related to activities, processes or products, and they concern either quantitative or qualitative findings.

In a broad sense, performance assessment involves reconciling the levels of service delivered to end-users against agreed standards and targets set out in service specification and service level agreements. Performance management requirements should have been defined as part of the FM strategy and policy, and then communicated to all the stakeholders. Performance indicators should have been defined to measure and report achievement and those which are regarded as more significant should be defined as Key Performance Indicators (Atkin & Brooks, 2015).

In the context of services performance management, the Building Performance Assessment (BPA) aims at improving the knowledge of an asset. This is crucial for a correct comprehension of the building behaviour and criticalities, so to make correct decisions at the right time.

The performance evaluation of buildings and their components has always been a very complex and controversial topic. The problem arose when it was necessary to introduce assessments on the duration of the components, within the wider topic of scheduled maintenance. If we assume that every maintenance intervention must be associated with a performance threshold, and that the status of failure must be identified and coded also for those components for which performance is not measurable, then methods and tools to evaluate the performances are needed.

For the assessment of building performance it is very important to evaluate whether it is necessary to intervene (Talon et al., 2005), because there is risk that maintenance interventions may have high costs if not necessary or urgent (Silva et al., 2016).

In fact, the performance assessment should be conducted in combination with other important activities, like inspections and maintenance operations. Maintenance operations, in terms of both schedule and costs, must be planned consequently to the building assessment to be the most effective as possible (Percy & Kobbacy, 2000). Evaluation techniques should give as output an index, a rate or a mark (Roulet et al., 2002; Salim & Zahari, 2011) to enable decision makers to create a building ranking inside the portfolio, to prioritise maintenance works and to evaluate refurbishment scenarios.

In the last decades, however, the concept of performance evaluation has strongly moved towards those concerning the environment and sustainability (Isaac et al., 2019; Greenbiz; Meir et al., 2007). In this sense, it can be said that building performances have a strong integration with building users (Wahab & Kamaruzzaman, 2011), and the reference methods have therefore become those that prefer aspects such as quality, health, safety, security, comfort, without neglecting others such as the social ones (Vischer, 2009).

As a consequence, decisions of asset managers are becoming more complicated and a deep knowledge of the asset condition is needed (Flores-Colen et al., 2010), even though this is not always easy to achieve. Typically, asset managers must make decisions about maintenance and renewal alternatives based on sparse data about the current state of their assets (Vanier et al., 2006). Surveys of maintenance management effectiveness indicate that one-third of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance (Mobley, 2002). The dominant reason for this ineffective management is the lack of factual data to quantify the actual need for repair or maintenance of plant machinery, equipment, and systems. Maintenance scheduling has been, and in many instances still is, predicated on statistical trend data or on the actual failure of plant equipment.

The lack of information, therefore, causes a series of other problems which may lead to: a) the use of unsafe buildings, i.e., buildings which do not comply with basic law requirements; b) unsatisfactory buildings, as buildings with poor performances; and c) low yield investments (**Figure 12**).

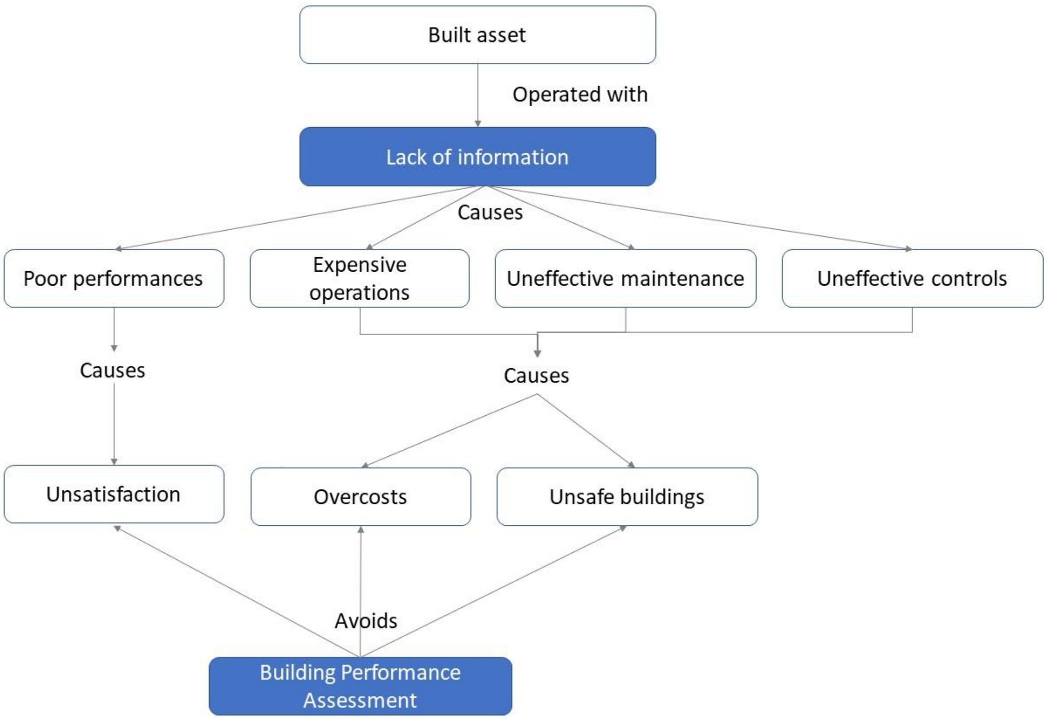



***Figure 12.*** *Main issues due to lack of information in the building process (based on Maltese, 2015).*

## 2.2.1 Building Performance Assessment methods

Various models, methods and tools are available to assist in measuring performances and in indicating where improvements are required, examples include benchmarking, Post Occupancy Evaluation (POE), Building Performance Evaluation (BPE), Critical Success factors (CSFs), Key Performance Indicators (KPIs), Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED).

The **benchmarking** is the process of comparing strategies, performances or other entities against practices of the same nature, under the same circumstances and with similar measures (UNI EN 15221-7:2012). Typically the purpose of benchmarking is to improve the entities under analysis. Measures can be quantitative or qualitative; the domain can be local or international and the frequency can be one-off, periodic or continuous.

The **Post Occupancy Evaluation** is a method developed in the 1960's, conceived to measure the performances of buildings that have been built and occupied for a set time duration.
POE is intended to determine how well a facility matches end-user requirements, for this reason it seeks the opinion of those directly affected by the evaluated service.

The **Building Performance Evaluation** is a method conceived in the 1990's. It upgrades the POE and aims at supporting the decision-making at every phase of building life cycle. This method was developed in order to improve the quality decision made at every phase of building life cycle (Preiser & Schramm, 2005). Thus, BPE can be used broadly in the Facilities Management field and can lead to business performance and future needs evaluation (Preiser & Vischer, 2005).
Both methodologies mostly tend to evaluate the performance of the whole building, and not those of the single components, essentially using analyses of users' satisfaction (Preiser, 1995; O Sanni-Anniber, 2016).

Some researchers (Amasuomo, 2017) consider methods such as the **BREEAM** or approaches such as **LEED** as real performance evaluation tools, although they refer to performances in a more than qualitative way but codified by means of scores and/or attributes.

**Critical Success Factors** are those actions that must be performed well in order that the organisation's set of business goals is achieved. Within each CSFs there will be one or more KPIs. The purpose of a KPI is to help in measuring, understanding and controlling progress in a CSF.

When establishing CSFs and KPIs it is vital that they correspond to goals that are aligned with organisation's objectives. Without this alignment successful attainment of service levels might not contribute to the success of the core business. KPIs indicate a level of achievement that can be compared over time to determine if performance is getting better, worse or staying the same (Atkin & Brooks, 2015).

**Key Performance Indicators** propose performance assessments mainly investigating the satisfaction of users through non-material indicators such as psychological or perceptive indicators, defined in facility management contracts.

Many researchers have emphasized the importance of measuring building performances through KPIs (Sinou & KYvelou, 2006, Lavy et al., 2014, Cable & Davis, 2004; Varcoe, 1996; Brackertz, 2006; Amaratunga et al., 2000; Lebas, 1995), and many others have categorized them in different ways.

Talon et al. (2005) list KPIs - at operational level - into the following: (1) technical, (2) functional, (3) behavioural, (4) aesthetic, (5) environmental.

Amaratunga and Baldry (2003) categorize KPIs according to four basic principles: (1) customer relations; (2) FM internal processes; (3) learning and growth; and (4) financial implications.

Augenbroe and Park (2005) divide the indicators into four other categories: (1) energy; (2) lighting; (3) thermal comfort; and (4) maintenance.

Hinks and McNay (1999) classify a list of 172 KPIs under eight categories: (1) business benefits; (2) equipment; (3) space; (4) environment; (5) change; (6) maintenance/services; (7) consultancy; and (8) general.

Lavy et al. (2010) present a literature-based list of categorized KPIs that covers the assessment of facility performance, breaking down the KPIs into: (1) financial, (2) physical, (3) functional, and (5) survey-based.

It has been highlighted (Bortolini & Forcada, 2018) that performance categories and examples of operational indicators, on the basis of studies conducted by several authors, can be summarized into: (1) technical; (2) functional; (3) behavioural; (4) aesthetic; (5) environmental.

Performance indicators are useful for measuring status and plan improvement activities and continuously assess changes over time (Talamo & Bonanomi, 2015). Technical performance indicators are considered the most critical, and within this category structural resistance to fire and stability are two important indicators to be considered (Weber & Tomas, 2005), while other researchers (Lützkendorf, 2005) identified asset failures and the severity of their consequences as an indicator.

Examples of indicators, considered relevant in the context of this thesis, are reported in the **Table 5**.

***Table 5.*** *Examples of Indicators (based on Marmo et al., 2019b).*

| Performance category | Indicator | Description | References |
|---|---|---|---|
| Economic | FCI - Facility Condition Index | Economic value of anomalies | Lavy, 2008 |
| | AME – Annual Maintenance Expenditure | Maintenance expenditure (i.e. $/m$^2$) | Lavy, 2004; Shohet, 2006 |
| | MEI – Maintenance Efficiency Indicator | Maintenance economic efficiency | Lavy, 2004; Shohet, 2006 |
| Technical | BPI – Building Performance Indicator | Physical condition of building systems | Lavy, 2004; Shohet, 2006 |
| | D – Service Life Index | Age of building systems | Dejaco et al., 2017 |
| | A – Degradation Index | Degradation of building systems | Dejaco et al., 2017 |
| | LOS – Level of Service | Technological performances with respect to environmental quality | Ali & Hegazy, 2014 |
| | EC – Environmental Condition | Environmental performances | Eweda et al., 2010 |

There are also possibilities, widely exploited, to use BIM as a source of data for a prediction of performance indicators of the planned building. That is for obtaining quantifiable predictions that can help in identifying strategies, tools and methods to improve the overall building performance.

BIM-based computational analysis tools provide possibilities for integrating design and analysis process from the earliest stages of design and can also assist in design decision making (Aksamija, 2012); some researchers (Aksamija, 2010) have emphasized the effectiveness of Building Performance-Based Design Method compared to theTraditional Method.

Recent publications have defined BIM-based workflows to compute and compare Key Performances Indicators in order to make a qualitative assessment of the building and its parts (Re Cecconi et al., 2017) and to automate the monitoring of buildings during their regular operation (Bonci et al. 2019). In both cases the digital model becomes the mirror of the building and stores its actual performances to support facility managers in making decisions. In the context of historical buildings, the residual performance assessment has recently been discussed, inferring conclusion about the condition of existing buildings from diagnostic survey (Bruno et al., 2018).

## 2.3 Maintenance Management

As for the Facility management, several definitions of maintenance have been proposed during the last decades. The maintenance concept can be defined as the set of various maintenance interventions (corrective, preventive, condition based, etc.) and the general structure in which these interventions are foreseen (Pintelon & Waeyenbergh, 1999).

A recent definition of maintenance is given by the Technical Committee CEN/TC 319 "Maintenance" (UNI EN 13306:2018), which defines maintenance as a "*combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function* ". Technical maintenance actions include observation and analysis of the item state (i.e., inspection, monitoring, testing, diagnosis, prognosis).

The maintenance management include "*all activities of the management that determine the maintenance requirements, objectives, strategies and responsibilities and implementation of them by such means as maintenance planning, maintenance control, improvement of maintenance activities and economics*" (UNI EN 13306:2018).

In literature (Alner & Fellows, 1990) the building maintenance objectives have been summarized in the following:

- to ensure that buildings and their services are in safe conditions and are fit for use;
- to ensure that the condition of the building meets all statutory requirements;
- to maintain the value of the building stock;
- to maintain or improve the quality of the building.

The organisation must define the most appropriate maintenance method or combination of methods, having regard to its business objectives. To support these objectives a maintenance strategy must be prepared. The strategy has to be reviewed during the time and must consider the assessment of stakeholders' needs and maintenance performances. A maintenance strategy generally provides different maintenance methods, such as corrective, preventive, condition-based, etc., as discussed in the section 2.3.1. A policy should be developed to support the preparation of operational plans in line with the maintenance strategy.

Maintenance planning considers (Atkin & Brooks, 2015):

- requirements for operational demands and constraints;

- financial circumstances;
- feedback on prior maintenance activities.

The link between maintenance methods, maintenance performance and service delivery should be established through KPIs. It is to say the optimal approach to maintenance needs to be determined so that there is clarity over what is expected and what has been achieved. A correct KPI can inform the organisation of any deviation from the expected results so that corrective actions can be taken.

The maintenance process involves several activities (**Figure 13**), starting from the asset requirements. After selecting the maintenance appropriate methods, the resources required for those methods can be examined and the maintenance plan can be prepared. Not only the maintenance has to be implemented according to the plan, but also monitoring activities are required.

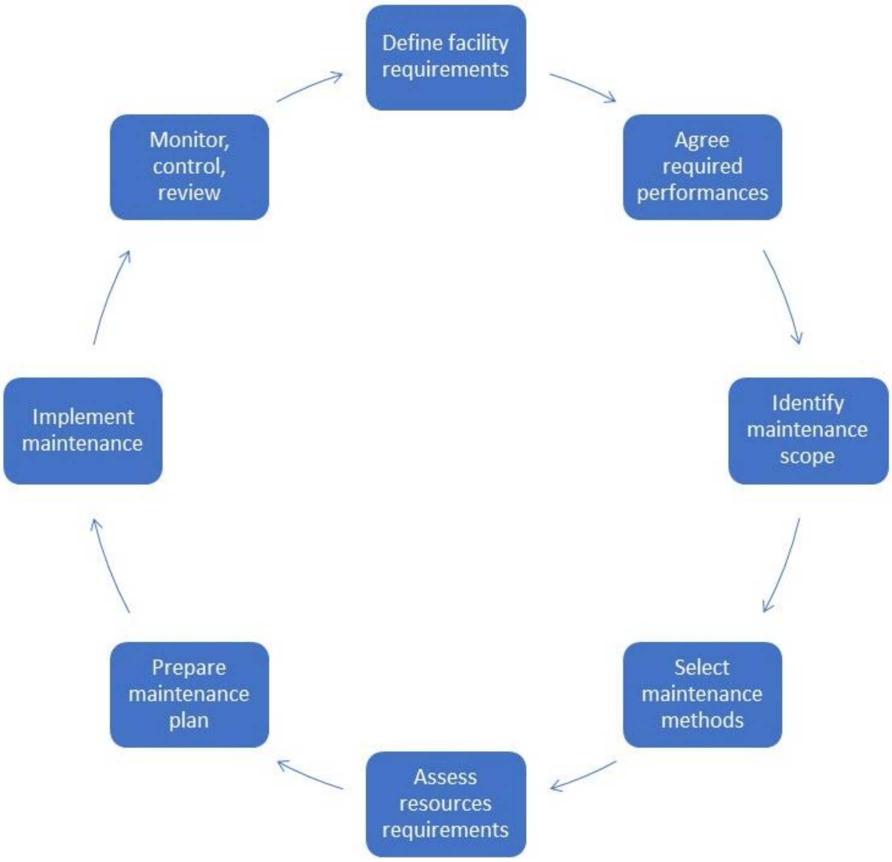



***Figure 13.*** *Maintenance process (based on Atkin & Brooks, 2015).*

### 2.3.1 Maintenance methods

The choice of the best maintenance strategy for an asset is firstly influenced by the maintenance policy adopted; most diffuse maintenance policies are essentially two: Total Productive Maintenance (TPM, replacing the component after its fault – corrective maintenance) and Reliability Centred Maintenance (RCM, replacing the component in advance – preventive maintenance) (Waeyenbergh & Pintelon, 2002). The RCM is a method used to determine maintenance required to ensure safe and correct asset function. It includes facility asset condition monitoring (Atkin & brooks, 2015). The TPM is a systematic approach to continuously improve the performance – effectiveness as well as efficiency – of certain industrial activities. In this sense it is more like a management strategy than a maintenance policy (Waeyenbergh & Pintelon, 2002).

All the maintenance approaches adopted in the past have been partially inefficient: on one hand redundant systems and surplus capacities immobilise capitals that could be used in a more profitable way and they show the fact that using an excessively cautious policy is quite an expensive way to obtain requested standards; on the other hand, a failure-based maintenance is often the cause of big disruptions and over-costs. The consequence is that maintenance transformed itself from an operational activity to a complex management system, oriented mainly to failure prevention (Maltese, 2015).

Maintenance strategy can be essentially grouped in three categories (**Figure 14**), according to UNI EN 13306:2018:

- Preventive maintenance, maintenance intended to assess and/or mitigate degradation and reduce the probability of failure of an item;
- Corrective maintenance, maintenance carried out after fault recognition and intended to restore an item into a state in which it can perform a required function;
- Improving maintenance, combination of all technical, administrative and managerial actions intended to ameliorate the intrinsic reliability and/or maintainability and/or safety of an item, without changing the original function.

A preventive maintenance strategy which do not provide the observation of degradation, but it is carried out in accordance with a predetermined time schedule, is called *predetermined maintenance.*

When a preventive strategy includes the assessment and the analysis of physical condition, that strategy is called *condition-based maintenance*. A condition-based maintenance can be *predictive* if it is carried out following a forecast derived from repeated analysis or known characteristics of the degradation of an item.

A corrective maintenance can be *deferred* if it is not immediately carried out after the fault detection, but it is delayed according to specific rules. On the contrary, a corrective maintenance is called *immediate* if it is carried out without delay after the fault detection in order to avoid unacceptable consequences.

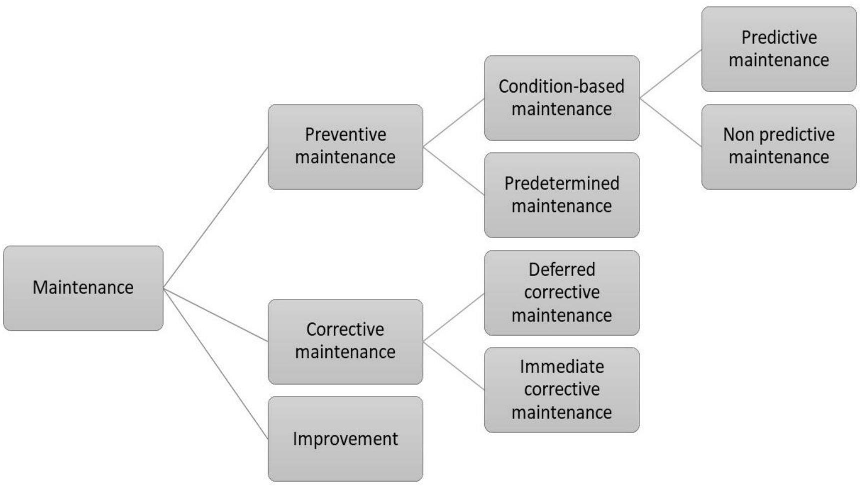



***Figure 14.*** *Maintenance strategies.*

A preventive activity can aim at detecting potential faults and degradations or at avoiding degradation and fault effects, while a corrective activity can aim at localizing faults, making diagnosis of faults or repairing components (**Figure 15**).

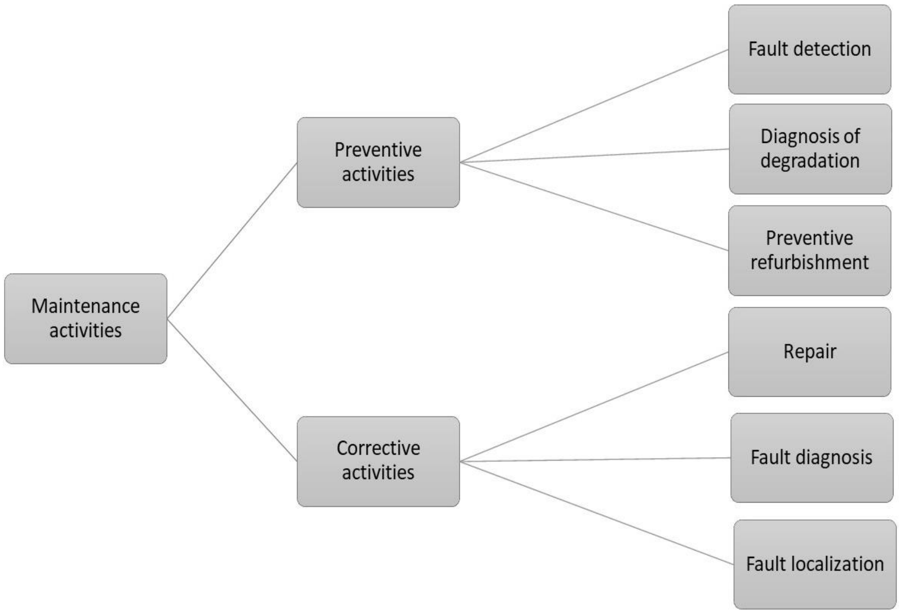



***Figure 15.*** *Maintenance activities aims.*

Lastly, according to the intervention planning, the maintenance can be *scheduled* or *unscheduled* (**Figure 16**). A scheduled preventive maintenance that is carried out without concerning the condition monitoring is called *predetermined* maintenance. A scheduled corrective strategy corresponds to the deferred corrective maintenance, while an unscheduled maintenance carried out immediately after the fault detection corresponds to the immediate maintenance.

The maintenance strategy adopted for unscheduled maintenance activities, performed independently from the fault detection, is an *opportunistic maintenance*, as it is undertaken at the same time as other maintenance actions or interventions to reduce costs or unavailability.

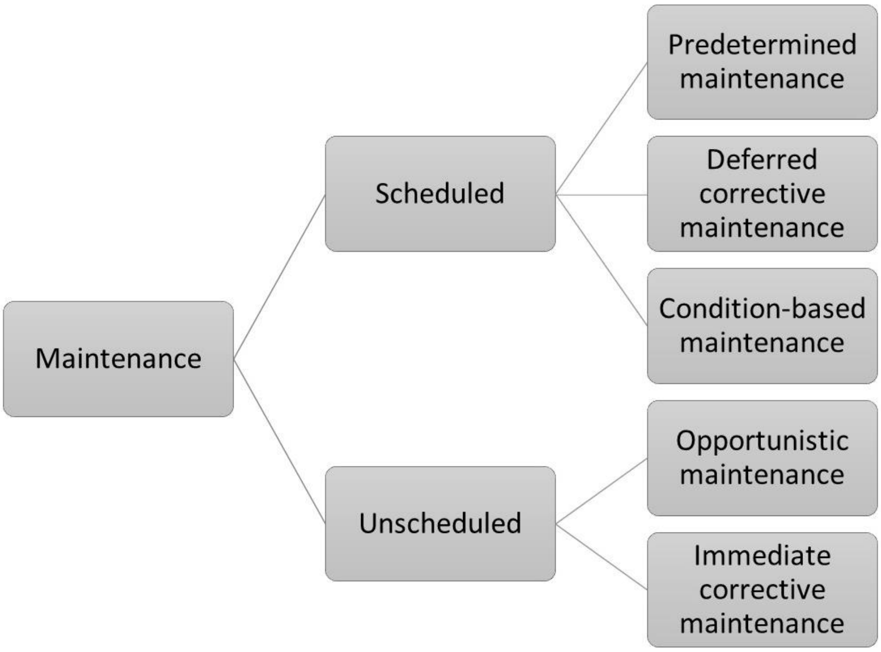



***Figure 16.*** *Scheduled and unscheduled maintenance.*

Less diffuse is the knowledge of preventive maintenance costs. To measure these expected economic benefits the concept of failure probability should be considered, as well as consequences that the failure can cause. A failure can cause, speaking in economic terms, consequences much bigger than the expenditure connected to the mere fixing. As instance, a water leakage in a pipe and the resulting presence of water in parts of the building not resistant to water, can cause, in addition to the plant dysfunction, damages to walls finishing, with dangerous consequences for users. Unfortunately, these damages connected to a component failure (called secondary failures), are far bigger than the replacement cost of the element. By the way it is impossible to quantify detachedly secondary failures because they depend on the damaged element position in the asset (Maltese, 2015).

### 2.3.2 Key Performance Indicators for maintenance

Developing performance metrics is an important step in the process of performance evaluation, as it includes relevant indicators that express the performance of the facility in a holistic manner. Consequently, it is significant to identify a set of KPIs to establish effective performance evaluation metrics for the facility under consideration (Lavy et al., 2014). However, a large number of KPIs adds a level of complexity and is narrow in perspective, thus lacking quantification and applicability across a range of projects (Shohet, 2006; Neely et al., 1997). The list of KPIs needs to be filtered through a certain set of criteria to identify those indicators that express one or more aspects of performance assessment effectively (Ho et al., 2000; Slater et al., 1997).

The UNI EN 15341:2019 lists key performance indicators of the maintenance function and gives guidelines to define a set of suitable indicators to improve effectiveness, efficiency and sustainability in the maintenance of existing physical assets.

According to this standard an indicator is a "*quantitative or qualitative measure of a characteristic or a set of characteristics of a phenomenon or performance activities, according to defined criteria or a given formula or a questionnaire*". A key performance indicator is an "*indicator considered significant*".

A Model of Maintenance Function is proposed in this standard. The maintenance function is a combination of 6 sub-functions with the addition of asset management methodology and the application of ICT and enabling technologies, such as the Industry 4.0 (**Figure 17**).

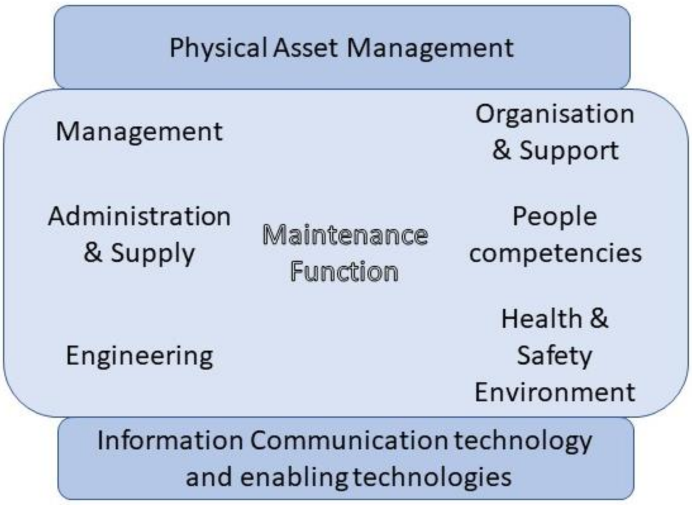



***Figure 17.*** *Maintenance function and core framework (based on UNI EN 15341:2019).*

Using KPIs the organisation can better measure the performances, compare the performances versus historical data of benchmarks, identify strength and weakness, control progress and changes, define plan for improvements, share the results.

The indicators can be periodically or occasionally used. They are often calculated as a ratio between factors measuring an activity, but they may also be the results of a questionnaire.

The Key Performance Indicators are structured in 8 groups: one for asset management, six for the maintenance sub-functions and the last one for the ICT (**Figure 18**). The KPIs related to each subsystem are divided in areas, which represent the fundamental contents or characteristics to be measured, controlled and improved.

For example, for the Health and Safety Environment (HSE) subsection 22 KPIs are proposed (HSE1-22). HSE procedures are fundamental to carry out Risk Analysis and to do preventive actions, keeping the integrity of each equipment in the condition that enable them to operate in a sustainable way according to laws requirements. The four main driven areas of HSE are:

- conformity to laws and rules (i.e., laws and rules implemented versus those required);
- statistical records (i.e., exposure to occupational disease);
- maintenance safety practice (i.e., frequency of items failures causing damages to the environment);
- prevention and improvements (i.e., safety and health improvement rate).

The PDCA process described in the section 2.1.1 referring the UNI EN ISO 41001:2018 can be applied also to KPIs through the following steps:

- to select the appropriate KPIs and reference values according to objectives and targets;
- to measure the actual value of KPIs;
- to compare the actual value with references in order to identify the gaps and to analyse them;
- to define and implement improvement actions on the existing status to achieve better values.

| SUB FUNCTIONS, TOOLS AND METHODOLOGIES | KPIs | MAIN AREAS | | | |
|---|---|---|---|---|---|
| Maintenance within physical asset management | $PHA_i$ | Sustainability i = 1 to 3 | Capacity Effectiveness Integrity i = 4 to 11 | Service Level i = 12 to 13 | Economics i = 14 to 20 |
| Sub-function 1 Health - Safety Environment | $HSE_i$ | Laws- Rules conformity i = 1 to 3 | Statistical Records i = 4 to 12 | Safe Practice i = 13 to 17 | Prevention and Improvements i = 18 to 22 |
| Sub-function 2 Maintenance Management | $M_i$ | Strategy i = 1 to 3 | Function i = 4 to 10 | Technical Assessment i = 11 to 16 | Continuous Improvement i = 17 to 22 |
| Sub-function 3 People Competence | $P_i$ | Maintenance Manager i = 1 to 3 | Maintenance Supervisor/ Maintenance Engineer i = 4 to 9 | Maintenance Technician Specialist i = 10 to 12 | Education i = 13 to 21 |
| Sub-function 4 Maintenance Engineering | $E_i$ | Capability Criticality i = 1 to 3 | Durability i = 4 to 9 | Preventive Maintenance i = 10 to 16 | Engineering Improvements i = 17 to 19 |
| Sub-function 5 Organization and Support | $O\&S_i$ | Structure and Support i = 1 to 8 | Planning and Control i = 9 to 22 | Productivity Effectiveness i = 23 to 28 | Quality i = 29 to 30 |
| Sub-function 6 Administration and Supply | $A\&S_i$ | Economics i = 1 to 6 | Budget &Control i = 7 to 19 | Outsourcing services i = 20 to 25 | Materials and spare parts i = 26 to 29 |
| Information Communication Technology, Enabling technologies | $ICT_i$ | Management i = 1 to 6 | Administration and Supply i = 7 to 10 | Organization and Support i = 11 to 13 | Engineering i = 14 to 20 TEC 18.20 |

***Figure 18.*** *Maintenance KPIs matrix (UNI EN 15341:2019).*

# 2.4 Building Information Modelling (BIM)

In this section an overview of the Building Information Modelling is provided. To better understand the BIM current adoption, main standards on the topic are discussed. A depth analysis of the use of BIM in the FM domain is also provided according to the scope of the thesis.

A Building Information Model is a built facility digital representation with huge information depth (**Figure 19**). It typically includes the three-dimensional geometry at a defined level of detail; non-physical objects, such as spaces and zones, a hierarchical project structure and schedules. Objects are semantically enriched and relationships between components are defined too.

The BIM model is used as a basis for all data exchange within the project. This avoids the need to manually re-enter data and reduces the accompanying risk of errors.

The term Building Information Modelling consequently describes both the process of creating such digital building models as well as the process of maintaining, using and exchanging them throughout the entire lifetime of the built facility (**Figure 20**). (Borrmann et al., 2018).

Researchers have examined various BIM interpretations based on the literature review and survey results (Matejka & Tomek, 2017). According to this research it is possible to divide current BIM understanding in three categories:

- BIM as a product (model)
- BIM as a method (modelling)
- BIM as a methodology

The first category represents basic understanding of BIM as a model. There are many different models (architectural, structural, mechanical, electrical, etc.) which can vary according to the construction project phase. The second category represents advanced understanding of BIM as a set of tools and processes. The third category represents the most sophisticated understanding of BIM as a methodology, considering the impact on construction projects. The model is a parametric, object oriented, attribute driven, digital representation of reality (i.e., an information model is a database), while modelling provides a set of methods (i.e., tools and processes), which can be used to create and use information models. At the methodological level, we can apply the BIM paradigm on the whole construction project life cycle as collaborative and information sharing environment, supported by various methods.

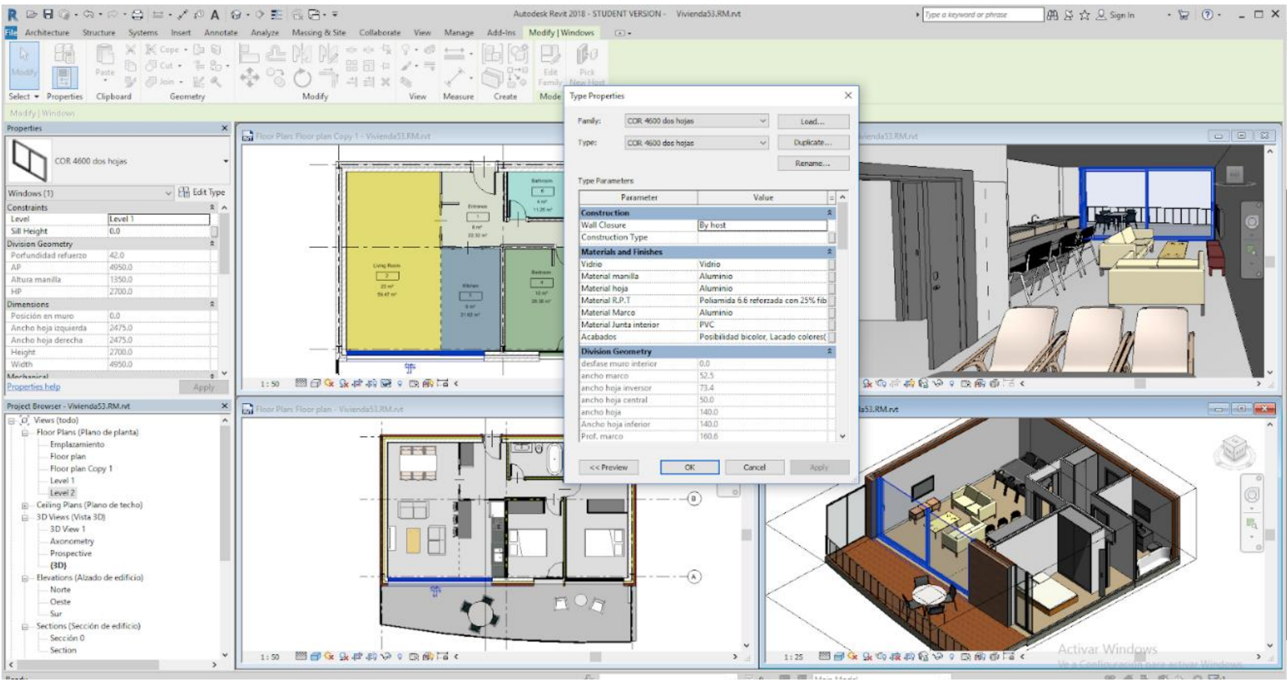


***Figure 19.*** *BIM models provide for 3D and 2D coordinate views of the asset, attributes and relationships among the components, hierarchical project structure.*

As evident, giving a single definition of BIM could not be enough to catch its understanding across the world, so the most recognized definitions are reported below.

A common definition of BIM is provided by the National BIM Standard-United States: *"Building Information Modeling is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.*" (National Building Information

Model Standard Project Committee, 2015). This definition outlines the applicability of BIM during all the lifecycle of a construction and its value in helping the decision making.

Similarly, the US Government General Services Administration defines Building Information Modelling as "*the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility.*" (US Government General Services Administration, 2007).

Eastman et al. (2008) exclude the notion of lifecycle support but defines BIM as a "*modeling technology and associated set of processes to produce, communicate, and analyze building models*". Building models are characterized by:

- Objects that 'know' what they are, and can be associated with computable graphic and data attributes and parametric rules;
- Components that include information and data describing their behaviour;
- Consistent, coordinated and non-redundant data through all views within the BIM environment.

In the same way, according to BIM Dictionary *"Building Information Modelling is a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. As a term, BIM has grown tremendously over the years and is now the 'current expression of digital innovation' across the construction industry".* (BIM Dictionary, 2019).

Finally the British Standard Institution declares "*BIM is the process of designing, constructing or operating a building or infrastructure asset using electronic object oriented information*." (British Standards Institution, BS PAS 1192-2).

Not depending on the definition, BIM is generally considered more than a group of interoperable software, as it can act as a paradigm to manage any construction phases. Nevertheless, BIM is still used more in the early design stages than in the operational stage, as discussed later on.

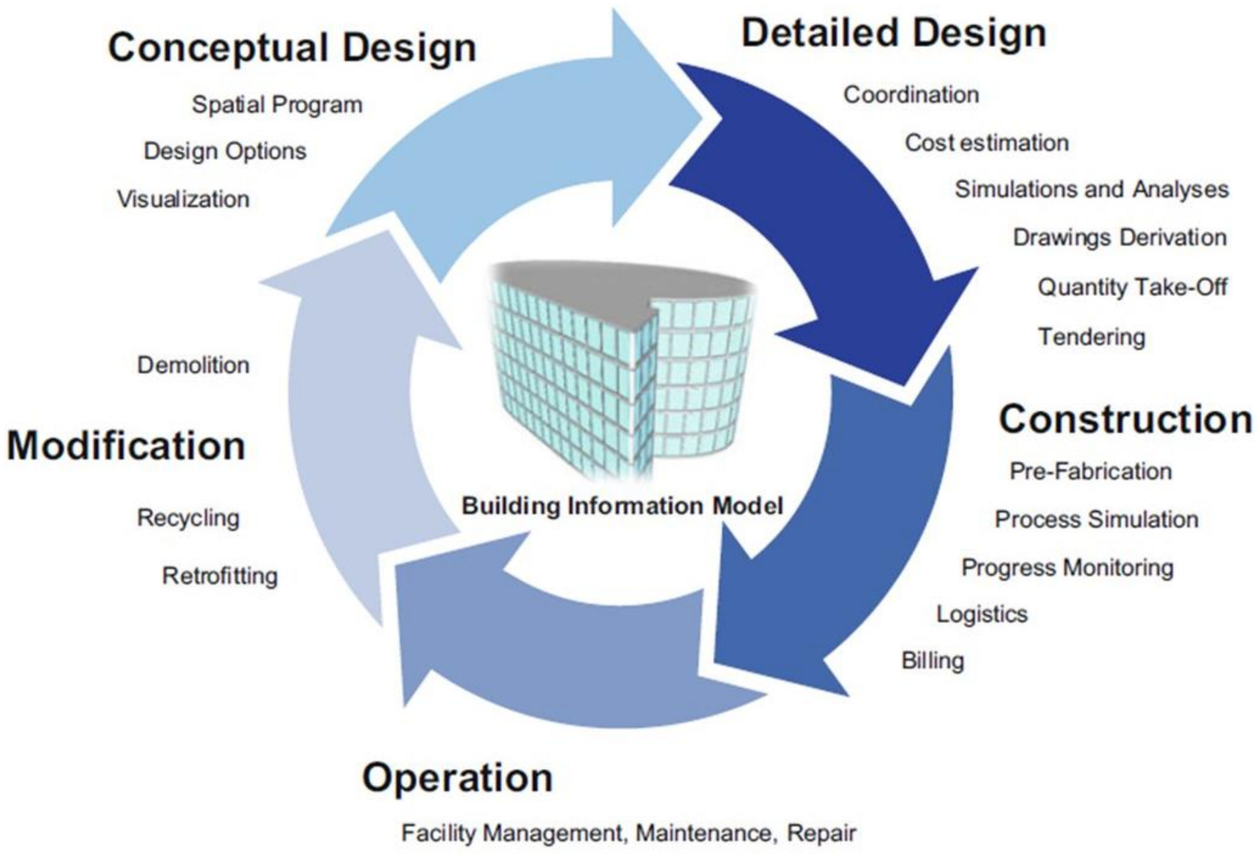



***Figure 20.*** *The concept of Building Information Modelling relies on the continuous use of digital information across the entire lifecycle of a built facility (Borrmann et al., 2018).*

### 2.4.1 BIM adoption, standards and policies

The adoption process of BIM goes through successive implementation steps, which gradually support the transition of the building industry from CAD drawings into the digital age. Standards and guidelines are necessary to work efficiently in a shared way. Moreover, each Country has its own set of regulations for the construction sector, consequently a set of standards for the BIM adoption has been published in the majority of European Countries as well as in Asia and America.

The **United States** is the pioneer in BIM development and adoption in the construction industry. In the US, the General Services Administration (GSA) in 2003 launched the "National 3D-4D program" with the goal to form strategy to gradually implement BIM for all major public projects (Wong et al., 2010). In 2007, the GSA included BIM for spatial program validation for all its projects (Burgess et al., 2018).

**Europe** hosts the greatest regional concentration of government-led BIM programmes in the world (NBS, National BIM Report 2016, 2016). Finland, Norway and UK were first to set standards for BIM projects. In particular in 2001 the UK government had required fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016 (Cabinet Office, 2011). Moreover, the European Commission encouraged the use of BIM as an enabler for delivering public works in the EU Public Procurement Directive (European Parliament, 2014). Following this Directive, many states are considering introducing BIM into the legislative system. For example, in Italy the Legislative Decree n.50/2016, code of public procurement (President of Italian Republic, 2016), introduces the use of "specific digital methods and tools for architectural and infrastructural modelling”. Subsequently the Ministerial Decree n.560/2017 (Minister of Transport and Infrastructure, 2017) was published with the intention of making BIM mandatory for all the public procurement by the 2025.

The European Commission has also co-founded the EU BIM Task Group aiming to bring Europe into a common and aligned approach in the construction sector and unifying BIM policy across Europe. The project involves fourteen EU Countries for designing an handbook explaining the common practices and principles for European countries (European Commission, 2016). The handbook was delivered in 2017 and gives general guidance and action recommendations for harmonization of the BIM strategy at a European level (EU BIM Task Group, 2017).

Singapore and South Korea lead BIM adoption in **Asia** and mandated the use of BIM in all public funded projects by 2015 and 2016, respectively (Cheng and Lu, 2015). In Hong Kong, the government mandated the use of BIM in the design and construction phases of all public projects (Development Bureau Hong Kong, 2017). Japan, the Middle East, Dubai and others have invested in BIM-related rail projects and large infrastructure, representing approximately 60 percent of global infrastructure spending by 2025 (Phang, 2017).

To sum up, the BIM adoption rate varies from Country to Country. Some countries like the US, the UK, the Scandinavian countries and Singapore lead BIM adoption (Ullah et al., 2019).

A new set of International Standards has been published to enable BIM to flourish across projects and borders, benefitting the industry as a whole:

- **ISO 16739-1:2018 -** Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. Part 1: Data schema;
- **ISO 19650-1:2018** - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. Part 1: Concepts and principles;
- **ISO 19650-2:2018** - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 2: Delivery phase of the assets.

The list of current British standards, relevant for the purpose of this thesis, is provided below:

- **PAS 1192-2:2013** - Specification for information management for the capital/delivery phase of construction projects using building information modelling. This standard has been withdrawn due to the publication of BS EN ISO 19650-1:2018 and BS EN ISO 19650-2:2018;
- **PAS 1192-3:2014** - Specification for information management for the operational phase of assets using building information modelling. This part specifies requirements once the construction phase of a built asset is completed and it’s in operation;
- **BS 1192-4:2014** - Fulfilling employers information exchange requirements using COBie. This standard defines a methodology for the transfer between parties of structured information relating to Facilities, including buildings and infrastructure;

- **PAS 1192-5:2015** - Specification for security-minded building information modelling, digital built environments and smart asset management. It specifies requirements for the implementation of cyber-security-minded BIM throughout the construction process;
- **PAS 1192-6:2018** - Specification for collaborative sharing and use of structured Health and Safety information using BIM.

The *Ente Italiano di Unificazione* (UNI) has provided for a set of guidelines for building and civil engineering works, as reported below:

- **UNI 11337-1:2017** - Building and civil engineering works - Digital management of the informative processes - Part 1: Models, documents and informative objects for products and processes;
- **UNI/TS 11337-3:2015** - Building and civil engineering works - Codification criteria for construction products and works, activities and resources - Part 3: Models of collecting, organizing and recording the technical information for construction products;
- **UNI 11337-4:2017** - Building and civil engineering works - Digital management of the informative processes - Part 4: Evolution and development of information within models, documents and objects;
- **UNI 11337-5:2017** - Building and civil engineering works - Digital management of the informative processes - Part 5: Informative flows in the digital processes;
- **UNI/TR 11337-6:2017** - Building and civil engineering works - Digital management of the informative processes - Part 6: Guidance to redaction the informative specific information;
- **UNI 11337-7:2018** - Building and civil engineering works - Digital management of the informative processes - Part 7: Knowledge, skill and competence requirements of building information modelling profiles.

The **Common BIM Requirements 2012** (BuildingSMART Finland, 2012), is a comprehensive publication series produced by BuildingSMART Finland. Today, coBIM requirements are commonly referred to in the appendices of public and private construction contracts. They are composed by the following parts:

- **Series 1: General part.** This document is about general technical requirement for BIM in architectural projects and the generation and utilization of models at different project stages;
- **Series 2: Modelling of the starting situation.** This document provides requirements pertaining to source data; modelling requirements; documents to be produced;
- **Series 3: Architectural design**. This series specifies requirements for the architect's BIM at various phases of the project;
- **Series 4: MEP design**. This document addresses mechanical, electrical and plumbing (MEP) modelling; systems BIMs for MEP, electrical and telecommunications design; the information content of the combined model and the as-built model information;
- **Series 5: Structural design**. This document covers structural BIM modelling and the required information content of the BIM models produced by the structural designer;

- **Series 6: Quality assurance**. In this context Quality Assurance is focused on checking the quality of building designs with the purpose of improve the quality of each designers work and making the overall design process more effective;
- **Series 7: Quantity take-off.** The purpose of this guidelines is to provide the reader with an understanding of what is meant by BIM-based quantity take-off;
- **Series 8: Use of models for visualization**. This document concerns the objectives of the visualization and the use of BIM to those purposes;
- **Series 9: Use of models in MEP analyses.** This document addresses the analyses made by the MEP designer on the basis of the available building information models;
- **Series 10: Energy analysis**. This series addresses essential tasks during design and construction regarding energy efficiency and management of indoor conditions. Utilizing BIM in this context ensure the use of correct information in calculations and that the verification of the energy efficiency of a building can be done at an early design stage;
- **Series 11: Management of a BIM project.** The purpose of these instructions is to present how building information modelling as a method of design should be examined from the perspective of the project management and BIM coordinator;
- **Series 12: Use of models in facility management**. This document has to do with the use of open data transfer BIMs and support tools for the FM;
- **Series 13: Use of models in construction**. This section presents construction production needs, modelling tasks for construction production and data delivery protocol for as-built modelling.

### 2.4.2 BIM maturity levels

The construction industry is increasingly realising the transition to digitised model-based working procedures, introducing new technologies step by step. In this scenario, the UK BIM Task Group developed the concept of BIM maturity levels which defines four discrete levels of BIM implementation (Bew, M., & Richards, M., 2011).

The purpose of defining the Levels from 0 to 3 is to categorise type of technical and collaborative working to enable a concise description of the processes, tools and techniques to be used. Indexing the maturity is also useful to allow supply organisations to recognize their level of expertise and to structure a progression over the time. As shown in **Figure 21**, the maturity levels are (NSB, 2014):

- **Level 0**: it is the 2D CAD level, it effectively means no collaboration. Outputs are shared by traditional paper drawings or electronic prints (e.g. PDF) constituting separate information sources. It is common that there is no perfect match between the drawings and data. Facility management has only geometry as a starting point and it manages data through spreadsheets and simple databases as a result of a data acquisition process;
- **Level 1**: it is the first step in using BIM within an organization. This typically comprises a mixture of 3D CAD for conceptual work, and 2D for drafting of statutory approval documentation and Production Information. As there is no link among disciplines models and Operation & Maintenance

documentation, manual work is needed to establish those connections. However, architectural models/drawings can be linked to CAFM systems to manage floor plans and allow space management;

- **Level 2**: it is the collaborative BIM level as all players create and use their own 3D models not necessarily working on a single shared model. This level requires an information exchange process which is specific to that project and coordinated between various systems and project participants. Any modelling software that each party uses must be capable of exporting to one of the common file formats such as IFC or COBie. All files are managed on a central platform called a Common Data Environment. A CDE records the status of each file which describes the maturity of the contained information as well as the level of access provided for other parties. BIM objects can be linked to CAFM systems including spaces and equipment, but additional properties are accessible only in the BIM model;
- **Level 3**: it has not yet been fully defined, however the vision for this is outlined in the UK Government's Level 3 Strategic Plan. Within this plan, 'key measures' are set out: the creation of a set of new, international ‘Open Data’ standards which would pave the way for easy sharing of data across the entire market; the establishment of a new contractual framework for projects which have been procured with BIM; the creation of a cultural environment which is co-operative, seeks to learn and share; training the client in the use of BIM techniques such as data requirements, operational methods and contractual processes; driving domestic and international growth and jobs in technology. All parties will access and modify a same model, and the benefit is that it removes the final layer of risk for conflicting information. This is known as ‘Open BIM’.

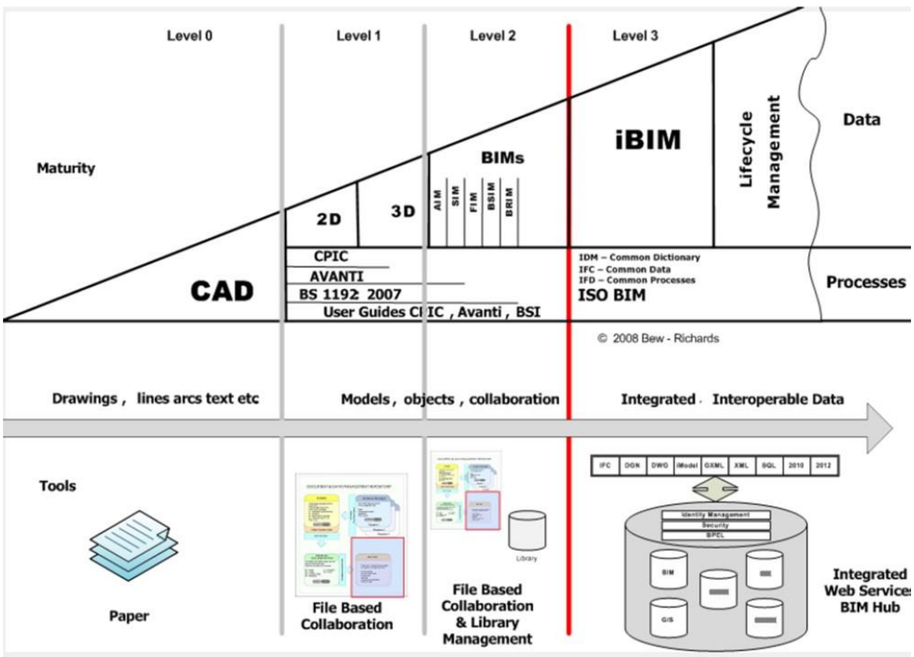



***Figure 21**. The BIM Maturity Ramp of the UK BIM Task Group (Bew & Richards 2008) defines four discrete levels of BIM maturity. Since April 2016, the British Government is mandating Level 2 for all public construction projects.*

UK government requires that all publicly funded construction works must be undertaken by using Building Information Modelling to Level 2. This mandate has been set as one measure to help in fulfilling their target of reducing waste in construction by 20%. It is considered that abortive work, discrepancies and mistakes, and inefficiencies in the information supply chain are major contributors to this waste; and that collaborative work environment can assist in their reduction (NBS, 2014).

Some tools have been developed in UK to enhance collaboration and data sharing, as the **NBS BIM Toolkit**. This is a *"free-to-use NBS BIM Toolkit will benefit both public and private sector construction projects. It provides step-by-step help to define, manage and validate responsibility for information development and delivery at each stage of the asset lifecycle. This toolkit is an indispensable way of delivering projects to meet the requirements of BIM according to ISO 19650, in accordance with the Government mandated use of this on all public sector projects.*" (NBS, 2016). The NBS BIM Toolkit includes also a function for drafting and allocating **Plain Language Questions** (PLQs) to project stages and appointments. These questions "*are a way of communicating a client/employer's broad information requirements (...). These PLQs inform key decisions and, ultimately, allow the client/employer to decide whether or not to proceed to the next project stage*" (NBS, 2017).

### 2.4.3 Level of development

The concept of "Level of Development" (LOD) is used to specify design and planning requirements, determining which information has to be delivered by whom and at which stage. This concept is analogous to scale drawings: a scale such as 1:200 contains only approximate information, while a detail drawing at a scale 1:10 contains information suitable for the production of building components (Borrmann et al., 2018). A LOD defines both the geometric detail (also denoted as Level of Geometry – LOG) and alphanumeric information (also denoted as Level of Information – LOI). Standards for levels of detail of building components have been created in various Countries. The American Institute of Architects (AIA) in collaboration with the American BIMforum has defined the following six LODs (AIA 2013; BIMforum 2013):

- **LOD 100**: The model element is represented graphically by a symbol or a generic representation. Information specific to the element such as costs per square meter can be derived from other model elements;
- **LOD 200**: The model element is represented graphically in the model by a generic element with approximate dimensions, position and orientation;
- **LOD 300**: The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation;
- **LOD 350**: The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation as well as its interfaces to other building systems;
- **LOD 400**: The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation along with information regarding its production, assembly and installation;
- **LOD 500**: The model element has been validated on the construction site including its size, dimension, form, position and orientation.

The AIA document, however, provides only minimal specifications regarding the LOI, as the required alphanumeric information depends heavily on the type of construction project and the respective BIM use cases. LOD requirements typically form part of the Employer's Information Requirements (EIR) defined by the client at the beginning of the project (Borrmann et al., 2018).

The developing of LODs can be easily associated with the information process of a construction project so that each LOD can be related to a specific project phase. This approach not always fits for projects involving existing buildings, where for some purposes, such as maintenance and facility management needs, a low geometric definition and a high level of information can be required.

Novel results in term of LOD definition are contained in the series of UNI 11337-4:2017. In this standard the Level of Development is identified by a letter, from A to G as shown in **Figure 22**. The scale of LOD for restoration purposes is also proposed. This can be expected from a scenario, as the Italian context, in which, due to the enormous amount of historical architectures, restoration projects are common.

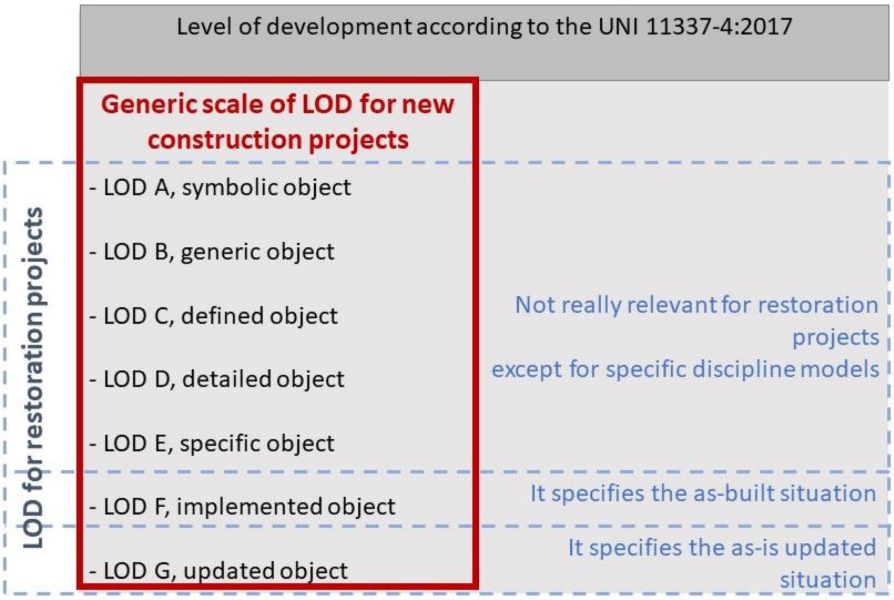



***Figure 22.*** *LOD according to the UNI 11337.*

### 2.4.4 "BIG BIM" vs "little bim"

According to the level of interoperability gained by the use of BIM, two different types of BIM implementation are distinguished: "*BIG BIM*" and "*little bim*" (Jernigan, 2008).

*Little bim* describes the application of a specific BIM software by an individual stakeholder to realise a discipline-specific design task. Typically, software are used to create a building model and derive drawings which serve as external communication tool. The building model is not used across different software packages and is not handed over to other stakeholders. Although, implementing *little bim* can offer efficiency gains, the big potential of comprehensively using digital building information remains untapped.

By contrast, *BIG BIM* involves consistently model-based communications between all stakeholders and across the entire lifecycle of a facility (**Figure 23**). For the data exchange and the coordination of the model-based workflows, digital technologies such as model servers, databases or project platforms are employed in a comprehensive manner (Borrmann et al., 2018).

If just one vendor software is employed it is possible to talk about "*closed BIM*", while the use of open data formats to allow data to be exchanged between different software vendors it is called "open BIM" (**Figure 23**).

In the overall process of a construction design and management, it is common to use different software for different purposes, i.e., for different disciplines. Exchanging data among the involved stakeholders is achieved using neutral data formats. To reduce the cost of the lack of interoperability the International Alliance for Interoperability was founded in 1994 by a number of software vendors, users and public authorities across the world. In 2003, it was renamed buildingSMART for marketing reasons. The international non-profit organisation succeeded in defining an object-oriented data model named Industry Foundation Classes (Borrmann et al., 2018). Further details about the use of neutral data format in AEC industry is provided in the 2.4.8 subsection.

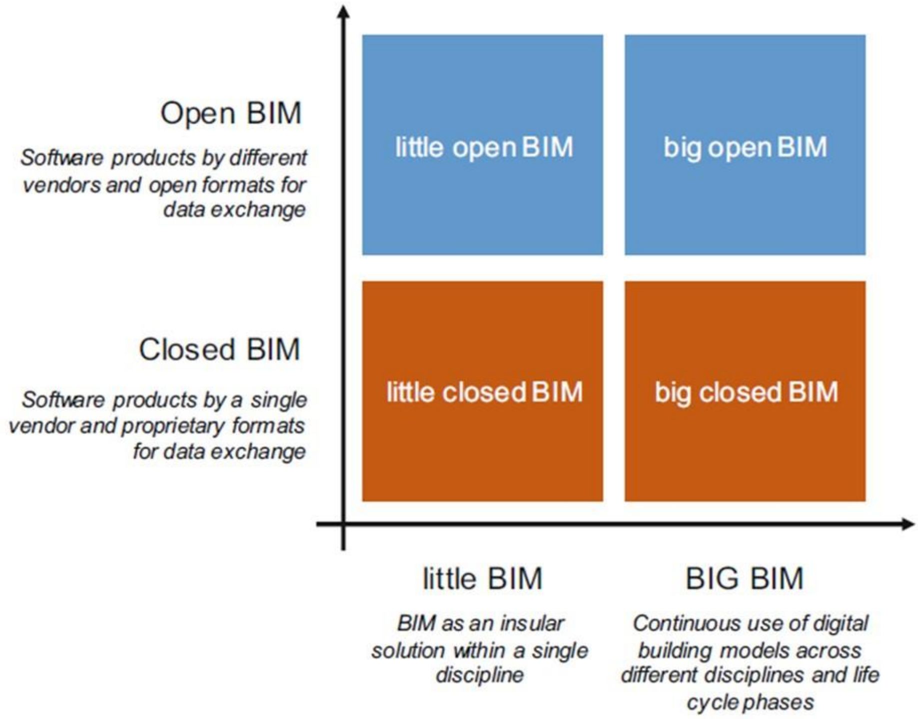



***Figure 23.*** *Little BIM vs BIG BIM, closed BIM vs open BIM (Borrmann et al., 2018).*

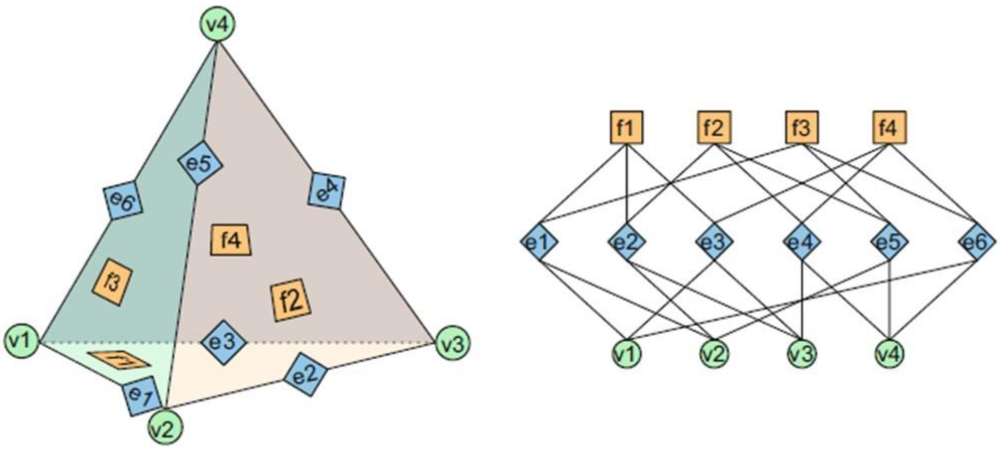
## 2.4.5 Geometric modelling

The digital representation of the three-dimensional geometry of a building design is one of the most fundamental aspects of Building Information Modelling. Even though the scope of the thesis does not require a deep analysis of the geometric modelling principles, it is appropriate to briefly discuss them as they are implicitly involved in BIM models development, and useful to understand the capabilities of modelling tools and information exchanging processes.

The representation of a building as a 3D volumetric model makes it possible to generate plans and sections from the 3D model, to determine possible collisions between construction elements, to automate quantity take-off, to generate mechanical or physical models for calculation and simulation and to compute photo-realistic visualisations of building designs (Borrmann & Berkhahn, 2018). There are two main approaches to model the geometry of a three-dimensional object:

- The **explicit modelling** describes a volume in terms of its surface, and it is therefore often known as *Boundary Representation*;
- The **implicit modelling** employs a sequence of construction steps to describe a volumetric body and is therefore commonly referred as *procedural approach*.

The *Boundary Representation* (*BRep*) involves defining a hierarchy of boundary elements, such as Body, Face, Edge and Vertex. Each element is described by elements from the level beneath, for example, the body is described by its faces, each face by its edges, each edge by a start and end vertex (**Figure 24**). This system of relationships defines the topology of the modelled body which must then be augmented with geometric dimensions to fully describe the object.




| solid | faces |
|---|---|
| 1 | 1,2,3,4 |

| face | edges |
|---|---|
| 1 | 1, 2, 3 |
| 2 | 2, 4, 5 |
| 3 | 1, 5, 6 |
| 4 | 3, 4, 6 |

| vertex | coordinates |
|---|---|
| 1 | 2, 0, 0 |
| 2 | 0, 0, 0 |
| 3 | 3, 0, 0 |
| 4 | 1, 1, 3 |

| edge | vertices |
|---|---|
| 1 | 1, 2 |
| 2 | 2, 3 |
| 3 | 3, 1 |
| 4 | 3, 4 |
| 5 | 2, 4 |
| 6 | 1, 4 |

***Figure 24.*** *A pyramid described in BRep (Borrmann and Berkhahn, 2018).*

A simplified variant of boundary representation is the description of the surface of a body as a triangle mesh. Triangulated surface modelling is often used in visualization software, for describing the surface of a terrain or as input for numerical calculations and simulations.

Among the implicit modelling, a classical approach is the *Constructive Solid Geometry* (*CSG*) method, which employs predefined basic objects (so-called primitives), such as cubes, cylinders or pyramids and combines them using Boolean operators such as union, intersection or difference to create more complex objects.

Many 3D CAD and BIM systems manage Boolean operators as well as extrusion or rotation operations. These methods provide for moving along a path a 2D geometry (typically a closed surface) to create a 3D solid. This offers a powerful means of intuitively modelling complex three-dimensional objects.

A relevant trend in the building sector is the **parametric modelling** with which it is possible to define a model using dependencies and constraints. The result is a flexible model that can be quickly and easily adapted to meet new or changing conditions.

Parameters can be as simple as geometric dimensions, for example the height, width, length; relationships between them, or dependencies, can be established by user-defined formulas.

BIM products that support parametric modelling include Autodesk Revit, Nemetschek Allplan, Graphisoft ArchiCAD and Tekla Structure.

To create parametric families, reference planes and/or axes are first defined, so that the resulting body can be referred/aligned to them. The position of the reference planes is specified with the help of distance parameters and the relationship between parameters can be defined with the help of equations (**Figure 25**).

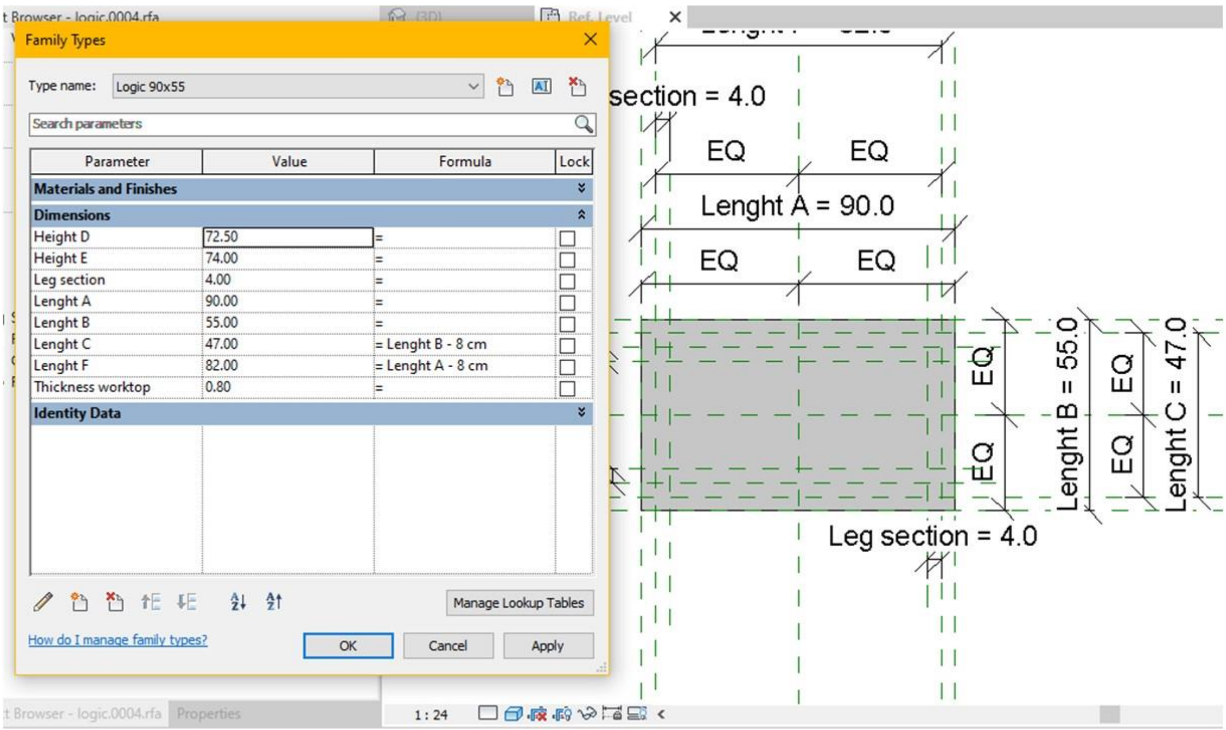



***Figure 25.*** *Definition of a table family in Revit, showing dimensions parameters and formulas.*

**Visual Programming Language** (VPL) is generally defined as a formal language with visual syntax and semantics (Preidel et al., 2017). Such a language describes a system of objects and relationships with the help of visual elements. VPL environments support the procedural and parametric design as well as data retrieval and manipulation. Examples of well-known Visual Programming applications in the AEC sector are Dynamo and Grassoppher3D.

In digital construction, VPLs are mainly used in two application areas: (1) for generating geometric as well as semantic information or (2) for checking or querying existing models. Most of the VPL environments provide opportunities for developers to extend the libraries by user-defined functions (Preidel et al., 2017).

## 2.4.6 Data modelling

When modelling building systems not only geometric data are required but also semantic data have to be considered. Examples of semantic data are construction methods, materials, spaces and rooms function or maintenance activities and procedures. These information are essential to fully describe a building or a facility.

An information model is a simplified representation of the reality which allows to collect, structure and examine data in order to support the design, planning, construction and operation of a real facility. Data modelling comprises the conceptualization of the reality, by defining entities, related attributes and relationships. The delivery of this first step is a conceptual data model. Then the realization step provides for defining specific instances of the conceptual model, such as in the form of tables stored in a database (Booch et al., 2007).

In this section primary data modelling concepts are presented, as they are commonly used in the BIM environment. A discussion about database design is provided in the section 4.

Different approaches can be used to design a conceptual data model, i.e., the *Unified Modeling Language* (UML) that graphically describes object-oriented models (OOM) or the *Entity-Relationship* (ER) approach, which represent a specific domain in terms of Entity types (classification of things) and Relationships among instances of these types.

Concepts related to the conceptual data model, which are constant despite the selected modelling language, are reported below (Koch and König, 2018):

An **entity/class/object** is a specific data item of interest within the real world. It can be either a physical or tangible item, for example a wall, or can represent a non-physical or notional thing, for example a room or a task. An example of entity is CUSTOMER Mario. Entities have identifiers, which are attributes that identify entity instances. For example, CUSTOMERS instances can be identified by the CustomerName or the CustomerNumber.

An **entity type** classifies and groups entities that share the same structure and characteristic (e.g. shape, appearance, purpose). It represents a template that is used to create specific entities. For example, the EMPLOYEE entity class is the collection of all EMPLOYEE entities. An entity instance of an entity class is the occurrence of an entity, for example within the class EMPLOYEE there are as many instances as each employee reported.

**Attributes** model the properties of an entity; for each entity types a set of attributes is defined, but each entity differs from another in terms of individual attribute values. Attributes have a name and a data type. Examples of data types are integer numbers, boolean, text, character, timestamp, etc. Properties of an attribute specify whether the attribute is required or optional, has a default value and any other constraints.

**Relations and associations** describe relationships or interdependencies between entities. Common relationships are the so-called binary relations, which model the relationship between exactly two entities (or objects). There are at least three types of binary relationships: one-to-one (1:1); one-to-many (1:N) and many-to-many (N:M). Binary relationships are also classified by their cardinality, that shows the number of entities that can occur on each side of the relationship.

Another essential concept is the **inheritance**, it allows to define specialized entity types (sub-classes) and generalized entity types (super-classes) in a way that the formers can inherit attributes of associated super-classes. This concept permits the creation of a hierarchical classification system (taxonomy) within a data model.

### 2.4.7 Process modelling

An important part of the BIM methodology is the modelling of processes to create, modify, use or share digital building information. The systematic and partially automated exchange of information between different organisational units to perform a task is often referred to as a **workflow**. Automation in this sense means that once a task is completed further specified actions (sending an email, for instance) are automatically triggered (Koning, 2018).

Data and geometric modelling have to be performed as a consequence of a standardised workflow, meant to fulfill client requirements. Then, the development of a workflow involves temporal, technical and resource requirements definition. The implementation of a workflow using suitable software systems is a key goal of workflow management. For this reason, the workflow management requires structured processes and data.

The IFC provides for the data structure (see paragraph 2.4.8), while additional specifications can be defined in the Information Delivery manual (IDM) which determines who provides which information when and to whom (buildingSMART, 2012). IDM standard makes it possible to organise data exchange processes in a graphical notation, and to subsequently derive exchange requirements for data exchanges occurring in that process (Beetz et al.,2018). The technical implementation of these exchange requirements takes the form of a Model View Definitions (MVD) that accurately specify which entities, attributes and properties may or should be used in a particular exchange (buildingSMART, 2013).

Processes can be structured and modelled in different ways. Civil engineering projects often use the **Business Process Model and Notation** (**BPMN**), which is also adopted by the buildingSMART Alliance for the formalisation of processes in the field of Building Information Modelling. BPMN provides a set of icons to document processes and their use so that the reader of the diagram can easily recognize the basic types of elements (**Figure 26**). Within the basic categories of elements, additional variation and information can be added to support the requirements for complexity without dramatically changing the basic look of the diagram. The five basic categories of elements are (Object Management Group, 2011):

1. **Flow Objects**, which include events, activities and gateways;

2. **Data**, which are represented by data objects, data inputs, data outputs and data stores;

3. **Connecting Objects**, such as sequence flows, message flows, associations and data associations;

4. **Swimlanes**, which consist of pools and lanes;

5. **Artifacts**, which are used to provide additional information about the process.

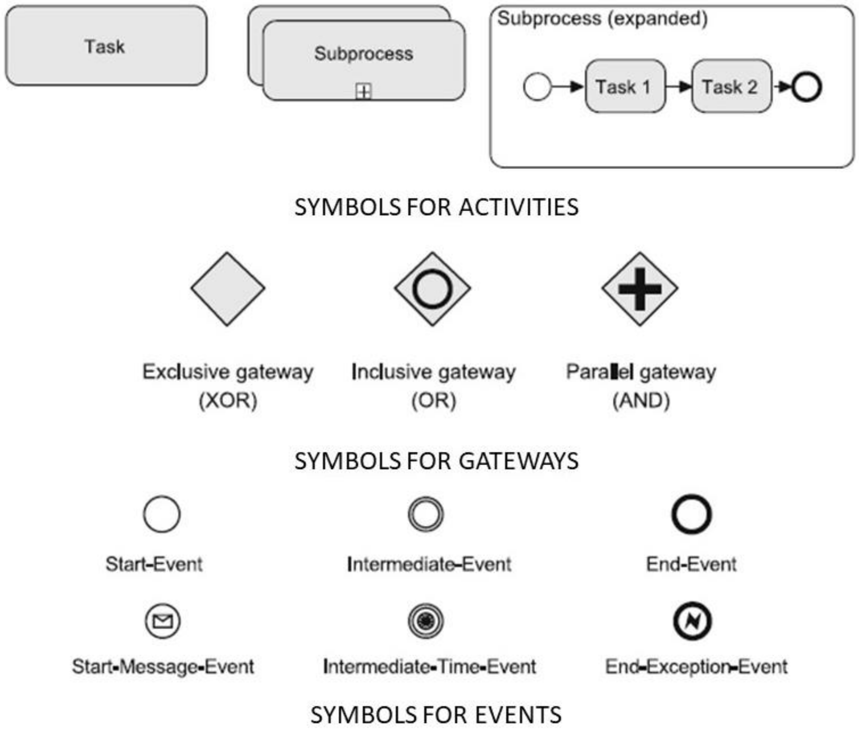



***Figure 26.*** *Examples of BPMN symbols (based on König, 2018).*

An *activity* in general describes a job to be done. A non-divisible activity is called a *task*. An activity that is composed of sub-activities or sub-tasks is referred to as *sub-process. Events* represent essentially external events that have an impact on the process under consideration. An event may, for example, start a single activity or terminate an entire process (Koning, 2018) (**Figure 27**).

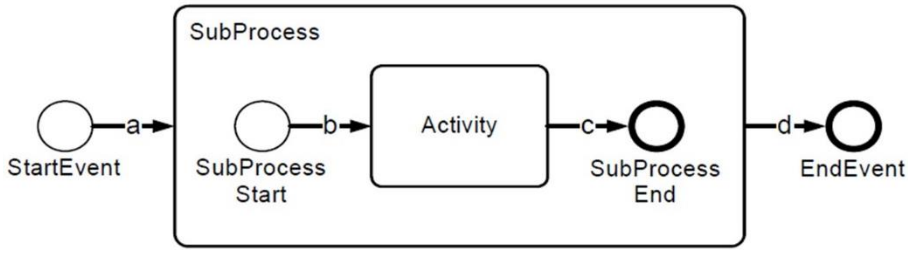



***Figure 27.*** *Expanded sub-processes example (Object Management Group, 2011).*

A so-called *pool* describes an organisation, a person or a company which perform a process. A *lane* is a subdivision of a pool. This allows individual responsibilities, roles or people to be represented in an enterprise (**Figure 28**).

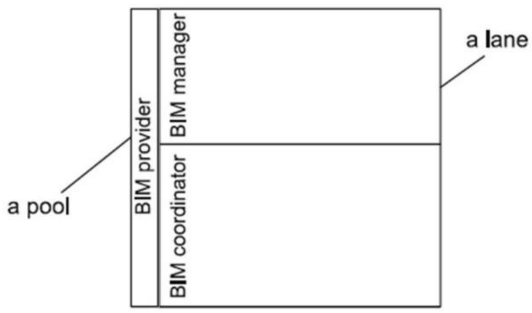



***Figure 28.*** *Example of pool and swim lanes (Koning, 2018).*

With the help of so-called *artifacts*, additional information can be described. There are two standardized set of artifacts (group and text annotation), but modelers or modeling tools are free to add as many artifacts as necessary (Object Management Group, 2011). For example, the data format, the level of detail and the contents of a building model can be specified using artifacts. The more accurate these artifacts are, the better complex processes can be monitored and controlled. Data objects can be defined and attached to activities and connections. By drawing an arrow, we can specify whether a data object is being used or required or whether it must be generated (**Figure 29**). With annotations, more information can be provided to users of BPMN. An annotation is a verbal piece of information and can be assigned to any element.

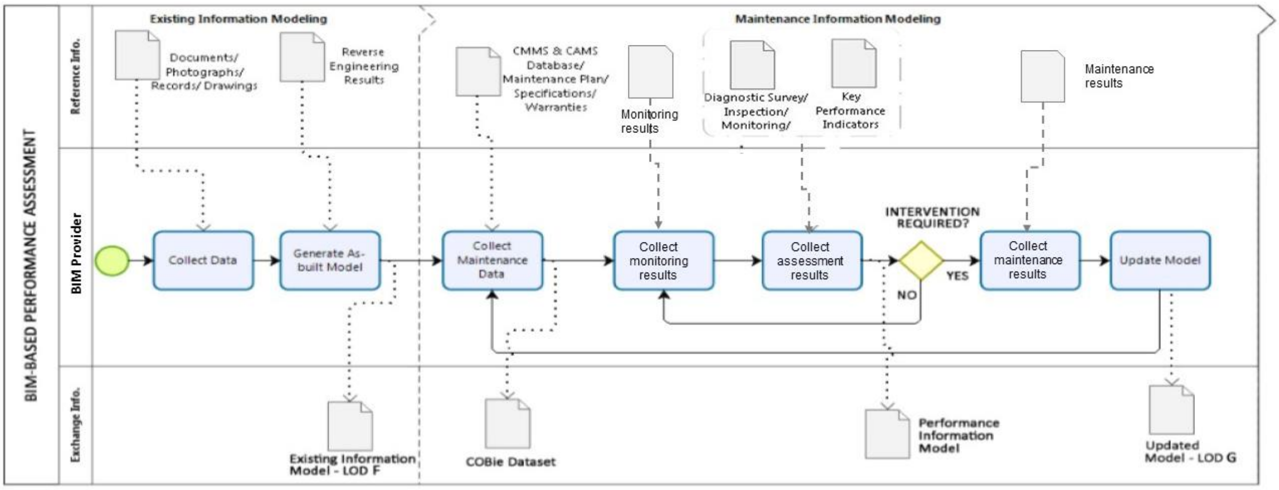



***Figure 29.*** *Example of BPMN diagram.*

BPMN diagrams have been used very successfully to model BIM processes. Based on the resulting process diagram, data exchange points and corresponding model contents can be clearly specified (Koning, 2018).

## 2.4.8 Interoperability

A common data exchange format is required in the AEC domain, as different companies, involved from the design to the operational phase, can require the use of several proprietary data formats, and consequently, risk to miss an effective information exchange.

To achieve the goal of BIG BIM, it became clear that a vendor-neutral, open and standardized data exchange format is needed. Such a format must set out uniform, unequivocal descriptions of geometric and semantic information of building components, including a common classification system, the description of the relationships between them and the definition of their relevant properties (Borrmann et al., 2018).

The international organisation buildingSMART has dedicated many years to the development of the **Industry Foundation Classes** (Industry Foundation Classes (IFC), 2019) as an open, vendor-neutral data exchange format. This is a complex data model with which it is possible to represent both the geometry and the semantic structure of a building model using an object-oriented approach.

The Industry Foundation Classes specify a data schema and an exchange file format structure (International Organization for Standardization, 2018). The data schema is defined in:

- EXPRESS data specification language;
- XML Schema definition language (XSD).

The exchange file formats for exchanging and sharing data according to the conceptual schema are:

- Clear text encoding of the exchange structure;
- Extensible Markup Language (XML).

EXPRESS employs the construct of an entity type as an equivalent to classes in object-oriented theory. For each entity type, attributes and relationships to other entity types can be defined (Borrmann et al., 2018). EXPRESS also implements the object-oriented concept of inheritance (**Figure 30**).

A relationship (association) between an object of Type A and an object of Type B is expressed by giving entity Type A an attribute from the type of Entity B. A special characteristic of the EXPRESS standard is the ability to explicitly define inverse relationships. In this case, no new information is modelled; just a relationship in the reverse direction. Attributes that can only contain specific values from a selection of predefined strings are modelled in EXPRESS with the help of the Enumeration Type. In addition, EXPRESS also offers a means of modelling data graphically. The corresponding graphical notation language is called EXPRESS-G (Borrmann et al., 2018).

The IFC schema consists of four layers, each containing sub-schemas (**Figure 31**) (Industry Foundation Classes Release 4 (IFC4), 2019).

The Core Layer contains the most elementary classes of the data model. Entities defined in this layer can be referenced and specialised by all entities above in the hierarchy. The core layer provides the basic structure, the fundamental relationships and the common concepts for all further specialisations. All entities defined in the core layer and above derive from *IfcRoot*, having unique identification, name, description, and change control information. The *Kernel schema* represents the core of the IFC data model and comprises basic abstract classes such as *IfcRoot*, *IfcObject*, *IfcActor*, *IfcProcess*, *IfcProduct*, *IfcProject*, *IfcRelationship*. The *Product Extension schema* describes the physical and spatial objects of a building and their respective relationships. It comprises the subclasses of *IfcProduct* such as *IfcBuilding, IfcBuildingElement,* etc. The *Process Extension schema* comprises classes for describing processes and operations. The *Control Extension schema* defines the basic classes for control objects such as *IfcControl* and *IfcPerformanceHistory* (Borrmann et al., 2018).

Classes defined in the Shared Layer are derived from classes in the Core Layer. For example, I*fcSharedBldgElements* defines subtypes of *IfcBuildingElement*, which is defined in the *IfcProductExtension*. Those subtypes are the major elements of the building structure. The elements (e.g. wall, beam, column, slab, roof, stair, ramp, window, door and covering) are the main components of the raw building (or carcass) which is central for the exchange of project data. The *IfcSharedFacilitiesElements* schema defines basic concepts in the facilities management domain. This schema, along with *IfcProcessExtension* and *IfcSharedMgmtElements,* provides a set of models that can be used by applications needing to share information concerning facilities management related issues. The *IfcSharedFacilitiesElements* schema supports ideas as furniture, grouping of elements of system furniture into individual furniture items, asset identification, inventory of objects (asset, furniture and space objects). The *IfcSharedMgmtElements* schema defines basic concepts that are common throughout the building lifecycle. The primary classes in the schema are all subtypes of *IfcControl* and act to manage the project in some way. The objective of the *IfcSharedMgmtElements* schema is to capture information that supports the control of project scope, cost, and time. The following are within the scope of this part of the specifications: cost schedules; orders including purchase orders, change orders, and work orders; permits for access and carrying out work; requests to be fulfilled.

Entities defined in the Domain Layer are self-contained and cannot be referenced by any other layer. The defined domains concern architecture, building control, construction management, electrical systems, heating, ventilation and air conditioning, plumbing and fire protection as well as structural elements (such as foundations, pylons, reinforcement, etc.) and structural analysis.

The Resource Layer contains entities which can be referenced by all entities in the layers below. Unlike entities in other layers, resource definition data structures cannot exist independently, but can only exist if referenced (directly or indirectly) by one or more entities deriving from *IfcRoot.*

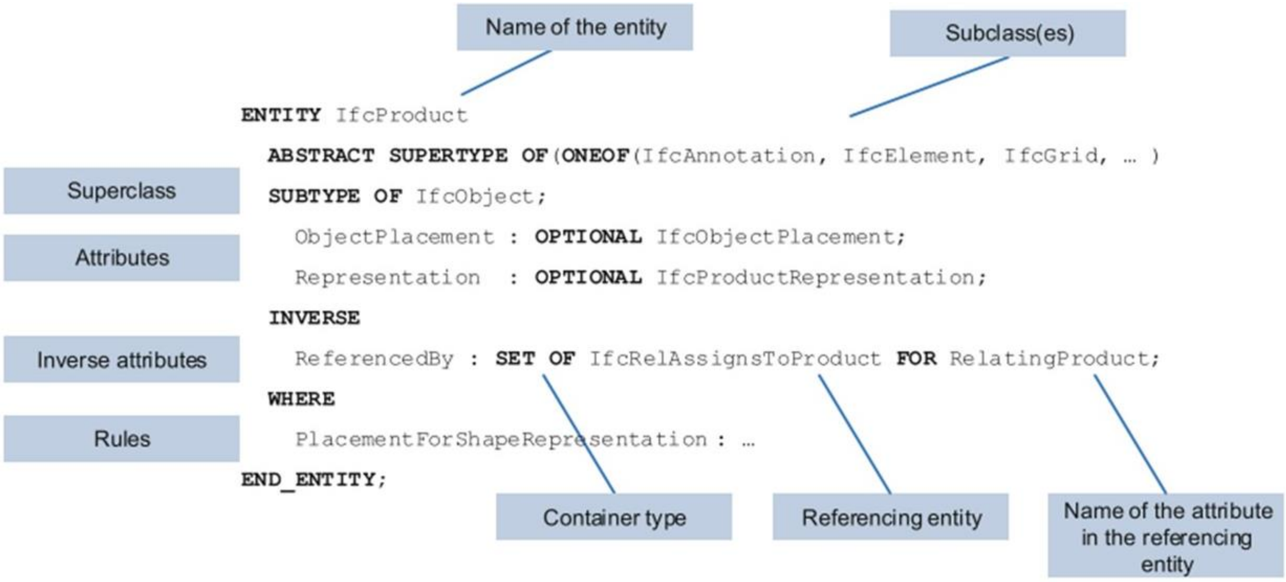



***Figure 30.*** *Definition of an entity type using the data modeling language EXPRESS principles (Borrmann et al., 2018).*

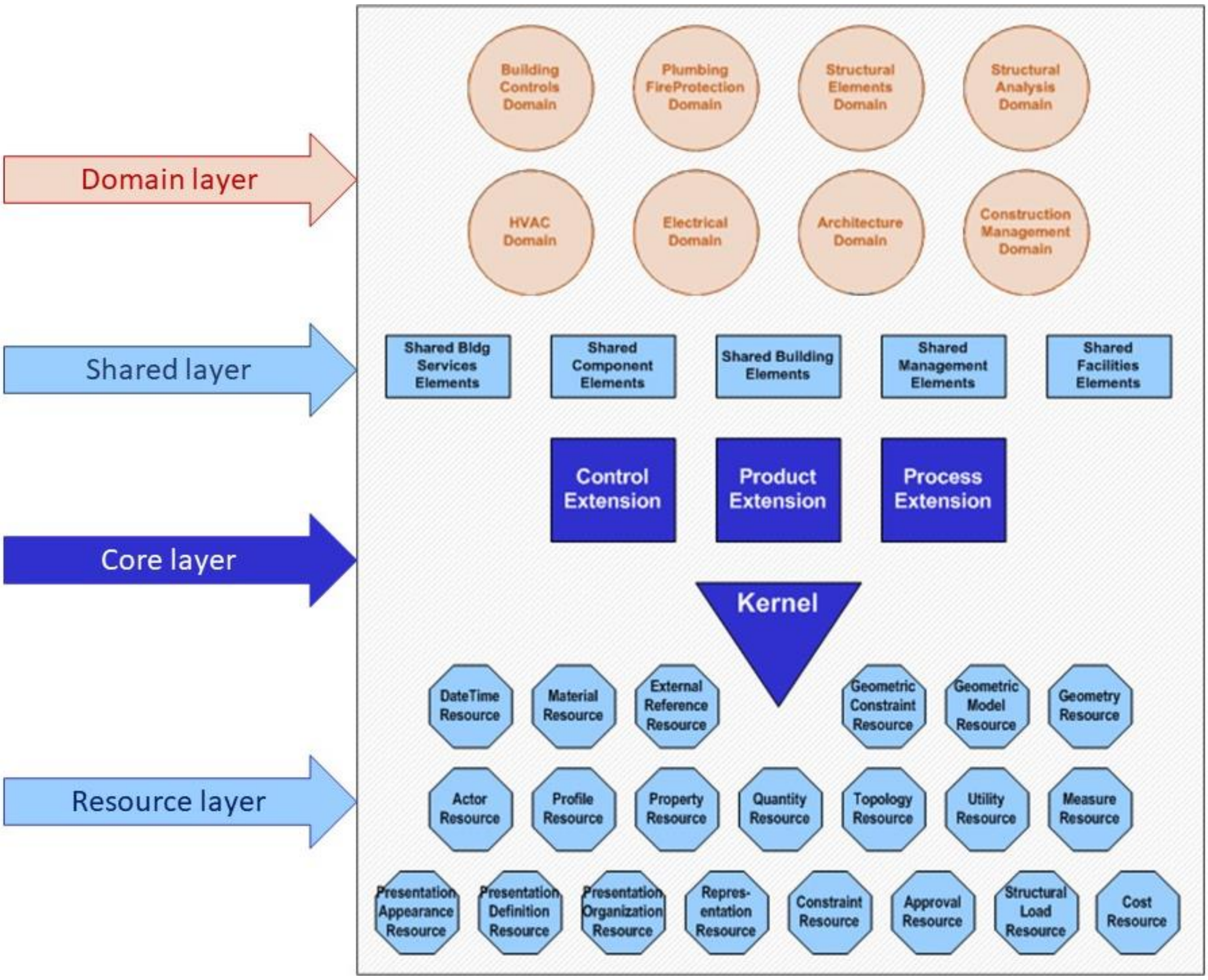



***Figure 31.*** *The layers of the IFC data model (based on Industry Foundation Classes Release 4).*

A subset of the data schema is referred to as a **Model View Definition (MVD)** (Model View Definition (MVD) - An Introduction, 2019). To support BIM interoperability across hundreds of software applications, industry domains, and regions, the IFC schema is designed to accommodate many different configurations and levels of detail. For example, a wall can be represented:

- as a line (or curve) segment between two points;
- as one of many types of 3D geometry for visualization and analysis (such as extruded solids or triangulated surfaces);
- as simple forms or with specific construction detail.

along with data such as engineering properties, responsible party, scheduling, and cost information. But not every construction domain needs all the same information delivered or received. Project delivery contracts may reference exchange specifications. An MVD will describe which objects, representations, relationships, concepts, and attributes are needed for the receiving stakeholder and their software application to accomplish a desired task. In this sense, an MVD will narrow the IFC broad scope depending on the client's information requirements and specific workflows. However, the specifics of an MVD may be influenced by more general software capabilities or needs. Typically, a BIM-authoring tool have a list of MVD options in their IFC export user interfaces. Depending on the type of BIM tool, the MVD will differ because of the domain the application serves, such as space planning, architectural, structural, or building system MVDs. Examples of MVDs include: Architectural Design to Structural Design; Architectural Design to Quantity Takeoff; Building Envelope Design to Energy Analysis; Construction Operations Building Information Exchange; Basic FM Handover View.

The **Basic FM Handover View**, based on IFC2x3 schema, it is meant to transfer information from planning and design applications to CAFM and CMMS applications, as well as information from construction and commissioning software to CAFM and CMMS applications.

One of the most common MVD used in FM domain is the **Construction Operations Building Information Exchange (COBie)**. This is a non-proprietary data format for the publication of a subset of building information models focused on delivering asset data as distinct from geometric information (NBS, 2018; East, 2016).

COBie, published by the US Army Corps of Engineers in 2007, is now part of standards such as the National Building Information Modeling Standard (NBIMS) of the USA and the British code of practice BS 1192-4:2014 (Lea et al. 2015). Earlier pilot studies tested the benefits of COBie utilisation, such as researching O&M data, locating equipment (building, floor, room, within room, other), accessing equipment warranties and other records (Griffith et al., 2011). The effective use of the COBie specification has been demonstrated by several public and commercial projects (East, 2016). It was introduced as tool to facilitate the transfer of information from as-built documents to CMMS. In fact, at the handover phase, maintenance technicians have to put a great effort in searching for information in paper-based documents to complete many of their jobs. COBie files contain information about:

- maintenance;
- operations and
- asset management

and this information is provided at different project stages mainly by designers and contractors. This implies that the information is gathered and entered progressively in small portions by different actors into a COBie deliverable. COBie deliverables are files that have to deliver certain data at a certain point in time. In addition, a COBie deliverable usually contains an appendix of e-documents such as product specifications, user manuals, maintenance instructions or technical drawings. Besides the traditional IFC formats STEP and ifcXML, this MVD allows the use of SpreadsheetML, which can be interpreted by common spreadsheet software, for example Microsoft Excel (Schwabe et al., 2018). Today COBie is commonly included in design and construction contracts thanks to its easy to use but efficient structure. In fact, the spreadsheet format is a "common denominator" data management tool that contractors and facility managers already are familiar with.

A common template of COBie in the spreadsheet version contains 18 sheets (**Figure 32**). The Introduction sheet is about project metadata, including the color scheme used for indicating information types (i.e required, external reference, etc.). The building information is structured hierarchically. A Facility consists of Floors which contain Spaces. Those spaces can be grouped into specific Zones. The worksheet Type characterizes superordinate items such as different door types which are represented as instances in the worksheet Component. Those components can form a system, all the systems are mapped in the System worksheet. Operations and maintenance jobs, such as a boiler inspection interval, are represented in the Job worksheet. The Resource and the Spare worksheets specify information about maintenance tasks. The Picklist sheet supports the definition of roles, facilities, spaces, etc. according to the classification system used.

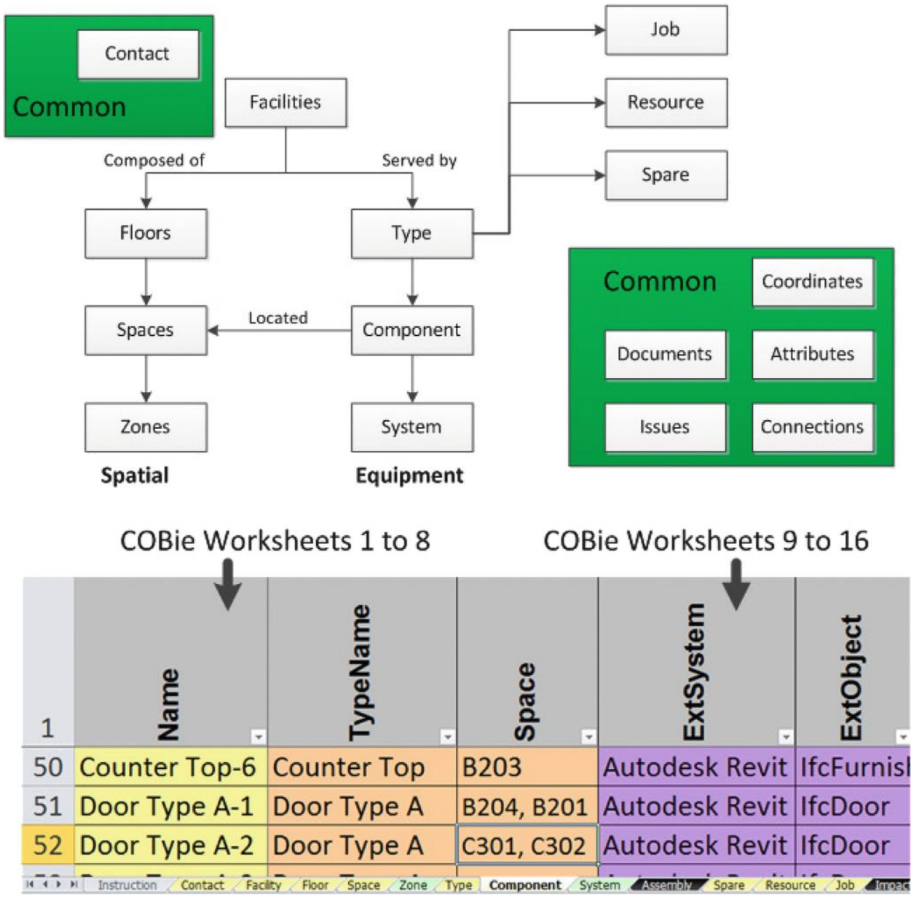


***Figure 32.*** *COBie structure and contents (Schwabe et al., 2018).*

## 2.4.9 BIM for design and construction phases

Building Information Modelling is a paradigm change. Unlike CADD (computer - aided design and drafting), which primarily automates aspects of traditional drawings production, BIM transforms architectural thinking by replacing drawings with a revolutionary 3D digital model (Eastman et al., 2008).

Unlike physical models, virtual models can be accurate at any scale, they are digitally readable and writable and they allow a better visualisation of the project, especially if integrated with rendering software tools (**Figure 33**). They may contain information to perform several analyses (i.e., structural, cost, lightning, energy, acoustics, etc.) interacting with a variety of other software tools (**Figure 34** and **Figure 35**).

BIM allows better collaboration among different design teams, which can work on a single shared model or on different sub-model, linked and coordinated among each other (**Figure 36**).

BIM also improves the consistency across all drawings and reports and the spatial interference checking (**Figure 37**). Due to its ability to automate standard forms of detailing, BIM significantly reduces the amount of time required for producing construction documents.

In addition, the model can be checked for compliance with codes and regulations, and it can be used to compute a very precise quantity take-off, providing the basis for reliable cost estimations and improving accuracy in the tendering and bidding process (Borrmann et al., 2018). As a result, BIM will likely redistribute the time and effort designers spend in different phases of the design.

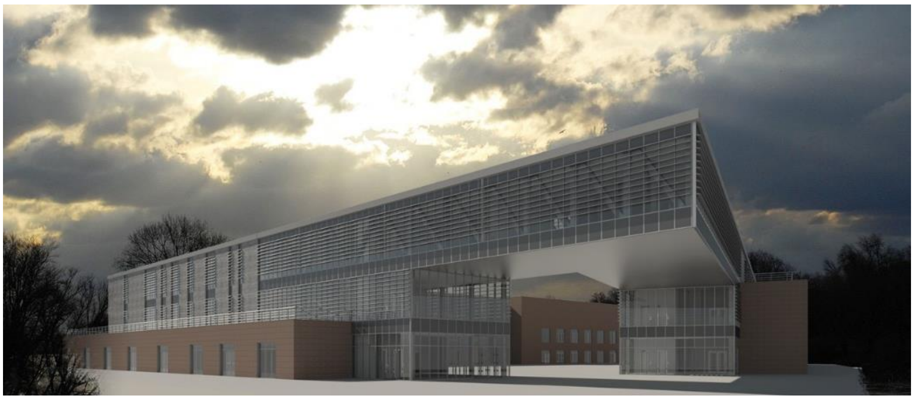


***Figure 33.*** *Photorealistic image of a school project made by Autodesk Rendering (Cimmino et al., 2018).*

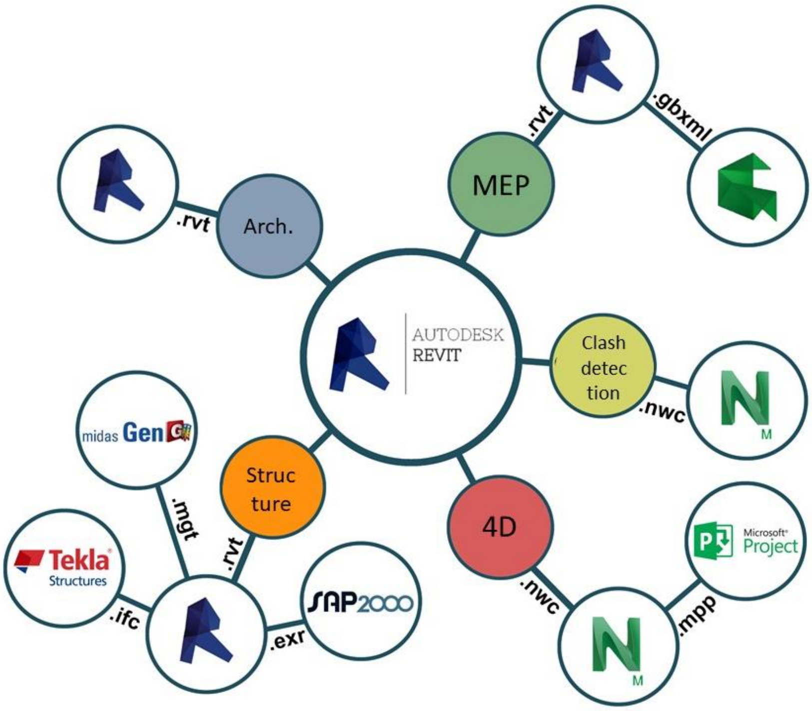



***Figure 34.*** *Instance of possible information exchange and analysis during the design phase. In the picture three main disciplines are included: architectural, mechanical, structural. In addition, the project management in terms of time is considered too. Also the coordination among these disciplines in terms of spatial collisions is facilitated in a BIM environment.*

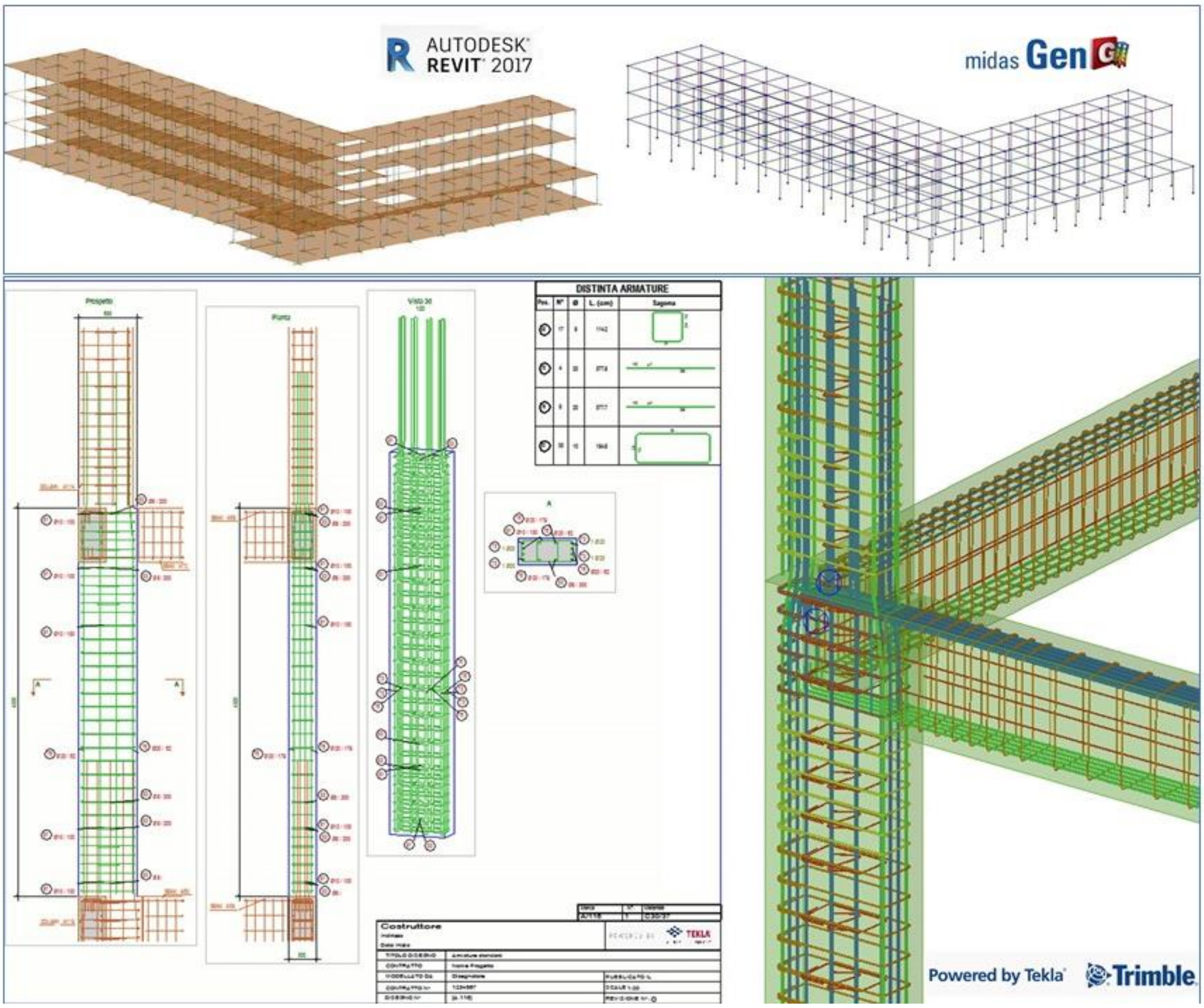



***Figure 35.*** *Structural analysis and details design on Revit, midasGEN and Tekla.*

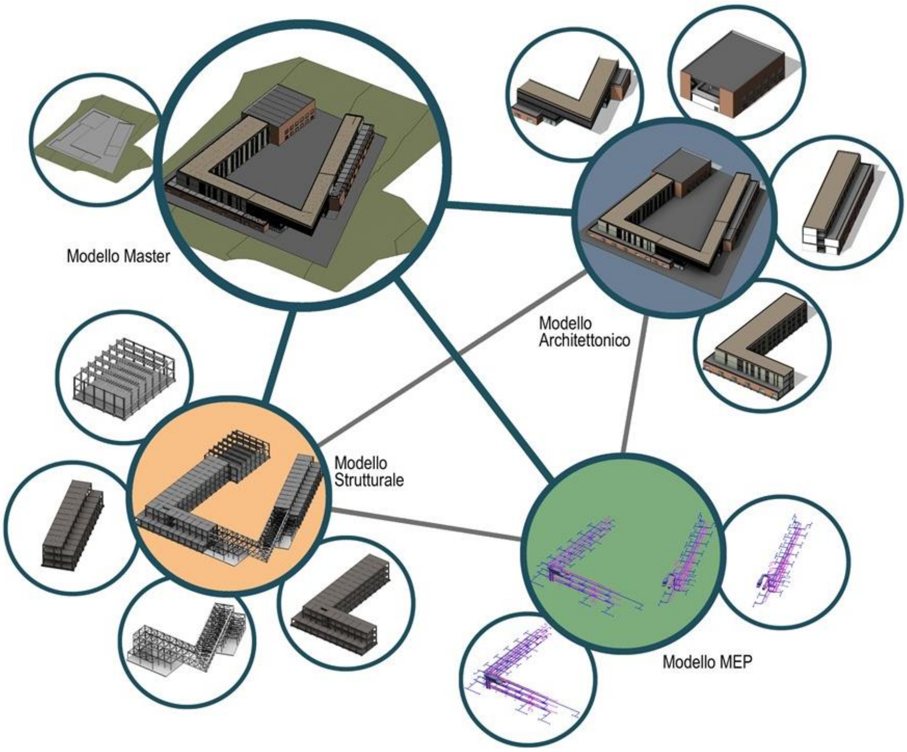



***Figure 36.*** *Instance of possible sub-models involved in a design project (Cimmino et al., 2018). A master model was defined by federated models related to specific discipline (architecture, MEP systems and structure). Each discipline model is composed by different linked sub-models, due to the complexity of the case study.*

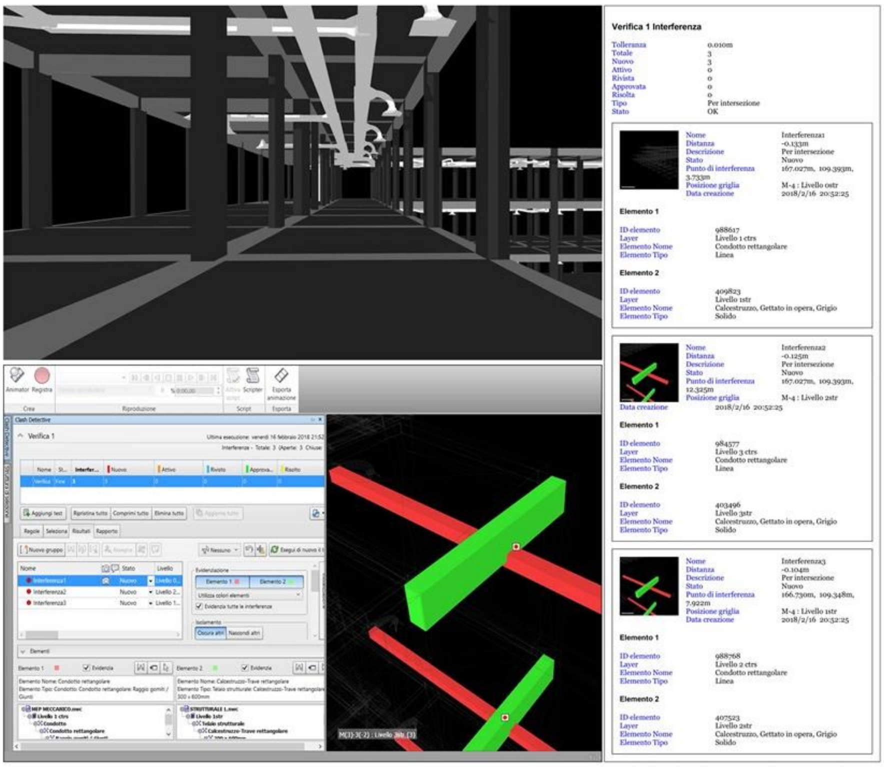



***Figure 37***. *Example of clash detection performed on Autodesk Navisworks.*

Positive Impacts of BIM on design can be grouped in (Eastman et al., 2008):

- At the **conceptual design level**, which typically includes 3D sketching, space planning, environmental analysis, BIM can positively impact the decision-making process (**Figure 38**). None of the tools available today fully support the conceptual design. Technicians have to rely on different software tools with a scarce interoperability between them;

- **Analysis and design of buildings systems** cover many functional aspects of a building's performance and can require the collaboration of various professionals (**Figure 39**). The exchange formats can be reduced to (1) one-way flow from the BIM design tool to analysis application; (2) two-way flow where the design application supports importing and exporting phases. Resulting plans and specific layout have to be coordinated and coherent, and BIM helps in this sense;
- **Construction level models** can be interpreted in two different ways: the model is a detailed design expressing the intent of the designer and the client, so that the contractors are expected to develop their own independent construction model and documents; the model needs to be further detailed for being used in construction and fabrication phases;
- **Design and construction integration** can be achieved by allowing construction considerations to influence the project from the beginning. In this sense a digital twin of the future building facilitates constructability checking to review and improve the design process.

The application of BIM offers significant advantages also for preparing and executing the actual construction of a building. It is possible to associate the individual building components with the scheduled construction times, the construction sequence can be validated, spatial collisions can be detected, and the site logistics can be organized. Additionally, a BIM model integrates cost information and can be used to simulate the cost development over time (Borrmann et al., 2018).

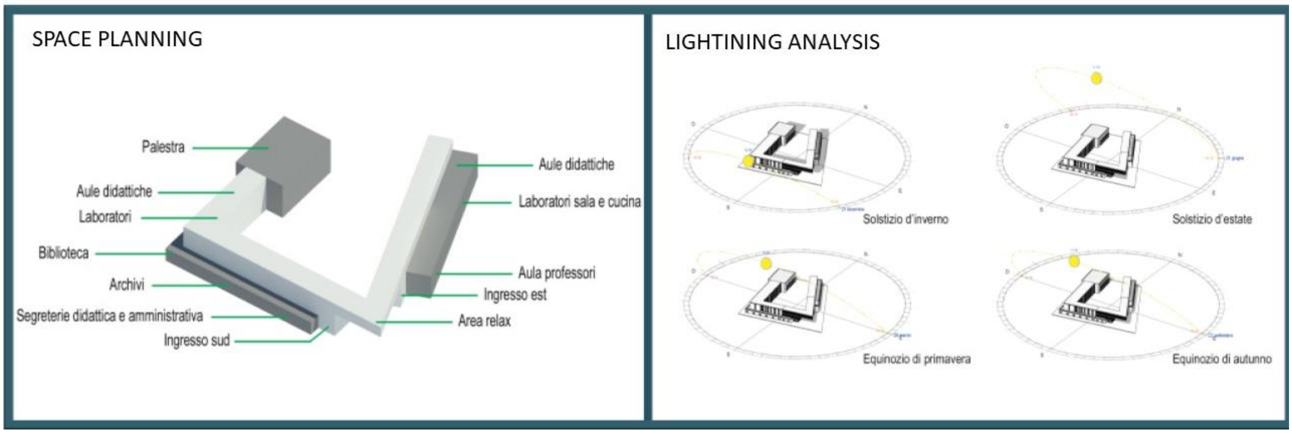



***Figure 38.*** *Example of space planning and lightning analysis carried out on Autodesk Revit.*

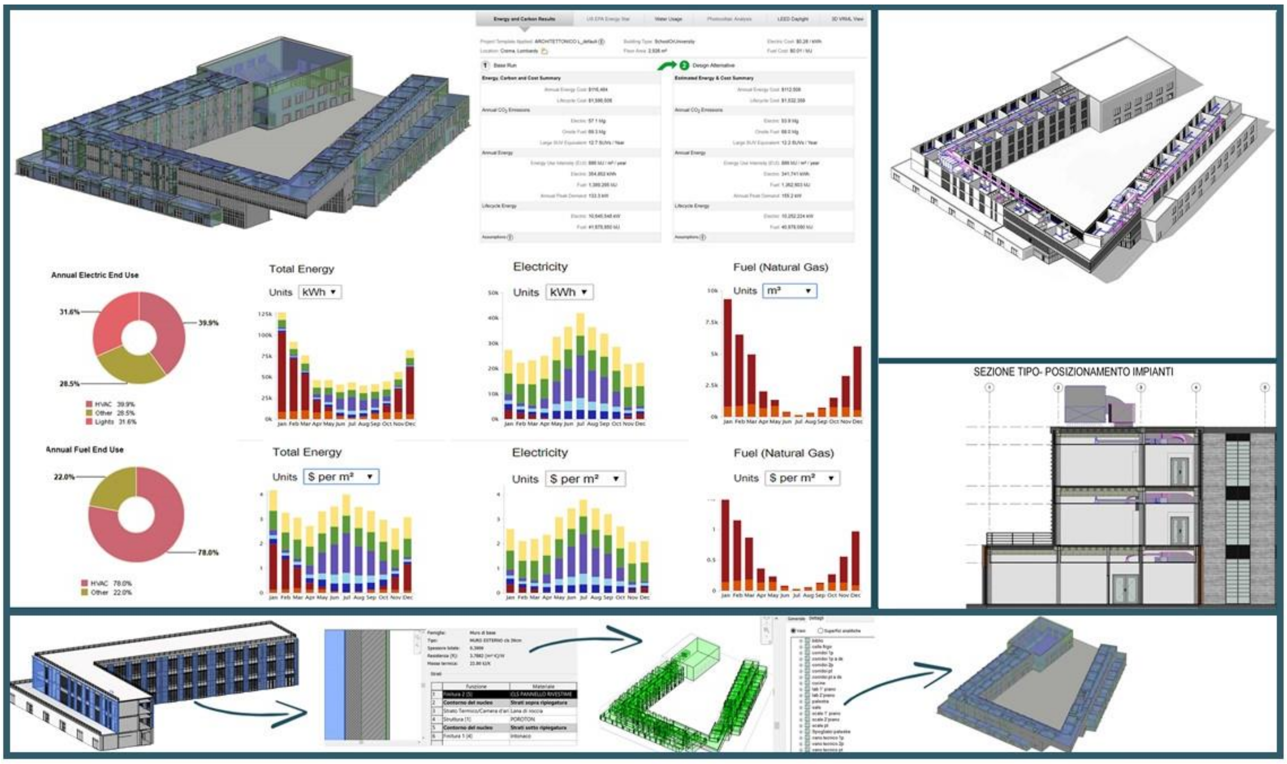



***Figure 39.*** *MEP design and energy analysis carried out on Autodesk Revit and Green Building Studio*.

## 2.4.10 BIM for the operational phase

Positive and negative impacts of BIM on facilities management are discussed in this section. Furthermore, case study projects are analysed in order to highlight the importance of using BIM as a tool for FM information systems. Results of this investigation are published in Marmo et al. (2019a).

A systematic literature review related to data and process requirements for BIM-FM integration was carried out via Scopus database with the following keywords: 'Building Information Model*', 'BIM', 'Information Management', 'Facilit* Management', 'Operation and Maintenance', 'CMMS', 'CAFM', 'case study', 'Building Performance Assessment' in title/abstract/keywords.

As evident, there was an interest in publications describing use cases too, to better understand the information exchange needs, the challenges to be faced and the expected results of BIM implementation in this research. For the scope of the thesis the case studies analysed concern BIM application in the O&M domain. **Table 6** summarizes the analysis of the selected publications according to the following categories: the purpose of the case study; the BIM use purpose; information requirements; information references; information exchange supports; benefits achieved; challenges encountered. In the table the "BIM use purpose" is mapped according to (Kreider & Messner, 2013) where a BIM use purpose is 'the specific objective to be achieved when applying Building Information Modelling during a facility's life'.

According to the **Table 6**, BIM is mostly appreciated for gathering (i.e., to capture, monitor, qualify), communicating (i.e., to visualize) and analysing (i.e., to coordinate, validate, forecast) data and information. In few cases (Eastman et al., 2008; CRC, 2007) the BIM model is integrated with a benchmarking system to report current performances, while it commonly contains maintenance activities records (Su et al., 2011;

Kassem et al., 2015; Fargnoli et al., 2019), asset characteristics and specification (Hallberg & Tarandi, 2011; Teicholz, 2013; Bortolini et al., 2016; Cavka et al., 2015; McArthur, 2015; Lucas & Thabet,2018; Pishdad-Bozorgi et al., 2018; Kassem et al., 2015) and space management information (Eastman et al., 2008; McArthur, 2015; Bortolini et al., 2016).

The main expected **benefits from BIM-FM integration** are cost reduction, thanks to ready to use data provided at the handover phase; performance improvement, it is to say more accessible FM data allows faster analysis and problems correction; integration of several information technologies (Teicholz, 2013) (**Figure 40**).

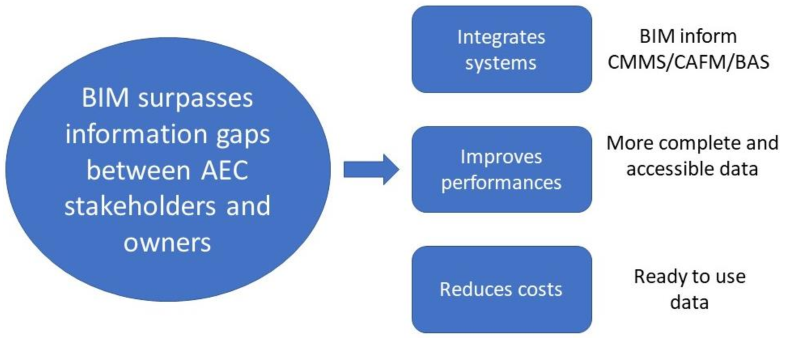



***Figure 40****. BIM-FM integration benefits (based on Teicholz, 2013).*

Owners can use a BIM model to quickly populate an FM database (Eastman et al., 2008). As-built BIMs can enable the transfer of facility information from the design and construction phases to the operational phase. Retrieving necessary facility information from a BIM model and importing them into CMMS allows relevant costs savings, avoiding recapturing and transferring information by architects, engineers, and contractors (Akcamete et al., 2010). BIM promises to provide a reliable database and integrated views across all facility systems (Akcamete et al., 2010) so that facility managers can base their decision on a more comprehensive knowledge of the building systems. BIM also provides 3D spatial information; therefore it supports visualization and spatial analyses of various maintenance activities. Such analyses might not be easily performed with traditional databases (Akcamete et al., 2010).

Owners can also use a BIM model strategically and effectively to manage facility assets. They can evaluate the impact of retrofit or maintenance works or associate each building object with a condition assessment over time, supporting critical analyses (Eastman et al., 2008) such as maintenance planning and sustainability management (Teicholz, 2013).

An important aspect is the constant upkeep of the digital building model; all changes in the real facility must be recorded in its digital twin. When larger renovations or modifications are required, the building model provides an excellent basis for the necessary design activities. When the built facility reaches the end of its life cycle and is going to be demolished, the digital twin provides detailed information about the materials used in its construction, in order to plan their environmentally-sound recycling or disposal.

However, the BIM implementation in FM systems is not currently achieved without challenges.

Three major **categories of issues** can be defined (Akcamete et al., 2010): challenges encountered by the facility team or facility owners (i.e., lack of knowledge about how to use BIM in their practice); challenges encountered by the designers and contractors (i.e., lack of guidance about data requirements and delivery); technical issues (i.e., interoperability).

To connect BIM data to FM systems, FM teams can face the interoperability issue in several manners (Thabet & Lucas, 2017). Examples of open standards are the Construction Operations Building Information Exchange or the Industry Foundation Classes, in particular the FM Handover Model View Definition. They define standard structure and minimum data fields to support facility management, as discussed in the sub-section 2.4.5.

Other BIM-FM linking approaches concern manual integration of data (i.e., through spreadsheets) and proprietary middleware (Ibrahim et al., 2016).

Due to the simplicity of their inherent structure, spreadsheets are useful means of moving data (text and numbers) between software (CRC, 2007). They are generally used in CAFM/CMMS or BAS, plus they are linkable to BIM objects. With a customized application, it is possible to read/write and import/extract data from a BIM based platform that also supports spreadsheet-based documents. For example, Dynamo, a tool for visual programming, which works within the Revit environment, can act as a bidirectional link from Revit to an Excel spreadsheet (Lucas & Thabet, 2018).

However, the transfer of data at the handover phase is commonly limited to graphical spatial information (i.e., room areas and attributes) and building inventory. Facility managers hardly update information from small projects, work orders, and major renovations in as-built BIM (Teicholz, 2013). In order to enhance the maintenance planning there is a need of capturing information about maintenance and repair works during the operational phase. Retrieving this information facilitate project financial analysis and maintenance works prioritization (Klamt, 2011).

In addition, an as-built model that is developed without early guidance is not effective for operational purposes (Lui & Zettersten, 2016). In early project phases, designers and contractors have to know what information the FM team will need, as well as what organizational standard structure for information inventories is needed (Mayo & Issa, 2016), which is not commonly known by the owners (Keady, 2013).

Defining the BIM-FM integration goals and developing the BIM-FM information collection and related information exchange process are necessary steps to effectively design the integration of BIM for FM (Lin et al., 2016). The strategic identification of operational information is critical, thus facility managers need to detail and prioritize their information requirements (Kassem et al., 2015; McArthur, 2015), identifying by whom and when the data should be provided through- out the project life cycle (Becerik-Gerber et al., 2012). This data will depend on specific user systems, organizational structure and scope of the model.

In conclusion, owners might not be accustomed to the technological side of building management issues and not educated on BIM, how to request it, or how to adopt it to their practices.  At the same time, few contractors are willing to perform BIM that does not directly benefit their daily work process without charging significant additional costs (Gleason 2013). For these reasons, the cost of BIM-FM integration can be high, requiring investment in infrastructure, training, and new software and hardware (Akcamete et al., 2010).

***Table 6.*** *BIM-O&M integration case studies.*

| Case study, ref. | Purpose of the case study | BIM use purpose | Information requirements | Information references | Information exchange supports and methods | Benefits | Challenges |
|---|---|---|---|---|---|---|---|
| Sydney Opera House (CRC, 2007) | Supporting building system alterations and asset management | To communicate and analyze | Properties of building elements; Building Condition Index | 2D CAD drawings and Sydney Opera House specifications | IFC model (integrated data model) | Control of costs and environmental data; support to decision-making | Not discussed |
| US Coast Guard (Eastman et al., 2008) (pp. 339-357) | Facilitating better decision-making for strategic planning and facility assessment | To gather | Facility Condition Index; Mission Dependency Index; Space Utilization Index | As-built documents (including 3D models); assessment team data; assessors' data; new BIM objects | Customized systems based on open standards (IFC, XML etc.) | Cost and time savings; standardizing processes and capturing knowledge digitally | BIM-based processes must support the integration of a variety of data and must be accessible to a wide range of users |
| A campus building, (Bortolini et al., 2010) | Integrating facility maintenance data with BIM to support maintenance planning | To communicate and analyze | Maintenance activities information such as replacement, installation and status change | Not discussed except for the work order records | Manual integration of maintenance data into BIM model | Spatiotemporal analysis to optimize future interventions | Data capture and collection; updating the model and related information |
| Taiwan's school, (Su et al., 2011) | Creating a single repository of facility data for facilities maintenance | To communicate and gather | Schedule of planned tasks; results of maintenance works; facilities maintenance documents | 3D CAD models; existing FM systems | Application Programming Interface and C# programming language | Improved information accessibility; enhancement of tasks planning and quality of inspection | Information exchange; updating information in BIM models |
| Norrtälje hospital (Hallberg, D., & Tarandi, 2011) | Developing a customized life cycle management system to support proactive maintenance | To gather, communicate and analyze | Geometrical model; material properties; environmental properties; condition assessment data; degradation model | 2D CAD drawings; administrative documents; condition surveys | wrl. file, transformed from a dwg. file by the use of a third software | BIM-based tools serve as information repository for life cycle management; simplified build-up of information; enriched data | Needs for BIM integrated life cycle solution based on open standards |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| University of Chicago, (Teicholz, 2013) (pp. 294-314) | Supporting maintenance activities | To communicate and gather | List of asset inventory information and data | Design and construction models; existing FM systems | Spreadsheet (modified version of COBie) | Improved data accuracy; streamlined data acquisition process | Handling with the variety of information resources; need for FM team information expertise |
| Manchester City Council Town Hall (Codinhoto & Kiviniemi, 2014) | Investigating the use of BIM in FM domain | Not discussed | Operation & Maintenance information | Various FM systems; 3D building information and cloud-based repository for digital documents | Not discussed | Faster maintenance process and shorter service disruption | Need for FM team BIM expertise; limited software interoperability; unclear BIM FM requirements etc. |
| Kerr Hall, Ryerson University (McArthur, 2015) | Testing how to overcome key challenges while developing 7D BIM | To communicate, gather and analyze | Space allocation; lighting feasibility calculations; asbestos hazard map | Survey and reports; existing space management systems | Spreadsheet | Improved data updating and assessment of potential energy retrofit | Identify critical information; create/modify BIM models; information transfer; documentation uncertainty |
| Northumbria University's campus 2015, (Kassem et al., 2015) | Investigating the value of BIM in space management | To communicate, gather, analyze and generate | Asbestos properties, location, date of removal and survey documentation | DWG floor plans, scans of elevations, JPEG sections, Excel databases | Not discussed | Improved space management and geometric information record | Identifying necessary information; need for FM team information and BIM expertise; interoperability; |
| University of British Columbia (Cavka et al., 2015) | Understanding the transition from a paper-based to a BIM-based approach in handover and FM | Not discussed | List of Operation & Maintenance information | Building management systems; facilities information systems; asset management systems | Not discussed | Not discussed | Methods and process changes |
| Terrassa Campus (Bortolini et al., 2016) | Investigating the benefits of the integration of Maintenance Management and BIM | To gather, communicate and analyze | List of building characteristics, space management, maintenance and building monitoring data | Physical stock and intranet; building management system; maintenance management systems | Definition of a unique identifier (ID) for each object and space | Improved data consistency, intelligence in the model and reports generation; integration of facility systems | Correlating different kind of data sources; information exchanges |
| Laboratory and office building (Lucas & Thabet, 2018) | Developing more efficient data collection in post-occupancy facilities management | To gather and communicate | Mechanical and electrical asset data | As-built 2D drawings; project documents; asset data list | Comparison among different methods: manual; spreadsheet; .CSV; IFC | Not discussed | Data transferring processes |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Public University building (Pishdad-Bozorgi, 2018) | Creating a central facility data repository to support FM tasks | To gather and generate | List of maintenance and equipment information | Owner’s guidelines and handover products | COBie and IFC | Easier updating of CMMS thanks to handover BIM models | Data transfer and data quality control; needs for resources and collaboration among teams |
| Melzo’s school buildings, (Carbonari et al., 2018) | Developing a decision support model to define the priorities of refurbishment actions | To gather and analyze | List of information regarding accessibility; energy efficiency; acoustic performance | Legislation and technical standards; thermal simulations; | SQL and Dynamo | Semi-automatic evaluation of the level of compliance of existing buildings, with reduced time and costs | Lack of information suitable to perform a complete assessment in BIM models |
| Training center (Fargnoli et al., 2019) | Merging BIM and Product-Service System to enhance maintenance operations | To gather and communicate | List of ordinary and extraordinary maintenance activities information | Maintenance reports and interviews with customers and suppliers | Not discussed | More effective management of maintenance activities, facilitated data record and tracking | Lack of knowledge and skills concerning the use of BIM tools |
| Hospitals in Scandinavia and Denmark (Koch et al., 2019) | Investigating the enabling and constraining elements of digital FM in Scandinavia. | Not discussed | Building inventory | Design and construction information | Manual integration of as-built information in FM systems (case A); customized classification system (case B) | Not perceived (case A); time savings thanks to common project library shared by different design teams (case B) | Information exchange; few interests in ICT investment; lack of knowledge concerning ICT implementation; needs for digitalization strategy |

The analysis of papers regarding BIM implementation for O&M purposes has demonstrated that BIM as a repository tool, able to support different analysis, has been tested in several applications. For example, BIM can support proactive maintenance through gathering information about materials, environmental and condition data so that a BIM-based life cycle management system can be developed (Hallberg & Tarandi, 2011). The prioritization of refurbishment actions can be improved too, developing a decision support model based on accessibility, energy efficiency and acoustic performance information (Carbonari). 3D data visualization allows analysis to optimize future interventions planning (Codinhoto & Kiviniemi, 2014; Kiviniemi & Codinhoto, 2014; Kassem et al., 2015; Akcamete et al., 2010; Su et al., 2011). Faster maintenance processes and shorter periods of disruption have been proved (Codinhoto & Kiviniemi, 2014; Kiviniemi & Codinhoto, 2014) and tested merging BIM and Product-Service System (Fargnoli et al., 2019).

In addition to the information exchange processes, it appears that a lack of BIM expertise among the FM team and the owners is a major challenge (Teicholz, 2013; Codinhoto & Kiviniemi, 2014; Kiviniemi & Codinhoto, 2014; Kassem et al., 2015; Fargnoli et al., 2019; Koch et al., 2019).

Furthermore, it can be deduced that a preliminary analysis of the FM process and policies, both currently adopted or expected, is necessary. In fact, the sources of required information for facility maintenance mostly involve the existing FM documentation, FM personnel's experience, and building management systems (Gao & Pishdad-Bozorgi, 2019). Interviews with the owner and the FM team allow to better understand the organisation’s information requirements, defining data needs based on current and future goals of O&M activities.

Finally, the integration of operational conditions and performances in BIM models is a lesser-known topic, even if it can facilitate the decision making for facility planning and assessment. For this purpose, specific set of information for a complete BIM-aided performance assessment must be defined (Carbonari et al., 2018), a wide variety of data and a wide range of users must be involved in BIM processes (Eastman et al., 2008) and BIM-FM links must be based on open standards (Hallberg & Tarandi, 2011).

# 3. Methodological approach for a Performance Information Model (PIM)

Literature findings reveal that Building Information Modelling can play a key role in the Performance Assessment and FM domain. It allows collaboration and information exchange among the users (as maintenance supplier, owner, employee, facility manager, etc.), can serve as the basis for further analysis and simulations (energy, cost, health and safety, etc.), it is able to store and process data related to elements properties (thermal, mechanical, etc.). The maintenance planning can be improved by enriching the model with actual building performances information and future interventions suggestions. For example, through a conditional logic, the model can make suggestions about inspections to be performed for each value of a given control variable. Furthermore, a BIM model is by default the digital inventory of a certain asset, so that not only the quantity take-off is automatized, but also the inventory management is facilitated.

In this context, a Performance Information Model is a BIM model meant to support FM activities by gathering and managing relevant information related to residual performances and operational conditions of an asset and its elements.

BIM and FM, separately, may be thought of as a closed model which has evolved into a controlled-dynamical-model, in analogy with dynamical systems with control. According to the monitored conditions different performances of an asset during its lifecycle can be assessed (i.e., sustainability, affordability, energy consumption, safety, efficiency, environmental quality, etc.) and their relative weights may become control/dynamical variables.

A PIM enables performances assessment results and evaluation of better corrective or preventive interventions intervention evaluation in different application areas. As an example, in the housing field several indicators can be defined, moving from architectural, energy and structural criticality to transformability evaluation (Diana, 2015). Similarly, providing adequate housing quality to older people is another relevant topic that can be addressed by using a set of indicators to assess the age-friendliness of housing (Luciano et al., 2020). Especially technologically advanced environments can benefit from a Performance Information Model. Industrial and manufacturing sites, laboratories and healthcare facilities rely on specific environmental, structural and technological conditions to function properly. Infrastructures can be digitalised too, to help monitoring and enhancing health and safety conditions. Infrastructure monitoring systems are widely adopted in civil structures, as bridges, tunnels and viaducts, to detect faults before they can lead to severe failures (Hodge et al., 2015). Within the infrastructures field performance-based maintenance contracts may provide several indicators (i.e., number of accidents, number of defects for track kilometers, maintenance cost per kilometers, etc.) which help evaluating the level of performance of the maintenance process and to quantify benefits of maintenance to traffic operation (Famurewa, 2013).

By having in mind the idea of integrating FM systems, BIM and BPA, a methodological approach for a Performance Information Model is presented below.

The approach has been developed considering healthcare facilities, which offered a complex application area.

The performance assessment regards operating rooms environmental quality as it has been recognised as a less-discussed topic within the existing literature, but extremely relevant in the interest of the minimum requirements achievement. To have an easier control and quantify this performance feature a new KPI has been defined. Evaluation of the environmental performance indicator was related to technical and equipment conditions, consequently it can facilitate the identification of maintenance works eventually needed. The PIM implementation case study, regarding operating rooms, is presented in section 5.

## 3.1 PIM implementation process

The process map for the Performance Information Model development is depicted in **Figure 41**. The monitored data can be gathered in the model, then analysed and translated in the form of performance indicators. Relevant information can be generated, such as the interventions needed to satisfy the organizational requirements. The KPIs, in form of objects properties, are visualized and managed by the digital model, allowing further spatiotemporal analysis and supporting decision making tasks of subcontractors and FM team. For the PIM implementation a specific set of information, needed for the performance assessment, are defined; a wide variety of data and users are involved; and open standards formats are considered.

The Performance Information Model is achieved by the following workflow (Marmo et al., 2019a):

<u>Identify building performances to be monitored and FM information requirements</u>.

To achieve a deep understanding of the required information to be gathered and managed through BIM it is crucial to acquire and study several documents and carry out interviews with future users of the model. Client’s and users’ perspectives are essential to have in mind which are the objectives they want to achieve. Analysing the facility management policy, maintenance tender specifications and monitoring reports allows to identify information to be managed in order to reach the FM goals.

<u>Establish methods of performance assessment.</u>

To identify how to achieve the performance assessment, procedures and systems currently in use have to be analysed. In this thesis KPIs have been chosen as performance measurement tool because their functionality is generally well-known and, above all, they best facilitate the achievement of the BIM-aided BPA as they can be managed in form of objects parameters within the BIM platform. For each performance to be assessed at least one KPI must be defined.

<u>Link the monitored performances to preventive/corrective activities.</u>

According to certain performance values the interventions needed can be identified. For example, from the environmental performance assessment, the performance of the technical system can be deduced. These relationships can be translated in a deterministic logic and then transposed in a BIM platform to inform and update the model, i.e., using:

- *IfcActionRequest* (description of maintenance request);
- *IfcApproval* (approval of maintenance request);
- *IfcActor* (person or organization(s) fulfilling the request such as a facilities manager or contractor.).

Define the BIM use purpose and PIM requirements.

Establishing the potential value of BIM use on the project helps to identify the BIM implementation goals and the specific BIM uses. Once the BIM uses are identified then the model requirements can be defined, i.e., in terms of parameters to be inserted in the model, level of development required, implementation process needs, etc. Once the implementation process has been established then information exchanges can be defined. The exchange files contain instances of a subset of entities compliant with the IFC data model, such as *IfcActionRequest*, which are addressing PIM requirements. A customized software is needed to improve the efficiency of information exchange.

Implement the PIM.

PIM input data come from facility information management systems, including the BPA process. The actual condition of the facility is also required, so that the model to which the FM attributes refer can be created. Monitoring information can be pulled in the model in an automatized manner, creating a link between the model and the database used to handle the monitoring results (i.e., in form of Excel spreadsheets or relational databases). The output data are the required inspection tasks associated with the failed systems. They can be visualized in the model, i.e., in the form of text shared parameters, but they can also be exported or linked to CMMS to inform future work orders.

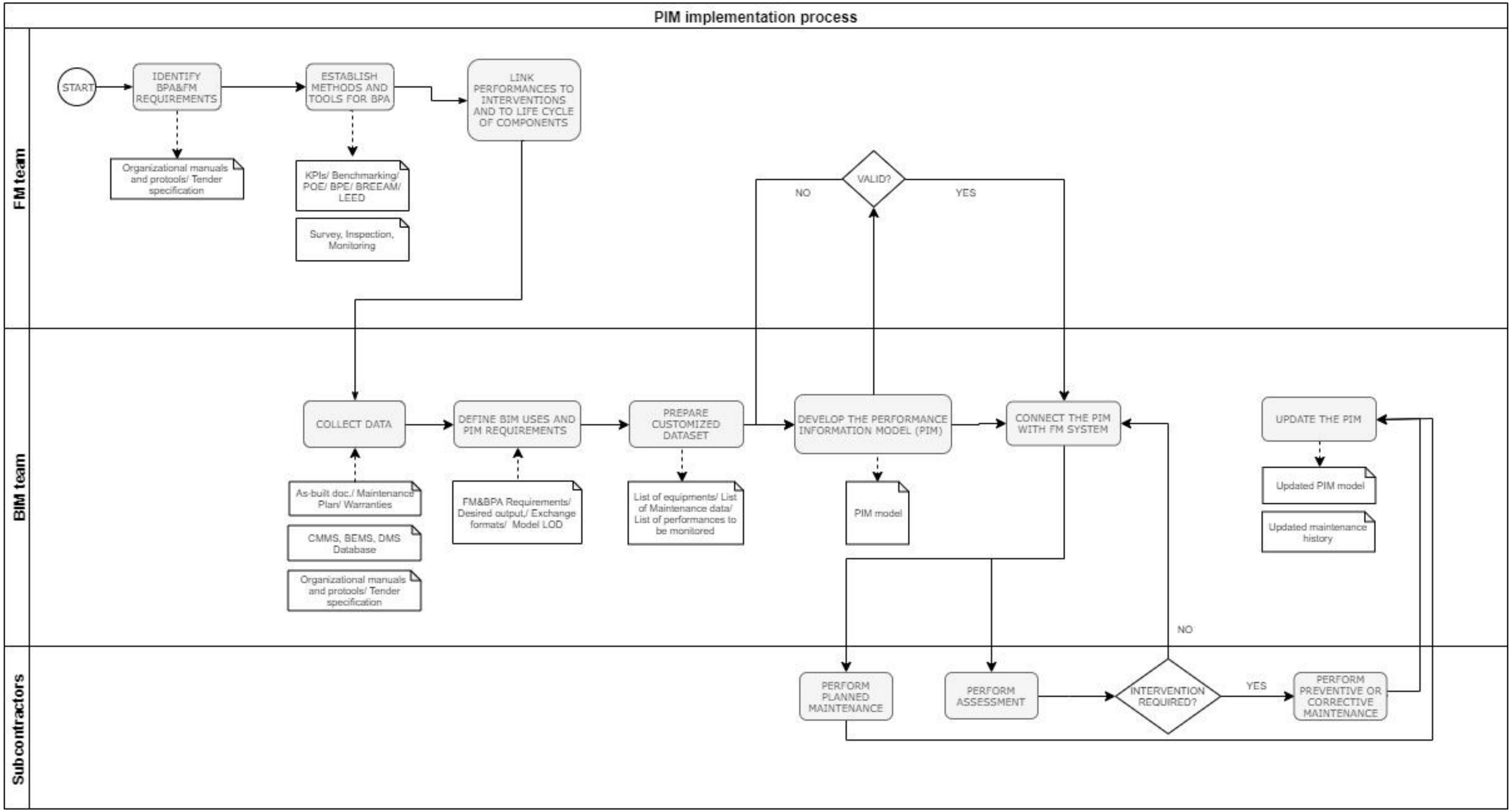



***Figure 41.*** *PIM implementation process in BPMN standard (Marmo et al., 2019a).*

## 3.2 Healthcare facilities field

The workflow proposed in Figure 41 has been tested and detailed in the field of healthcare buildings, as complicated and difficult types of facilities (Lavy & Shohet, 2007). Hospitals facility managers must make daily decisions in numerous areas, such as maintenance policy, level of performance, sources of labor, acceptable level of risk, etc., which affect the organization’s business performance.

Examples of key processes for successful implementation of FM in healthcare buildings are customer care, benchmarking, environmental management (Gallagher, 1998), service planning (Amaratunga et al., 2002; Gallagher, 1998), health and safety processes (Amaratunga et al., 2002), supplier and contractor management, performance management, risk management (Amaratunga et al., 2002; Shohet and Lavy, 2007).

The complexity of healthcare facility management is characterised by the existence of different types of data, including both quantitative data (e.g., maintenance costs, environmental performance), and qualitative data (e.g. customer satisfaction and maintenance quality).

Attempts at developing an integrated FM model for healthcare buildings have been discussed in literature (Lavy et al., 2014; Lavy & Shohet 2007; Shohet & Lavy, 2017). The starting point is the quantification of the effect of defined parameters, such as the maintenance expenditure or the age of the building, on the performance of the facility and its systems. Then a multi-disciplinary (managerial, economic, technological) hierarchical knowledge base is established for supporting the evaluation of performances and risks associated to those systems and facilities.

Similarly, this thesis discusses the identification of environmental control parameters and the quantification of their impacts on the surgery unit environmental performance. A surgery room is a very complex system, it has to comply with a set of requirements established by laws and regulations.

With a Presidential Decree (President of Italian Republic, 1997) minimum requirements for public and private healthcare facilities have been approved. They regard structural, technological and organisational aspects of healthcare units, such as specialised clinics, laboratories, diagnostic imaging units, mental health centres, triage, hospital ward areas, surgery units, etc. Specific technological and system requirements for surgery units are listed by law as reported in **Table 7**.

***Table 7.*** *Minimum requirements for operating unit in Italy, according to the DPR 14/01/1997.*

| **Minimum structural requirements for operating units** | |
|---|---|
| filter area for patients | preparation area for personnel |
| filter area for personnel | preparation area for patients |
| storage room for surgery equipment | storage room for dirty equipment |
| awakening room | operating room |
| **Minimum system requirements for operating rooms** | |

| | |
|---|---|
| temperature among 20-24°C | relative humidity among 40-60% |
| air changes 15v/h | air filtering 99,97% |
| medical gases system | pressure difference |
| fire detection system | alarm system for medical gases |
| **Minimum technological requirements for operating room** | |
| operating table | anesthetic machine |
| vital signs monitor | bovie |
| autonomous surgical aspirators | shadowless lamp |
| diaphanoscope | appropriate equipment for surgical operation |

The requirements presented in Table 7 have been further examined by the Italian guideline for safety and hygiene standards in the surgery unit (ISPESL, 2009). It describes optimal characteristics of the design, the construction and the management of surgery units, considering the existing knowledge of environmental, hygienic and safety matters.

Using a set of established KPIs simplifies the performance evaluation process and helps the management team to make strategic decisions towards the organization's mission (example of external control of the dynamical model).

In the context of this research an **Environmental Condition Index** (ECI) was defined ex-novo. It is meant to evaluate and quantify the environmental quality of a surgery room (environmental unit) or a surgery unit (functional area). The terminology used in this context (environmental quality, environmental unit, etc.) refers to the **UNI 10838** (UNI 10838:1999). This national guideline proposes a classification system and defines relevant terms in the field of performance assessment and building processes.

It defines the building system as the union of spatial and technological elements. The **environmental quality** is the whole of the environmental performances, while the **environmental performances** are spatial element performances referred to an environmental requirement. Finally, the **environmental requirement** is the translation of a demand into physical, technological and spatial factors in order to identify the compliance condition of an environmental unit.

The **environmental system** is a structured set of the environmental units and of the spatial elements defined in their performances and relations.

A **spatial element** is a portion of space meant to host an activity of an environmental unit.

An **environmental unit** is a set of homogeneous activities, compatible with each other, aimed at identifying a space suitable for carrying out such activities (e.g., surgery room).

The technological system is further described in the **UNI 8290–1** (UNI 8290-1:1981) which provides for an organised breakdown of the building in three levels:

- class of technological units;

- technological units;
- class of technical elements.

These classification scheme can be extended. For example, including more detailed components at the bottom of the technological system, it is possible to define material and resources for each technological element. Adding levels to the environmental system it is possible to group different environmental units. In this sense, this thesis refers to a more articulated structure proposed by the literature (Terranova, 2005) which considers:

- the **environmental unit** as the group of homogeneous activities spatially and temporally compatibles;

- the **functional area** as the group of environmental units required to perform a complex activity, formed by several elementary activities which ensure an autonomous functionality (e.g. surgery unit, the first aid, etc.);

- the **functional sector** as a set of functional areas characterized by elements of homogeneity related to the complex functions they represent, aimed at identifying the grouping of specific articulated macro-functions (e.g. the sector Diagnosis and Therapy which groups the surgery unit, the first aid, etc.).

The resulting hierarchically decomposition is depicted in **Figure 42** and detailed in **Table 8.**

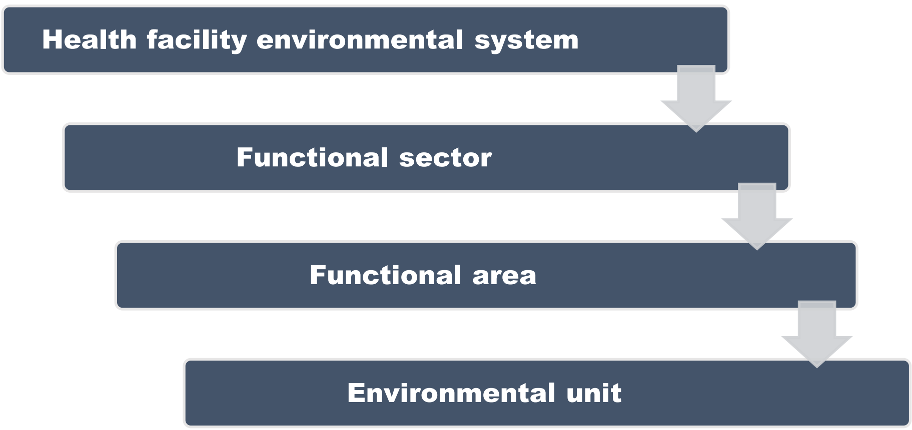



***Figure 42.*** *Hierarchically breakdown of a hospital.*

***Table 8.*** *Detailed hospital breakdown structure.*

| Functional sectors | Functional areas | Functional sub-areas | Environmental units |
|---|---|---|---|
| **Hospitalization** | Rehab | | |
| | Day Hospital | | |
| | Ordinary stay | | |
| | Specialist stay | | |

| | | | |
|---|---|---|---|
| | Intensive/sub-intensive stay | | |
| **Diagnosis and therapy** | Emergency | | |
| | Critical care | | |
| | Out-patient department | | |
| | Functional and endoscopic exams | | |
| | Imaging diagnostics | | |
| | Pathology | | |
| | Laboratory | | |
| | Rehab | | |
| | Radiotherapy | | |
| | Dialysis | | |
| | Day Hospital | | |
| | **Surgery unit** | **Reception sub-area** | ---- |
| | | **Surgery sub-area** | **Clean corridors** |
| | | | **Dirty corridors** |
| | | | **Surgery room** |
| | | | **Changing rooms** |
| | | | **Preparation and reviving of patients** |
| | | | **Filter Zones** |
| | | | **Sub-sterilization** |
| | | | **Surgery room slop sink** |
| | | **Staff services sub-area** | **Staff room** |
| | | | **Staff rest room** |
| | | | **Staff toilets** |
| | | **Support sub-area** | **Dirty storage area** |
| | | | **Clean storage area** |
| | | | **Storage area for sterilized material** |
| | Sterilization | | |
| | Maternity unit | | |
| | Blood bank | | |
| | Transfusion center | | |
| | Pharmacy | | |
| **General services** | Supply | | |
| | Canteen | | |
| | Distribution | | |
| | Laundry | | |
| | Police | | |
| | Maintenance | | |
| | Stores | | |
| | Technological plant | | |
| | Dressing room | | |
| | Morgue | | |
| **Management** | Heath direction | | |
| | Administration offices | | |
| | Reception | | |
| | Health information system | | |
| | Study and research offices | | |

### 3.2.1 Healthcare information requirements

Especially when no BIM exists yet, it is crucial to make the prior analysis of stakeholders' information requirements to optimise geometric modelling and information handling effort. Prior to modelling, local health authority's specifications on surgery rooms (related to maintenance, risk management and work organization) have been examined.

For this purpose, two Italian healthcare organisations were involved, and they provided documents, information and data about a public hospital in the province of Salerno (South of Italy), and a public hospital in Verona (North of Italy). Among the documents analysed there were:

- tender specifications about facilities management, in particular specification on O&M management;
- tender specification about surgery units environmental condition assessment;
- database of the monitoring process and results;
- adjustment plans;
- organizational documents on risk assessment;
- technical drawings and plans of the healthcare buildings.

Interviews and focus groups were conducted in person and involved the FM personnel, the maintenance team and the prevention and safety team. These interviews resulted in deeper understanding of the information needed to control performances and conditions; processes and systems in use to obtain and gather those information; means by which communicate the results. Furthermore, maintenance contractors were involved too. Thanks to them the following documents have been obtained and studied:

- the CMMS database, including the history of corrective maintenance intervention, planned and preventive maintenance tasks and schedule;
- register of work orders;
- further details on maintenance processes and information flows.

This process of information enrichment led to the definition of the stakeholder's information requirements, a crucial knowledge to inform the BIM model efficiently. The list of collected data related to preventive and corrective maintenance tasks is reported in **Table 9**.

***Table 9.*** *List of preventive and corrective maintenance information that can fill the model as objects properties.*

| **Work Orders History** | |
|---|---|
| WorkOrderID | Description |
| BuildingID | DateOfRegistration |
| DateOfCompletion | Duration |

| Requests for Intervention | |
|---|---|
| RequestID | Created by |
| Reported by | Description |
| Location | ContractualAuthority |
| SiteID | BuildingID |
| FloorID | UniteID |
| RoomID | Equipment |
| DateRequestCreated | UrgencyLevel |
| UrgencyTimeConstraints | ProblemType |
| InterventionType | ResolutionType |
| InsuranceDeductable | ExpectedCompletitionDate |
| MaintenanceCompany | DateOfCompletion |
| Notes | StatusID |

Monitoring significant parameters related to the condition of hygienic/engineering/structural systems allows healthcare facilities to adopt preventive procedures. Hospital facility manager can commission a specialized company to evaluate, analyse and report the environmental and equipment condition of surgery areas or rely on Building Automation Systems. The list of information to be monitored is reported in **Table 10**.

***Table 10.*** *Monitored conditions in surgery rooms.*

| Parameter name | |
|---|---|
| Particle concentration | Air volumes/ Air exchanges |
| Microbiological concentration | Noise |
| Anesthetic gases | Recovery time |
| Microclimatic conditions | Water quality |
| Pressure gradient | Lighting intensity |

## 3.3 Methods for data assessment

In this paragraph the Analytic Hierarchy Process (AHP) and the Delphi method are discussed in broad terms. The demonstration of certain hypothesis that typify the AHP is avoided, while concepts helpful to understand the achieved results are illustrated.

The AHP created by Saaty (Saaty, 1980) has been selected to deal with the relative importance of the environmental quality factors. It is a robust, repeatable, commonly recognised method which has been used in many different researches on the same topic (Maltese, 2015; Akadiri, 2011) and in general in the construction industry (Zheng et al., 2010).

The Analytic Hierarchy Process is a theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales. These scales reflect the relative importance of compared factors. The comparisons are made using a scale of absolute judgements that represents to what extent one element dominates another with respect to a given criterion (Saaty, 2008). **Table 11** exhibits the scale.

***Table 11***. *The fundamental scale of absolute numbers (based on Saaty, 2008).*

| *Intensity of importance* | *Definition* | *Explanation* |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to the objective |
| 3 | Moderate importance | Experience and judgement slightly favour one activity over another |
| 5 | Strong importance | Experience and judgement strongly favour one activity over another |
| 7 | Very strong or demonstrate importance | An activity is favoured very strongly over another; its dominance demonstrated in practice |
| 9 | Extreme importance | The evidence favouring one activity over another is of the highest possible order of affirmation |
| Reciprocals of above | If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i* | A reasonable assumption |

The pair comparison matrix is made by the results of the comparison between objects $i$ and $j$. The AHP assumes that it is possible to calculate the criticality weights of each factors through the main eigenvector of the comparison matrix. To do so it is necessary to calculate eigenvalues of the matrix, accepting only real outcomes, discarding complex eigenvalues and selecting the maximum of the real eigenvalues. After that it is possible to calculate the eigenvector associated to the maximum eigenvalue. The result is a vector with as many components as the matrix rank. To get the weights it is necessary to normalise eigenvector components with the sum of the components of the eigenvalue.

At the end it is necessary to calculate the consistency index $CI$ of the matrix $A$ with the formula (3):

$$CI = \frac{\lambda \max - n}{n-1} \tag{3}$$

Where $\lambda max$ is the maximum eigenvalue of matrix $A$ and $n$ is the number of factors being considered (which coincides with the matrix rank, as it is a square matrix). If the matrix is perfectly consistent, then $\lambda max$ will be equal to $n$ and consequently $CI$ = 0. This index is a percentage with the consistency ratio $CR$, given by formula (4):

$$CR = \frac{CI}{RI} \tag{4}$$

$RI$ is a random consistency index obtained by a big series of simulations. Values of $RI$ for square matrixes with rank from 1 to 10 are reported in **Table 12**. $CR$ varies depending on the matrix rank and in the **Table 13** there are the acceptability limits (based on Maltese, 2015).

***Table 12.*** *Random index (based on Maltese, 2015).*

*RI -random index*

| Matrix rank (n) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

***Table 13.*** *Matrix rank and acceptability limits (based on Maltese, 2015).*

| *Matrix rank* | *Acceptability limit* |
|---|---|
| 3 | 0.05 |
| 5 | 0.08 |
| >5 | 0.10 |

The Delphi Method was used to provide the pair comparison matrix. The Delphi is a method for structuring a communication within a group. The main features of the method are providing some feedback of individual contributions, opportunities for individuals to revise views, and some degree of anonymity for the individual responses (Czinkota & Ronkainen, 1997). The objective is to develop a technique to obtain the most reliable consensus of a group of experts (Dalkey & Helmer, 1963).

The method consists of iterative rounds: selecting the panel of experts; brainstorming and initial collection of factors (i.e., defining the parameters to be compared); validation of categorized list of factors; ranking the chosen factors (Okoli & Pawlowski, 2004). A 'facilitator' leads the rounds and iterate the collection of data until a satisfactory level of consensus between the experts is reached. The process is not carried out in person, but it can involve the use of e-mails or phone. The final forecasts are usually constructed by giving equal weight to all the experts' forecasts (Hyndman & Athanasopoulos, 2018).

## 3.4 Data assessment results

In the context of this thesis the Delphi involved a panel of 17 experts in the field of maintenance and risk management from the Local health Authority of Salerno and the University Hospital of Verona. The group of experts comprises:

- 11 technicians among engineers and architects;
- 3 medical doctors;
- 2 nurses;
- 1 chemist.

The experts were asked to compare:

- the importance of each environmental factors that affects the environmental quality of a surgery room;

- the importance of each environmental unit that affects the environmental quality of the surgery functional area.

The pair comparisons referred to the Saaty's values scale. The first round was conducted to list the environmental quality factors and to achieve an agreement about the list of environmental units to be compared. The second round regarded the ranking of the chosen factors.

The Delphi questionnaire included a first section regarding general expert's information (such as the professional backgrounds) and a second section dedicated to environmental quality variables assessment. Experts were asked to compare control parameters directly filling the pair comparison matrix, as shown in **Figure 43**. The questionnaire provided for examples and explanations to clearly describe the pair comparison logic and filling process. At the end of the questionnaire experts were asked to express how much they were confident with the answers provided (**Figure 43**).

You are asked to compare the following measurable parameters which affect the environmental quality of operating rooms: (1) Contamination at rest; (2) Contamination in operational; (3) Microclimatic conditions at rest; (4) Microclimatic conditions in operational; (5) Air exchanges/Recovery time; (6) Anesthetic gases concentration; (7) Noise.

| PAIR COMPARISON MATRIX OF MEASURABLE CONTROL PARAMTERS FOR A SURGERY ROOM | | | | | | | |
|---|---|---|---|---|---|---|---|
| | (1) Contamination at rest | (2) Contamination in operational | (3) Microclimatic conditions at rest | (4) Microclimatic conditions in operational | (5) Microclimatic conditions in operational | (6) Anaesthetic gases concentration | (7) Noise |
| (1) Contamination at rest | 1 | | | | | | |
| (2) Contamination in operational | | 1 | | | | | |
| (3) Microclimatic conditions at rest | | | 1 | | | | |
| (4) Microclimatic conditions in operational | | | | 1 | | | |
| (5) Air volumes/Recover y time | | | | | 1 | | |
| (6) Anaesthetic gases concentration | | | | | | 1 | |
| (7) Noise | | | | | | | 1 |

| How do you feel about the given opinion? |
|---|
| (Express your feeling through an integer within 1 and 10, where 1 = absolutely unsure and 10 = absolutely sure): |

***Figure 43.*** *Example of questions included in the Delphi questionnaire.*

The collected data have been analysed in order to calculate the mode, the median, the average, the first and the third quartile, the standard deviation and the variance as shown in **Tables 14** and **Table 15**. In order to give the equal importance to all the experts' opinions, the mode was used to build the two final pair comparison matrixes. For each of them the vector of weights was calculated by AHP. These weights have been deduced by calculating, in the MATLAB programming platform, the main eigenvector associated to the main eigenvalue of the pair comparison matrix.

***Table 14.*** *Data analysis regarding the environmental quality factors.*

| | *Comparison 2-1* | | | | | | | | | *Mod.* | *Med.* | *Ave.* | *Q1* | *Q3* | *S.D.* | *Var.* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | | **2** | | | **9** | **5** | **1** | **5** | **5** | **5.27** | **5** | **7** | **2.12** | **4.24** |
| | *Comparison 3-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **3** | **3** | **2** | **7** | | | | **2** | **1** | **1** | **1.57** | **1/5** | **1** | **3.98** | **7.97** |
| | *Comparison 4-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **2** | **4** | | **1** | **7** | **1** | **2** | | **3** | **3** | **2.48** | **1/5** | **3** | **2.59** | **5.19** |
| | *Comparison 5-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | **5** | **1** | **1** | **1** | **2** | **6** | **1** | **7** | **5** | **3.90** | **1/5** | **7** | **5.52** | **11.03** |
| | *Comparison 6-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | | | **1** | **1** | **4** | **5** | **6** | **9** | **7** | **6.65** | **5** | **9** | **2.81** | **5.62** |
| | *Comparison 7-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **3** | **6** | **2** | **1** | **5** | | | | **1/5** | **1/5** | **1.08** | **1/5** | **3** | **0.84** | **1.68** |
| | *Comparison 3-2* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | **3** | **6** | **6** | **1** | **1** | | | | | **1/7** | **1/7** | **0.22** | **1/7** | **1/5** | **0.02** | **0.04** |
| | *Comparison 4-2* | | | | | | | | | | | | | | | |
| | 1/9 | 1/7 | 1/5 | 1/3 | 1 | 3 | 5 | 7 | 9 | | | | | | | |
| **Freq.** | | **1** | **6** | | **7** | **1** | **1** | **1** | | **1** | **1** | **1.37** | **1/5** | **1** | **1.82** | **3.64** |
| | *Comparison 5-2* | | | | | | | | | | | | | | | |
| | 1/9 | 1/7 | 1/5 | 1/3 | 1 | 3 | 5 | 7 | 9 | | | | | | | |
| **Freq.** | | | **5** | **2** | **3** | **6** | **1** | | | **3** | **3** | **2.27** | **1/3** | **3** | **1.86** | **3.71** |
| | *Comparison 6-2* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | | | **5** | **5** | **3** | **4** | | **1** | **3** | **3.71** | **1** | **5** | **2.74** | **5.47** |
| | *Comparison 7-2* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | **1** | **5** | **7** | **4** | | | | | | **1/5** | **1/5** | **0.21** | **1/7** | **1/5** | **0.00** | **0.01** |
| | *Comparison 4-3* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | **1** | | | **1** | **12** | **3** | | **5** | **5** | **4.94** | **5** | **5** | **1.50** | **3.00** |
| | *Comparison 5-3* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | | **1** | | **1** | **7** | **7** | **1** | **5** | **5** | **5.39** | **5** | **7** | **2.08** | **4.16** |
| | *Comparison 6-3* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | | | | | **8** | **4** | **5** | **5** | **7** | **6.65** | **5** | **9** | **1.56** | **3.12** |
| | *Comparison 7-3* | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **3** | **6** | | | **4** | **4** | | | **1/5** | **1/5** | **1.98** | **1/5** | **3** | **2.18** | **4.36** |
| | *Comparison 5-4* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | **1** | | **2** | **6** | **6** | **2** | | **3** | **3** | **3.78** | **3** | **5** | **1.92** | **3.85** |
| | *Comparison 6-4* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | **1** | | **1** | **2** | **9** | **4** | | **5** | **5** | **4.72** | **5** | **5** | **1.93** | **3.86** |
| | *Comparison 7-4* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **3** | **5** | **6** | **3** | | | | | **1/3** | **1/3** | **0.38** | **1/5** | **1/3** | **0.05** | **0.09** |
| | *Comparison 6-5* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | **1** | | **5** | **2** | **6** | **3** | | **5** | **5** | **3.66** | **1** | **5** | **2.89** | **5.78** |
| | *Comparison 7-5* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | **1** | **3** | **5** | **7** | | **1** | | | | **1/3** | **1/5** | **0.40** | **1/5** | **1/3** | **0.23** | **0.45** |
| | *Comparison 7-6* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | **1** | **5** | **11** | | | | | | | **1/5** | **1/5** | **0.18** | **1/7** | **1/5** | **0.00** | **0.00** |

***Table 15.*** *Data analysis regarding the environmental units.*

| | *Comparison 2-1* | | | | | | | | | *Mod.* | *Med.* | *Ave.* | *Q1* | *Q3* | *S.D.* | *Var.* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | | | | **1** | | **1** | **13** | **2** | **7** | **7** | **6.69** | **7** | **7** | **1.71** | **3.42** |
| | *Comparison 3-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **1** | | **1** | **2** | **2** | **9** | **2** | | **5** | **5** | **3.97** | **3** | **5** | **2.35** | **4.71** |
| | *Comparison 4-1* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **2** | | **2** | **4** | **2** | **7** | | | **5** | **3** | **2.70** | **1** | **5** | **2.28** | **4.57** |
| | *Comparison 3-2* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **11** | **2** | **1** | **1** | **2** | | | | **1/7** | **1/7** | **0.55** | **1/7** | **1/5** | **0.45** | **0.90** |
| | *Comparison 4-2* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **4** | **4** | **6** | **2** | | | **1** | | **1/3** | **1/3** | **0.73** | **1/5** | **1/3** | **1.34** | **2.68** |
| | *Comparison 4-3* | | | | | | | | | | | | | | | |
| | *1/9* | *1/7* | *1/5* | *1/3* | *1* | *3* | *5* | *7* | *9* | | | | | | | |
| **Freq.** | | **3** | **3** | **2** | | **9** | | | | **3** | **3** | **1.69** | **1/5** | **3** | **1.03** | **2.06** |

The pair comparison matrix concerning the environmental units (Consistency Ratio equal to 0,03) and its related vector of weights are reported in **Table 16**.

The pair comparison matrix concerning the environmental quality factors (Consistency Ratio equal to 0,07) and its related vector of weights are reported in **Table 17**.

The **Annex 1** contains the original questionnaire as it was sent, by email, to the experts.
The **Annex 2** shows how to calculate the vector of weights on MATLAB, the example is related to the environmental units weights.

***Table 16.*** *Pair comparison matrix and criticality weights of environmental units.*

| | | 1 | 2 | 3 | 4 | **Weights (%)** |
|---|---|---|---|---|---|---|
| Reception | 1 | 1 | 0.15 | 0.25 | 0.37 | **7** |
| Operational | 2 | 6.69 | 1.00 | 1.83 | 1.37 | **42** |
| Employees services | 3 | 3.97 | 0.55 | 1.00 | 0.59 | **22** |
| Additional services for the functional area | 4 | 2.70 | 0.73 | 1.69 | 1.00 | **29** |

***Table 17.*** *Pair comparison matrix and criticality weights of environmental quality factors.*

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | **Weights %** |
|---|---|---|---|---|---|---|---|---|---|
| Contamination at rest | 1 | 1.00 | 0.19 | 0.64 | 0.40 | 0.26 | 0.15 | 0.93 | **4** |
| Contamination in operational | 2 | 5.27 | 1.00 | 4.57 | 0.73 | 0.44 | 0.27 | 4.78 | **14** |
| Microclimatic conditions at rest | 3 | 1.57 | 0.22 | 1.00 | 0.20 | 0.19 | 0.15 | 0.51 | **4** |
| Microclimatic conditions in operational | 4 | 2.48 | 1.37 | 4.94 | 1.00 | 0.26 | 0.21 | 2.64 | **12** |
| Air volumes/Air exchanges/Recovery time | 5 | 3.90 | 2.27 | 5.39 | 3.78 | 1.00 | 0.27 | 2.47 | **21** |
| Anesthetic gases concentration | 6 | 6.65 | 3.71 | 6.65 | 4.72 | 3.66 | 1.00 | 5.62 | **40** |
| Noise | 7 | 1.08 | 0.21 | 1.98 | 0.38 | 0.40 | 0,18 | 1.00 | **5** |

## 3.3 Environmental Condition Index

The ECI is a weighted average of control parameters values. The weights are related to the criticality of the parameters in relation to the environmental quality. First, it was necessary to identify which parameters describe the KPI, then their weights. To do so the Local Health Authority of Salerno and the University Hospital of Verona were involved. The list of measurable control parameters was obtained by two focus groups with expert panels from the above-mentioned healthcare authorities. To reach an agreement on the criticality of each parameter referred to operating room air quality, a Delphi was conducted. Then the criticality weights were obtained by a combination of Delphi method and Analytical Hierarchy Process (AHP) as has been described in the paragraphs 3.3, 3.4.

The Environmental Condition Index referred to a single environmental unit has the following formula (1):

$$ECI_{UAk} = \frac{\sum_i^n \; P_i \, x \, W_i}{\sum_i^n \; W_i} \tag{1}$$

Where:

- $ECI_{UAk}$ = Environmental Condition Index referred to the environmental unit k. It varies from 0 (best scenario) to 1 (worst scenario). In the PIM case study (exposed in section 5.1) the ECI for the orthopedic surgery room resulted to be 0.09, while for the general surgery room it was equal to 0.21. In both cases the ‘noise’ and the ‘contamination at rest' controls were not satisfied, but in the latter case also the ‘microclimatic condition in operational’ was not fulfilled
- $P_i$ = value of each environmental quality factors. It is evaluated with binary numbers: $P_i$ is equal to 0 if the control associated to it is fulfilled, otherwise it is equal to 1. As an example, for the orthopedic surgery room (section 5.1) the value 1 was associated with the parameters ‘noise’ and ‘contamination at rest’, while the value 0 was associated with the remainder
- $W_i$ = criticality weight of each factor. The sum of all the weights is 1 (100%). In the orthopedic room case (section 5.1) the sum of the products was 0.09 as the ‘noise’ and the ‘contamination at rest’ weigh respectively 4% and 5%.

ECI has the following features:

- It eliminates overlapping and redundant information, as some parameters are grouped when depending on the same equipment element. Then the identification of the required intervention was simplified;
- It expresses each relevant aspect of the system assessed. The list presented in **Table 10** was discussed in two focus groups to select 7 parameters necessary and sufficient to evaluate a surgery room environmental quality;
- It provides for a wide applicability across the authority FM systems, as it is based upon their requirements;
- It is expressed by a number, which values can vary from 0 to 1. This is a consequence of two factors: the formula which expresses the KPI and the evaluation mechanisms.

Once the ECIndex for each environmental unit is known it can be computed for the upper level of the breakdown structure, that is the functional unit (the sub-areas are not considered for simplification purposes). To do so, formula (2) must be implemented:

$$ECI_{AFj} = \frac{\sum_{k}^{m} ECI_{UAk}\, x\, W_k}{\sum_{k}^{m} W_k} \quad (2)$$

Where:

- $ECI_{AFj}$ = Environmental Condition Index referred to the functional area j. It varies from 0 (best scenario) to 1 (worst scenario) according to the value of the $ECI_{UAk}$.

- $ECI_{UAk}$ = Environmental Condition Index referred to the environmental unit k.

- $W_k$ = criticality weights of each environmental unit (i.e., operating room) with respect to the environmental quality of the functional area (i.e., the operating unit).

Having a single index for each functional area helps the facility manager in ranking the facilities under his responsibility and the decision making becomes easier. If more than one index is considered, then a comparison between the condition of the assessed building and an optimal one can be done, using, as an example, a radar graph (**Figure 44**).

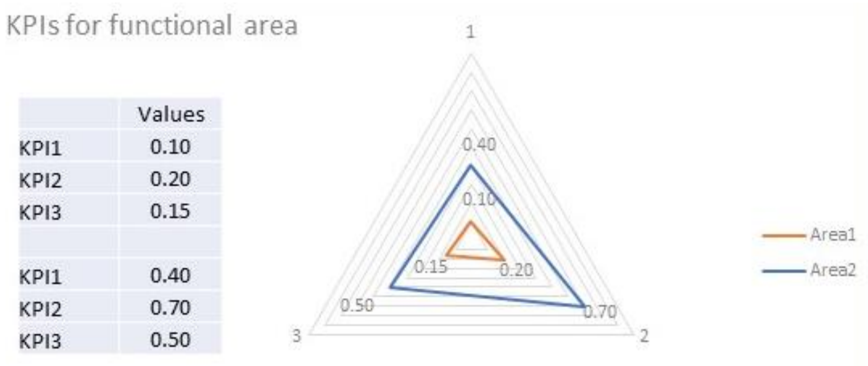



***Figure 44.*** *Example of radar chart.*

## 3.3.1 Correlation between environmental and technical performances

In order to integrate BPA with maintenance planning and to enhance the value of the ECI use, a link was established between control parameter values and the interventions required. These interventions are defined in terms of inspections and checks to be performed in order to verify possible failures or inadequate operational conditions within the technological and functional system. **Table 18** proposes the correlations list. The links between environmental and technical performances were defined with the collaboration of mechanical systems and indoor air quality experts, taking into account the way by which the environmental quality is monitored and the type of installed plants.

***Table 18.*** *Links between environmental and technological system.*

| N° Parameter | Parameter Name | N° Task | Task Description |
|---|---|---|---|
| 1 | Contamination at rest | 1.1 | HEPA filters inspection |
| | | 1.2 | HVAC pipes inspection |
| 2 | Contamination in operational | 2.1 | Behavioral protocols check |
| 3-4 | Microclimatic conditions at rest and in operational | 3.1 | Project condition check |
| | | 3.2 | ATU supplied power control |
| 5 | Air exchanges/Recovery time | 5.1 | Filters inspection |
| | | 5.2 | Load loss check |
| | | 5.3 | Forced air volume calculation |
| | | 5.4 | Mixing and ventilation efficiency control |
| 6 | Anesthetic gases concentration | 6.1 | Pipes fitting controls (High- and Low-pressure systems) |
| | | 6.2 | Gas evacuation system controls |
| 7 | Noise | 7.1 | Air-cooled inspection |
| | | 7.2 | HVAC ducts inspection |
| | | 7.3 | ATU inspection |

# 4. OpenPIM: towards an IFC-based PIM

The previous section proposes a methodological approach to integrate FM systems, BIM and Building Performance Assessment, supporting organisational, environmental and technical requirements.

The construction sector needs to document and share all information by one open format. BuildingSMART provided for the IFC schema for openBIM data exchange. OpenBIM simply means working with BIM using open standards (BuildingSMART, 2018). This is a universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows (BIM dictionary, 2019).

In alignment with the concept of openBIM, this thesis proposes an openPIM, that is a Performance Information Model based on IFC schema. The BIM-FM integration issue is addressed by mapping Industry Foundation Classes into a relational database regarding maintenance and performance management. The Visual Programming Language (VPL) is used to automate information exchanges between facility information systems and BIM.

Performance assessment results, preventive and corrective maintenance information and requests for intervention are modelled into the relational database, using standardised IFC entities identified as relevant for FM scopes. Pilot implementations of openPIMs are conducted referring to surgery rooms of a healthcare facility, and they are discussed in section 5.

The current section provides for a brief introduction to database design concepts. In this thesis a database is considered as a tool for managing and retrieving data related to facilities and maintenance management activities. The discussion is limited to concepts and tools required for developing the applications presented in this thesis. Firstly, the basic concepts of database design are introduced, the database development process is discussed, and the language used to query the database is described. Secondly, the openPIM database development is presented.

## 4.1 Database design

A BIM model includes typed entities with their attributes and referenced geometric shapes, as well as relationships between entities. Also, non-geometric information can be analysed and filtered in different ways. The most common vendor-neutral schema for building information models is the Industry Foundation Classes. The IFC data model can be mapped to a relational database and then filtered by a query language (Preidel et al., 2017). This transformation is not standardized but has a great potentiality if considering that facilities management requires to process a huge amount of data from several actors and disciplines. In this sense, a relational database, referred to the IFC schema, can assist users in filtering and analysing the right information, with the additional value of the 3D representation of the object eventually involved in the query.

### 4.1.1 Relational databases concepts

A *data item* is the smallest named unit of data that has meaning in the real world—for example, last name, first name, street address, ID number. A group of related data items treated as a single unit by an application is called a *record*. A *file* is a collection of records of a single type. In a relational database, a data item is called a *column* or *attribute*; a record is called a *row*; and a file is called a *table* (Teorey et al., 2011).

A database is used to help people keep tracks of entities. It is a collection of interrelated stored data that serves the needs of multiple users within an organization. Despite simple lists of data, a database avoids modification problems. A *relational database* contains a collection of separate tables, each of them holds data about one and only one theme. The process of partitioning a table with more than one theme into a set of tables containing only one theme each is called *normalization*. A relational database takes its name from the fact that each entity (or relation) is presented as a two-dimensional table with special characteristics, as reported below (Kroenke and Auer, 2009):

- Rows contain data about an entity;
- Columns contain data about attributes of an entity;
- Cells of a table hold a single value;
- All entries in a column are of the same kind;
- Each column has a unique name;
- The order of the column is unimportant;
- The order of the rows is unimportant;
- No two rows should be identical.

In order to create, process and administer databases, a *database management system* (DBMS) can be used. For each relation of a DBMS it is essential to define the *primary key*, which is the column used by the DBMS to uniquely identify each row in a relation. We place values from one relation into a second relation to represent a relationship. The values we use are the primary key values of the first relation, the attribute in the second relation that holds these values is called *foreign key*. A referential integrity constraint is a rule to ensure that every value of a foreign key matches the value of the primary key. It is possible to query and process databases through several approaches, but the Structured Query Language (SQL) emerged as the leading technique for this purpose (Codd, 1991). A DBMS receives requests encoded in SQL and translates those requests into actions. DBMS are generally licensed by software vendors. Examples of well-known DBM products are Microsoft Access, SQL Server, MySQL, PostgreSQL (Kroenke and Auer, 2009).

### 4.1.2 Database development process

The database development process consists of four major stages: requirements, design (logical and physical) and implementation (Kroenke and Auer, 2009).

During the **requirements stage** the purpose of the database is established, system users are interviewed and lists of data and functional requirements are obtained. These requirements are used to create a conceptual data model (Teorey et al., 2011).

During the **design stage,** a *conceptual data model* is developed. It means that the facility under consideration has to be described in an abstract way. The data requirements are analysed and modelled using ER or UML so that an Entity-Relationship diagram or a class-diagram in UML can be resulted. The most important elements of a conceptual data model are discussed in the section 2.4.6. The data model is then transformed into SQL tables. First, for each entity of the data model a table is created, then each table has to be properly normalized and finally relationships between table are specifically defined. The table creation includes the definition of tables and columns name, data type and columns properties as well as primary and foreign keys (Kroenke and Auer, 2009).

The last stage of the database development is the **implementation stage**, where the database is constructed and filled with data, queries and reports are created and tested. The database can be created through implementation of the formal schema using the data definition language (DDL) of a DBMS. Then the data manipulation language (DML) can be used to query and update the database, as well as to set up indexes and establish constraints. The language SQL contains both DDL and DML constructs; for example, the CREATE TABLE command represents DDL, and the SELECT command represents DML.

### 4.1.3 Basis of Structured Query Language

The SQL is a data sublanguage for defining and processing databases. The Structured Query Language has been available as an ISO standard starting from the ISO 9075:1987 and has been revised periodically since the latest ISO/IEC 9075:2016, structured in nine parts. The SQL has several components, two of which are mostly used: Data Definition language (DDL) and Data Manipulation Language (DML).

**Data Definition Language** commands modify the actual structure of a database, rather than the database's contents. Basic DDL commands are:

- CREATE TABLE: defines a table and all its attributes. Each column is described in three parts: column name, data type and optional column constraints. Common column constraints are primary key, not null, unique. For example, to create a table of customers:

  ```
  CREATE TABLE customer (
  CustNum Int Primary Key,
  CustName Text Not Null,
  Address Text Not Null
  CreditLevel Int
  );
  ```

- ALTER TABLE: add new columns, drop columns, or modifies existing columns in a table,

- DROP TABLE: deletes an existing table.

The **Data Manipulation Language** contains the subset of SQL commands used to simply manipulate the contents of a database. Common commands are:

- SELECT: retrieve information from the database. The SQL select command is the basis for all database queries. To display the entire customer table the asterisk (*) is used, it denotes that all records from a table are to be read and displayed. As an example, the command:

  ```
  SELECT * FROM customer;
  ```

  reports the complete customer table. It is possible to define also some conditions in querying data, such as through the WHERE command. Condition after WHERE require single quotes around values for Char and VarChar columns but no single quotes for Integer and Numeric columns. Compound conditions can be specified with AND and OR. It is possible to sort the results by using the ORDER BY command. For example, to display customer name, customer number, and credit level for all customers of the Enterprise who have a credit level greater than 7, ordered by ascending sequence of customer name, you can query:

  ```
  SELECT CustName, CustNum, CreditLevel
  FROM customer
  WHERE address = 'Enterprise'
  AND CreditLevel > 7
  ORDER BY CustName asc;
  ```

- INSERT: add new information to a database,
- UPDATE: modify information currently stored in a database and
- DELETE: remove information from a database.

## 4.2 OpenPIM database development

The development of the PIM database follows three main steps as presented in the section 4.2.2. The initial stage comprises the definition of the scope of the database and the information requirements. The openPIM database aims at enabling the maintenance and monitoring activities record and is meant to enrich a model with specific FM information. The database has been designed to keep track of:

- Corrective maintenance activities;
- Planned maintenance activities;
- Monitoring activities;
- Performance assessment results through KPIs;
- Actors involved in those processes.

The database information requirements refer to the section 3.2, with some modification according to the entities and related attributes defined in the IFC schema. Interviewing the organisations involved in this study and considering their tender specifications, the maintenance and monitoring processes have been further analysed. As an example, the corrective maintenance process, depicted in **Figure 45** in BPMN standard, has been examined to identify the involved actors, activities and data. The result of this initial stage is the list of the main entities included in the database, as follows:

- Action request;
- Actor;
- Approval;
- IFC model;
- Key Performance Indicator;
- Measurement;
- Product;
- Project order;
- Task;
- Work plan.

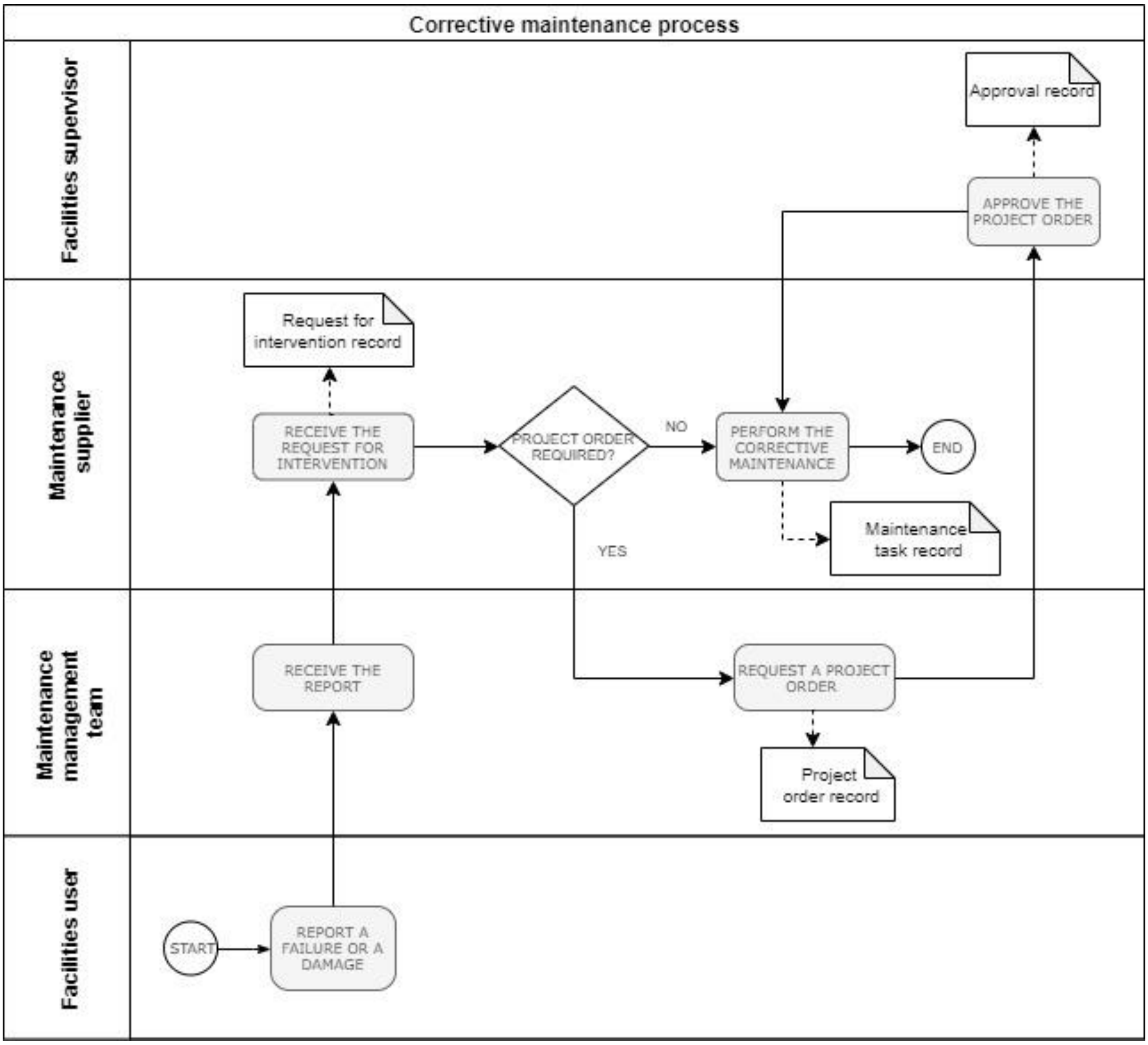



***Figure 45.*** *Corrective maintenance process within an organization in BPMN standard. It has been assumed that an employee detects a failure and contacts the maintenance management team. A project order can be required for certain tasks, but it can be avoided for minor works.*

## 4.2.1 Mapping IFC schema into an ER model

Once the main required entities are identified, the IFC schema serves as reference for checking their definition, including their relationships and attributes. It must be said that the listed entities are covered by the international schema except for the *Key Performance Indicator*, the *Measurement* and the *IFC model* objects. The *IFC model* entity has been used to refer each product to the model it belongs to. The concepts of measured, derived or simple values are contained in the Resource layer of the IFC schema, through the *IfcValue* select type. Furthermore, the *IfcPerformanceHistory* entity is meant to represent performance assessment results. It can be related to products, controls and measurement values through a complex system of relationships. For improving the efficiency of the database, it has been decided to define two new tables containing the KPI results and related measurements.

The resulted openPIM can be referred to as a **customized Model View Definition** for performance assessment and maintenance management.

An **Entity-Relationship model** (ER model) has been created by the Pony web-based and free access editor. **Figure 46** presents an extract of ER diagram. The **annex 3** contains the overall ER diagram in high resolution.

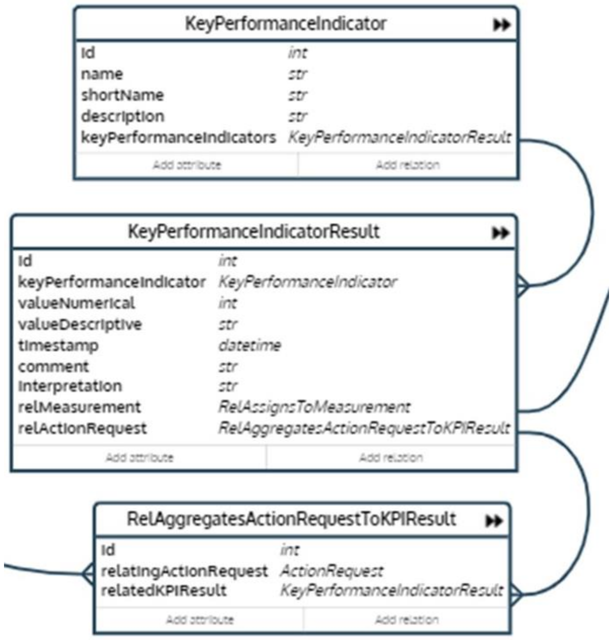



***Figure 46.*** *Extract of the Entity Relationship diagram as designed in the Pony editor.*

The openPIM model can be represented by the following main concepts, borrowed by the IFC schema 4x2 (Industry Foundation Classes. Version 4.2 bSI draft Standard, 2019):

**Actor**. The *IfcActor* defines all actors or human agents involved in a project. The *IfcActor* entity is a subtype of the *IfcObject.* It facilitates the use of person and organization definitions in the resource part of the IFC object model.

The *IfcActorResource* schema and related classes are used to define the *IfcActor* entity. The *IfcActorResource* schema enables the representation of information concerning a person or an organization who will undertake work or hold responsibility. For this purpose, it is necessary to define the following entities: *IfcPerson*; *IfcOrganization*; *IfcPersonAndOrganization; IfcActorRole* (**Figure 47**). Once these entities are defined, the *theActor* select type attribute allows a person, or an organization, or a person associated with an organization to be referenced.

The **Person** represents an individual human being. The **Organization** is a named and structured grouping with a corporate identity. The **PersonAndOrganization** represents a person acting on behalf of an organization. The **ActorRole** indicates a role which is performed by the previous entities. The actual role played by a person or an organisation is described by the attribute *Role*, that is a **RoleEnum** type (an enumeration of roles). The *Actor* has relationships defined by the *IfcRelAssignsToActor* entity, which defines a relationship between an *IfcActor* and one or many objects. A determined role of the actor played in that relationship can be associated. Furthermore, reference to the objects on which the actor acts upon in a certain role is specified in the inherited *RelatedObjects* attribute. For example, an actor can issue an action request, so that in the *IfcRelAssignsToActor* relationship the *RelatingIssuingActor* and the *RelatedActionRequest* will be defined (**Figure 48**).

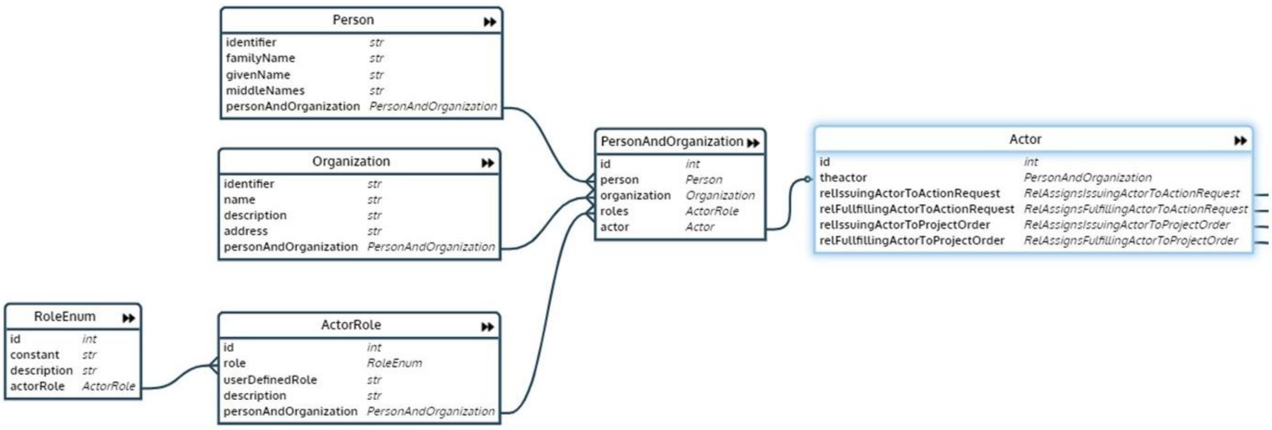



***Figure 47.*** *The Actor entity and related resources.*

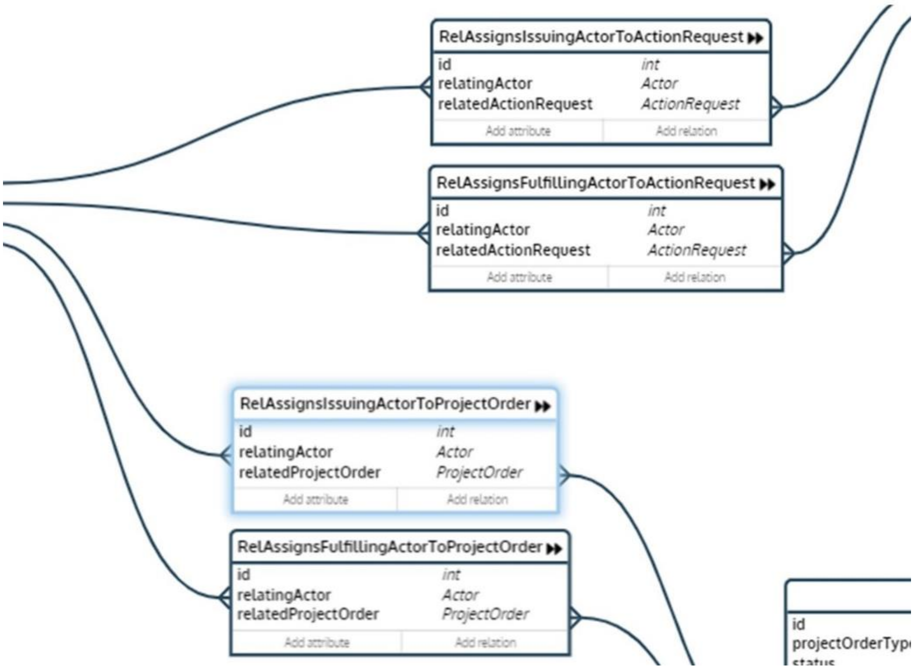



***Figure 48.*** *The Actor's relationships.*

**ActionRequest.** The *IfcActionRequest* entity is defined as the act or instance of asking for something. Requests may take many forms depending on the need including fault reports for maintenance and requests for small works.

This entity has been described by: identification, type, status and long description. Each *ActionRequest* instance is identified by a unique identification number through the *id* attribute. The *identification* attribute is inherited by the *IfcControl* and it constists of an identifying designation. The *type* attribute is selected by the **ActionRequestTypeEnum**, an enumeration of sources through which a request can be made (phone, fax, email, etc.). The *status* attribute admits values as: hold; no action; schedule; urgent. The *longDescription* attribute defines a detailed description of the permit. The *ActionRequest* entity is related to the *IssuingActor* and the *FulfillingActor* through the *RelAssignsToActor* relationship, it is also the object to which a *Task* can be related, and it is related to the *Product* entity, in  the sense that an *ActionRequest* is an act to be performed upon an *Object.*

Furthermore, an *ActionRequest* is related to *ProjectOrder* and to *KeyPerformanceIndicatorResult* entities as each request can generates a work order or can lead to the quantification of the measured performances (**Figure 49**). Even though this idea is not included in the openPIM model here presented, according to the IFC schema 4x2, action requests may nest further controls and requests (**Figure 50**).

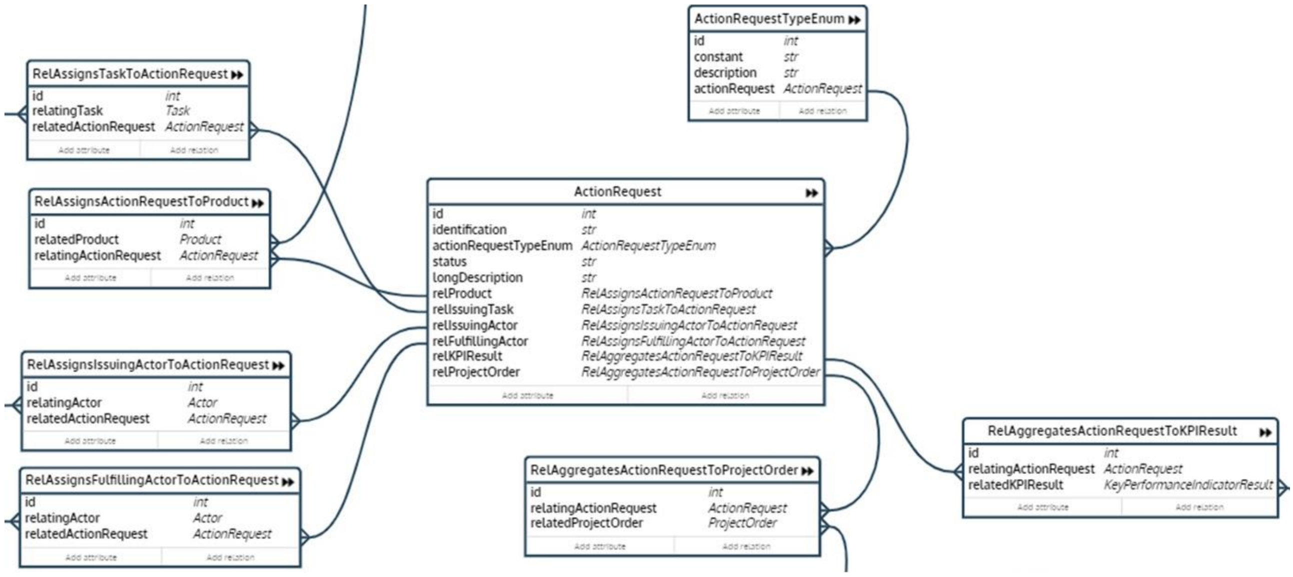



***Figure 49.*** *The ActionRequest entity.*

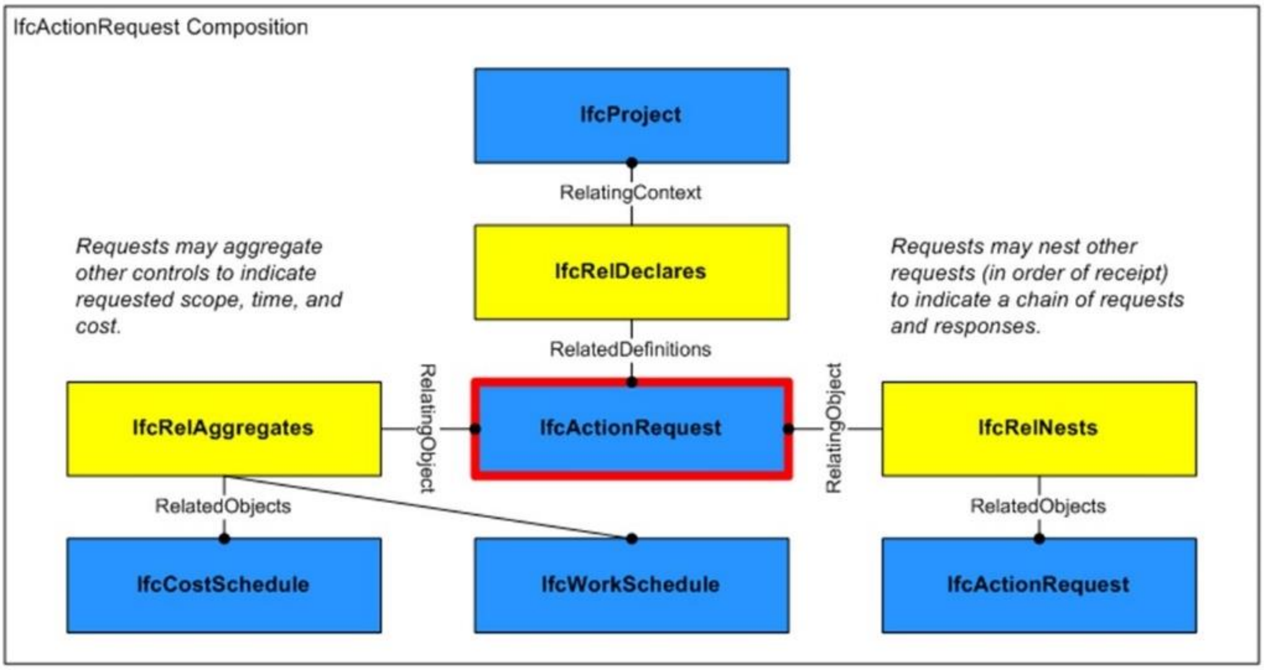



***Figure 50.*** *The ActionRequest composition (Industry Foundation Classes. Version 4.2 bSI draft Standard).*

**ProjectOrder.** A project order is a directive to purchase products and/or perform work. Each *ProjectOrder* instance is identified by a unique identification number through the *id* attribute. The *projectOrderTypeEnum* attributes is specified in an enumeration of project order types through the **ProjectOrderTypeEnum** entity (instances of the enumeration are move order, change order, maintenance work order, etc.). The *status* of a project order might be planned, requested, approved, etc. The *longDescription* attributes provides for a detailed description of the project order describing the work to be completed. The *ProjectOrder* is related to the *Actor* similarly to the *ActionRequest*.

The Approval entity may be associated to indicate the status of acceptance or rejection using the *IfcRelAssociatesApproval* relationship where *RelatingApproval* refers to an *IfcApproval* and *RelatedObjects* contains the *ProjectOrder* (Figure 51).

As for the action request entity, according to the IFC schema 4x2, project orders may nest further orders, for example to indicate amendments.

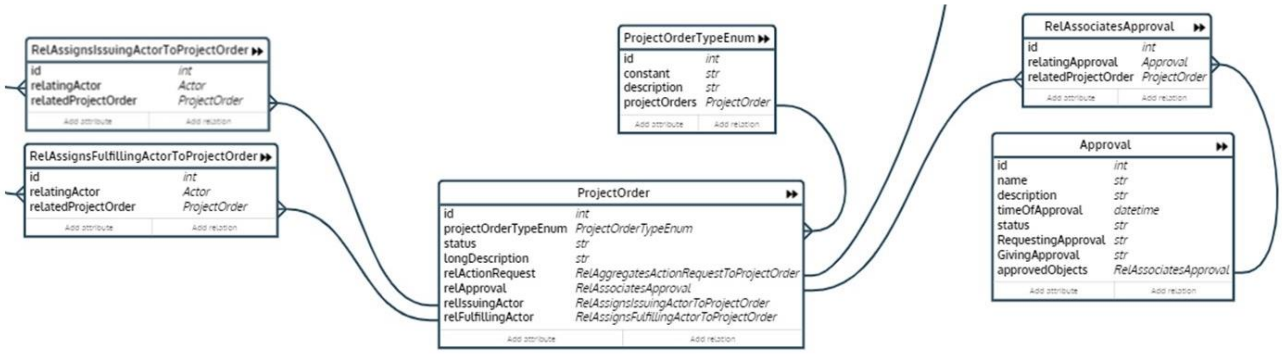



***Figure 51***. *ProjectOrder entity.*

**WorkPlan.** This entity represents work plans in facilities management activities. A work plan has information such as start date, purpose, creation date (inherited from the *IfcWorkControl*). Its own attribute is the type, selected from the **WorkPlanTypeEnum**, an enumeration data type that specifies the types of work plan (instances are actual, baseline, planned, etc.). Each *WorkPlan* instance is identified by a unique identification number through the *id* attribute.

A work plan contains a set of work schedules for different purposes A **WorkSchedule** is related to the *WorkPlan* through the *IfcRelAggregates* relationship. An *IfcWorkSchedule* represents a task schedule of a work plan, which in turn can contain a set of schedules for different purposes. A *WorkSchedule* controls a set of *Tasks* defined through *IfcRelAssignsToControl* (**Figure 52**).

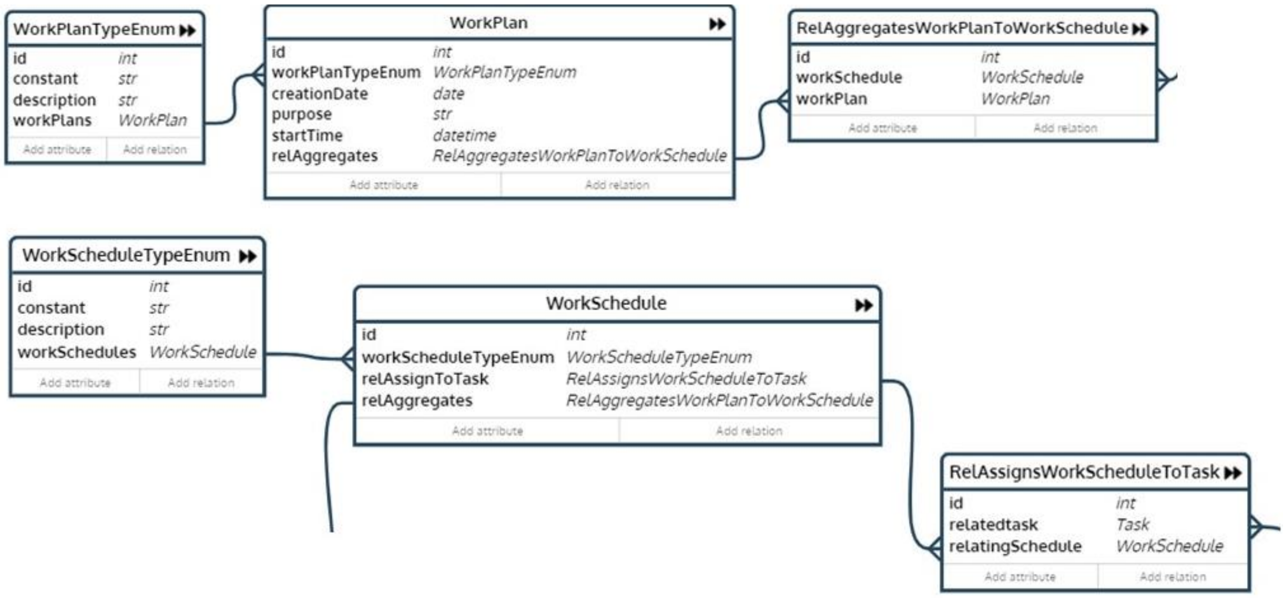



***Figure 52.*** *WorkPlan and WorkSchedule entities.*

**Task.** This entity represents an identifiable unit of work to be carried out in a project. Each *Task* instance is identified by a unique identification number through the *id* attribute. A textual description of the task may be provided by a long description. A work method may be declared for describing how to carry out a task. A task is identified as being either a milestone task or not. Task time information are defined through the *TaskTime* attribute. According to the IFC 4x2 schema recurring tasks are defined through *IfcTaskTimeRecurring*. The *IfcTaskTimeRecurring* is described by the *IfcRecurrencePattern* that defines repetitive time periods on the basis of regular recurrences such as each Monday in a week, or every six per year. The *IfcTaskTypeEnum* defines different types of task (i.e., construction, demolition, maintenance, removal, etc.).

The *Task* entity is related to the *WorkSchedule* as the object to which the work schedule is assigned. It is also related to *Product* and *ActionRequest* entities, in order to define the product to which a determined task has to be performed and the action request generated by an instance of a task.

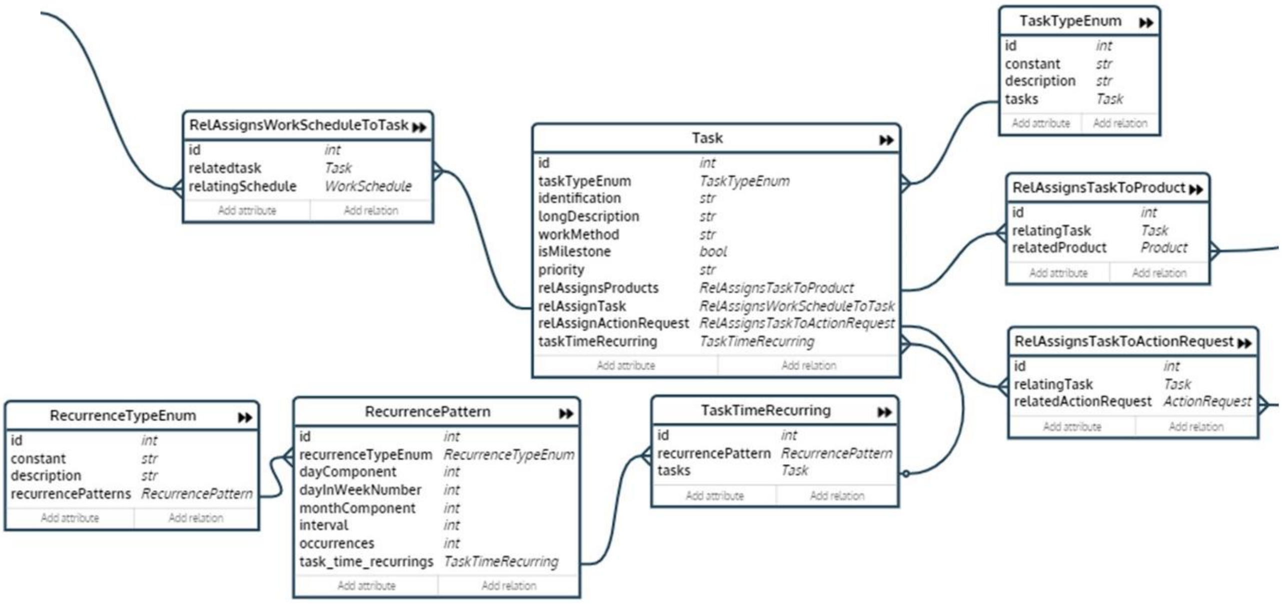



***Figure 53.*** *Task entity, related attributes and relationships.*

**Product.** This entity is equivalent to the IfcProduct, an abstract representation of any object that relates to a geometric or spatial context. Products include manufactured or created objects (physical elements) and non-physical objects, such as spaces, annotation, structural actions, etc.

For inheritance, attributes as GUID (globally unique identifier), object type, name, description can be applied. In addition, the *localId* attribute has been added to make the identification of the product in a BIM platform (such as Revit) easier. Each instance of the product entity is related to *Task*, *ActionRequest*, *Measurement* and *IFCModel* through the relationship *RelAssignsToProduct* (**Figure 54**).

**IFCModel**. This entity has been added to relate each product to the model it belongs to. In this way the database is aware of the informed model. Each *IFCModel* instance is identified by a unique identification number through the *id* attribute. Additionally, the *modelContent* attribute defines the information contained in the model, for example through the declaration of the discipline treated by the model (**Figure 54**).

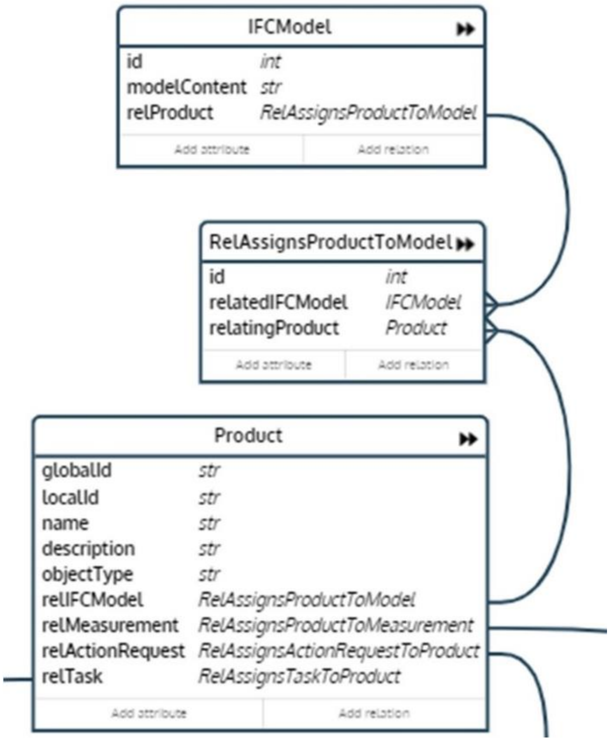



***Figure 54.*** *Product and IFCModel entities.*

**Measurement.** The Measurement entity is meant to conceptualise the monitoring activities and related results. An instance of a Measurement identifies a control variable. Each *Measurement* instance is identified by a unique identification number through the *id* attribute. The time of the *Measurement* is defined through the *timestamp* attribute. The result can be expressed by both numerical and description value. A *description* of the measured parameter may be defined too. Each instance of the Measurement entity is associated to a Product. For example, the measurement of thermal properties can be associated to a wall, the noise intensity to a space, etc. The measurement is also related to the **KeyPerformanceIndicatorResult**, as according to monitored parameters values, the related KPI is calculated. In the *RelAssignsToMeasurement* relationship it is possible to define the acceptability of measurement results and the interpretation of them (**Figure 55**).

**KeyPerformanceIndicator.** The concept of KPI is expressed by this entity, so that each KPI is identified by a unique identification number, furthermore its description, its explicit name and its acronym are reported. Each *KeyPerformanceIndicator* is reported also in the **KeyPerformanceIndicatorResult** entity. The time of the KPI evaluation is defined in the *timestamp* attribute, the KPI value can be both numerical and descriptive. A *comment* and an *interpretation* can be used to analyse the result. This entity is also related to *ActionRequest* through the *RelAggregatesActionRequestToKPIResult* relationship, as the performance assessment through multiple KPIs can be define by an action request (**Figure 55**).

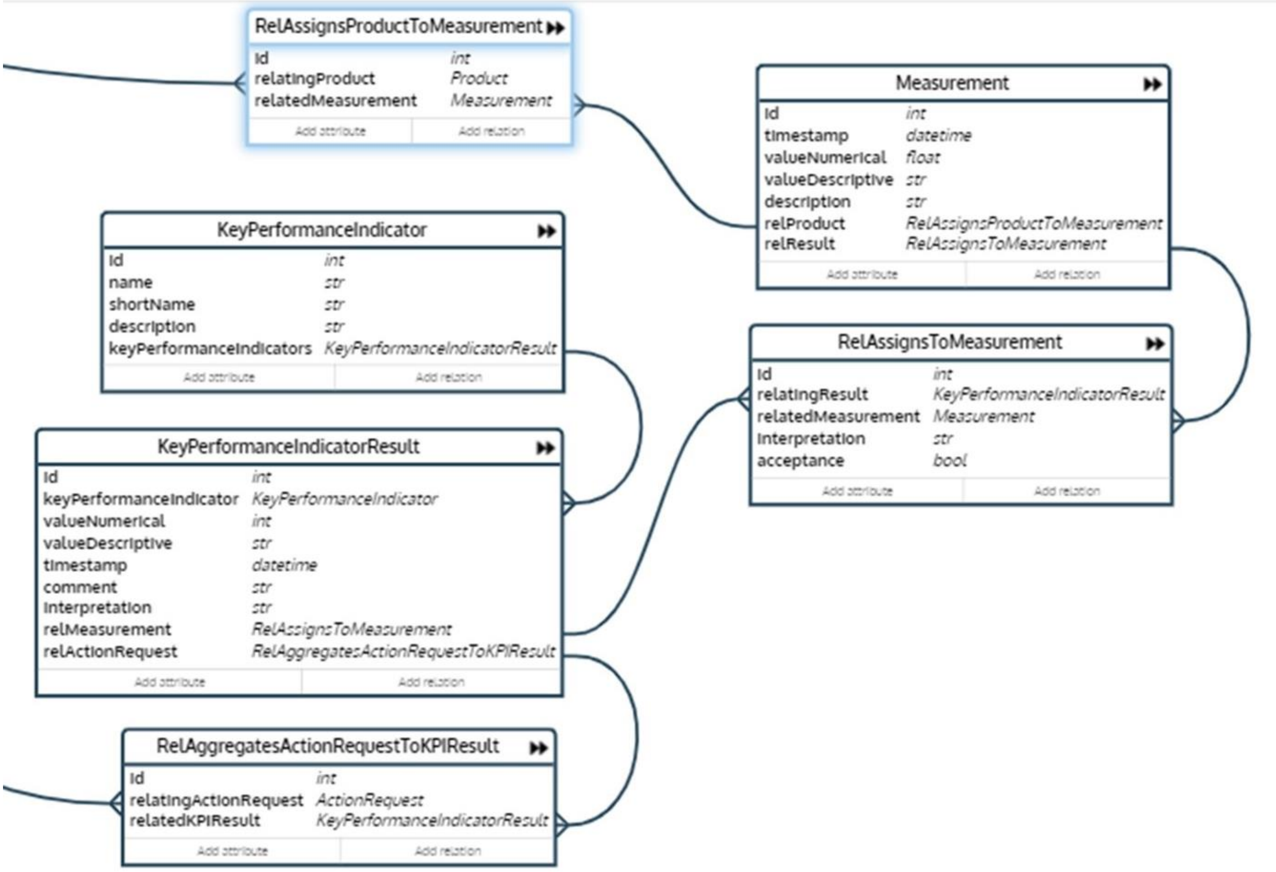



***Figure 55***. *KPIs and Measurement entities.*

## 4.2.2 Creation of the openPIM database from the ER model.

The ER model has defined entities, attributes and relationships. The database defines tables and attributes, specifying properties for attributes (i.e., data types and constraints) and identifying the primary key for each table. This operation has been carried out on Pony Editor.

The class of each attribute has been specified in:

- Primary key, for an attribute that will be used by the Database Management System to uniquely identify each row in a table;
- Required, when an instance of the attribute is needed for each row;
- Optional, if the instance of the attribute is not required.

The data type has been selected among:

- Str, it stands for string and means a textual attribute;
- Int, it stands for integer and means a numerical attribute;
- Float, it is a shortened term for floating point, and it is used to define numeric values with floating decimal points;
- Decimal, it is used for storing numbers that have fixed precision and scale;
- Datetime, it contains both date and time parts, for example in 'YYYY-MM-DD hh:mm:ss' format;
- Date, it has only the date component, for example in 'YYYY-MM-DD' format;

- Time, it has only the time component, for example in ‘hh:mm:ss' format;
- Timedelta, it represents a duration and can be expressed in different units, such as years, months, days, minutes;
- Bool, it stands for Boolean;
- Longstr, it stands for long string;
- UUID, it stores universally unique identifiers. It is a sequence of lower-case hexadecimal digits, in several groups separated by hyphens, for a total of 32 digits.

Other specifications can regard default values for certain attributes, the attribute property of being nullable, auto incrementable or unique (**Figure 56**).

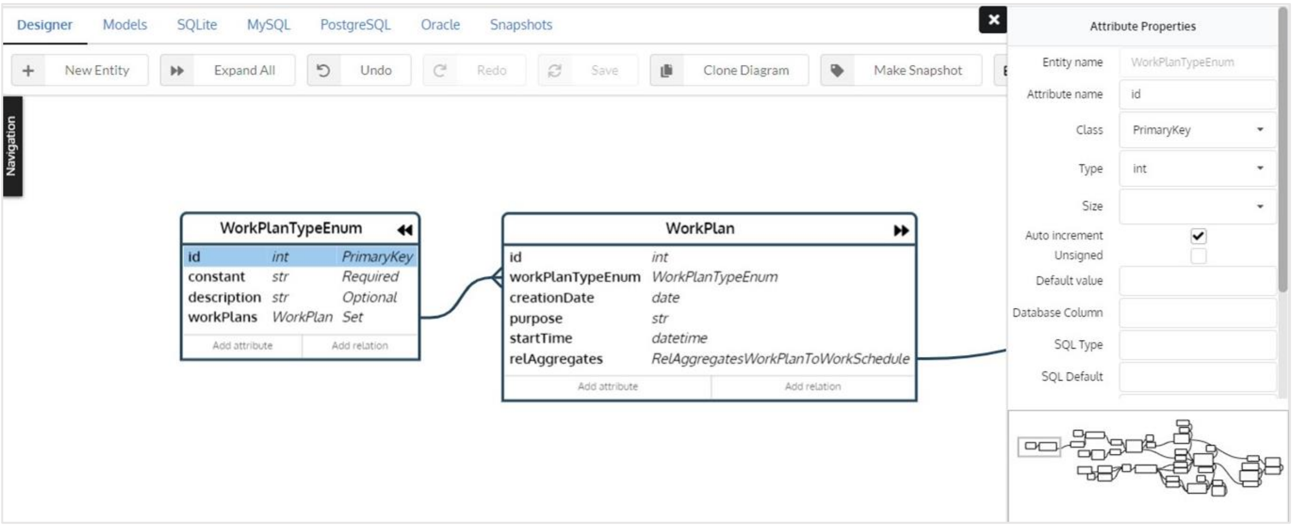



***Figure 56.*** *Attributes properties panel in Pony editor.*

The database editor used in this thesis translates queries to SQL using a specific database ‘dialect’. The resulted database consists of 40 tables, listed below:

1) ActionRequest
2) ActionRequestTypeEnum
3) Actor
4) ActorRole
5) Approval
6) IFCModel
7) KeyPerformanceIndicator
8) KeyPerformanceIndicatorResult
9) Measurement
10) Organization
11) Person
12) PersonAndOrganization
13) Product
14) ProjectOrder
15) ProjectOrderTypeEnum
16) RecurrencePattern
17) RecurrenceTypeEnum
18) RelAggregatesActionRequestToKPIResult
19) RelAggregatesActionRequestToProjectOrder
20) RelAggregatesWorkPlanToWorkSchedule
21) RelAssignsActionRequestToProduct
22) RelAssignsFulfillingActorToActionRequest
23) RelAssignsFulfillingActorToProjectOrder
24) RelAssignsIssuingActorToActionRequest
25) RelAssignsIssuingActorToProjectOrder
26) RelAssignsProductToMeasurement
27) RelAssignsProductToModel
28) RelAssignsTakToActionRequest

29) RelAssignsTaskToProduct
30) RelAssignsToMeasurement
31) RelAssignsWorkScheduleToTask
32) RelAssociateApproval
33) RoleEnum
34) Task
35) TaskTimeRecurring
36) TasTypeEnum
37) WorkPlan
38) WorkPlanTypeEnum
39) WorkSchedule
40) WorkScheduleTypeEnum

As an example, for creating the *WorkPlanTypeEnum* and *WorkPlan* tables in PostgreSQL the fragment of the DDL is the following:

```
CREATE TABLE "workplantypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "workplan" (
  "id" SERIAL PRIMARY KEY,
  "workplantypeenum" INTEGER NOT NULL,
  "creationdate" DATE,
  "purpose" TEXT,
  "starttime" TIMESTAMP
);

CREATE INDEX "idx_workplan__workplantypeenum" ON "workplan"
("workplantypeenum");

ALTER TABLE "workplan" ADD CONSTRAINT "fk_workplan__workplantypeenum"
FOREIGN KEY ("workplantypeenum") REFERENCES "workplantypeenum" ("id") ON
DELETE CASCADE;
```

The CREATE TABLE command is used to create a table. The names of the tables and of each column are defined and all attributes have specified properties.

The CREATE INDEX statement is used to create indexes in tables. Indexes are used to retrieve data from the database more quickly than otherwise.

In this case the statement means that index named *workplantypeenum* is created in the table *WorkPlan* for the attribute *workplantypeenum*.

A relationship between the tables exists in the sense that the *WorkPlan* type attribute is selected from the table *WorkPlanTypeEnum.*

The *WorkPlan* table was altered by the ALTER TABLE command in order to insert a foreign key on the *workplantypeenum* attribute which refers to the *id* attribute of the *WorkPlanTypeEnum* table.
Implementing the SQL DDL in a DBMS it is possible to create the database and managing it.

Database schema changes, regarding table name, column name, data type, etc., can be carried out in the DBMS itself. As an example, the need of changing the datatype of the ‘relatedproduct’ column in the *relAssignsProductToModel* relationship occurred. The SQL command used for performing that change is reported below:

```
ALTER TABLE "relassignsproducttomodel" ALTER COLUMN relatedproduct TYPE TEXT;

ALTER TABLE "relassignsproducttomodel" ADD CONSTRAINT
"fk_relassignsproducttomodel__relatedproduct” FOREIGN KEY
("relatedproduct") REFERENCES "product" ("globalid") ON DELETE CASCADE;
```

In the context of this thesis different SQL ‘dialects’, available on the utilised editor, have been analysed and implemented in appropriate DBMS. The purpose was to test the connectivity between the database and the IFC model, through a VPL application. The integration results are exposed in the section 5. The **annex 4** contains the statements for creating the database on PostgreSQL.

The following pictures show resulted databases on PgAdmin, for PostgreSQL syntax (**Figure 57**), on MySQL Workbench for MySQL syntax (**Figure 58**) and on DB Browser for SQLite syntax (**Figure 59**).

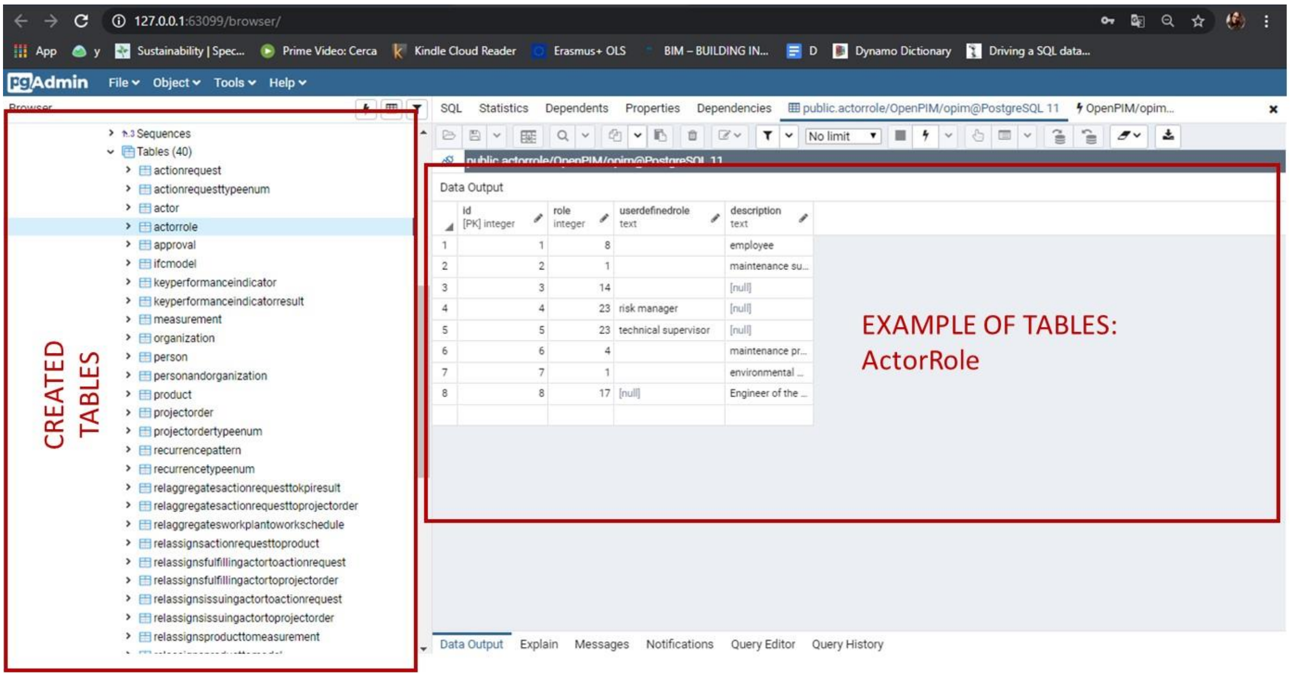



*Figure 57. PgAdmin 4 v4.16 database administrator. In this case the database is not hosted on a local server but can be accessed online.*

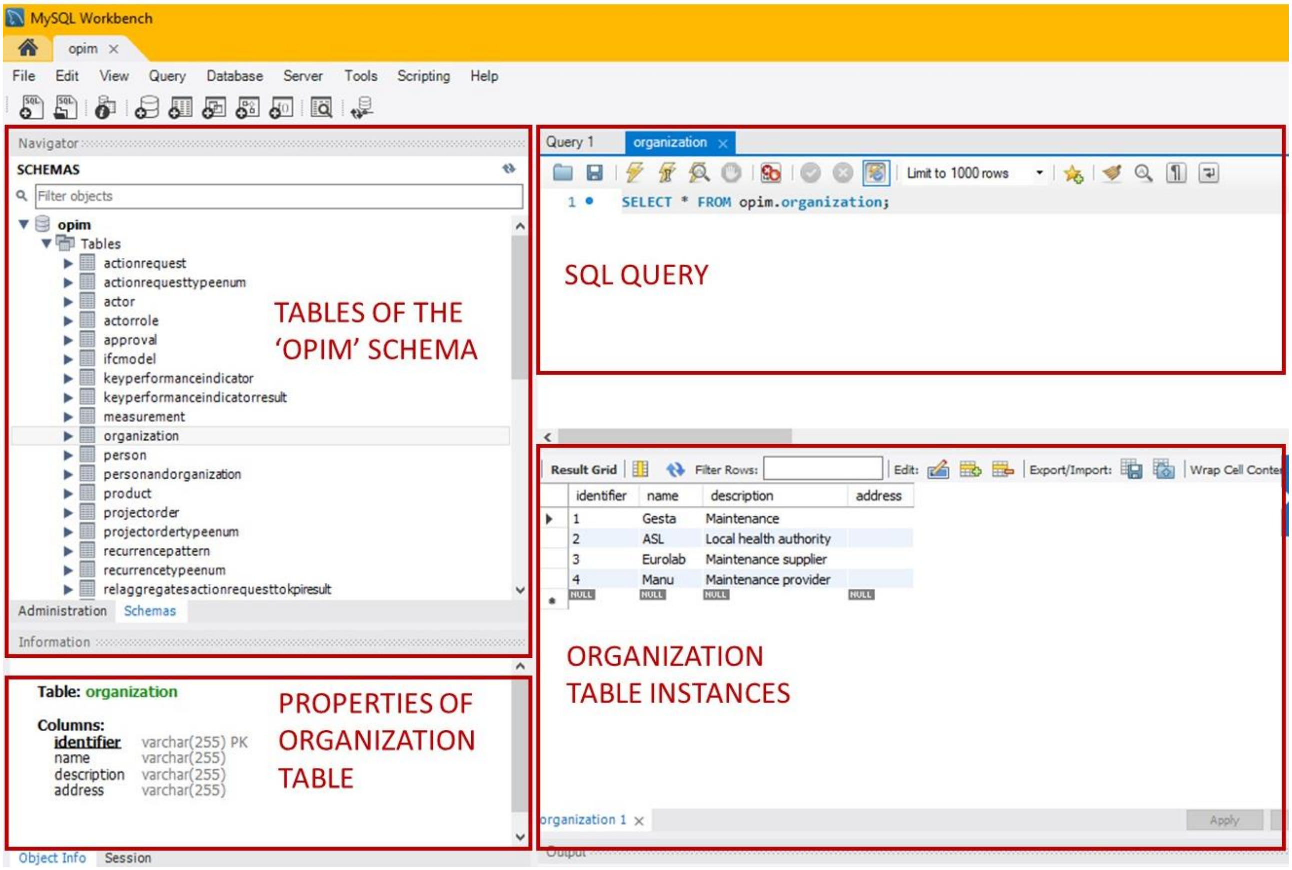



***Figure 58.*** *MySQL Workbench 8.0 database administrator.*

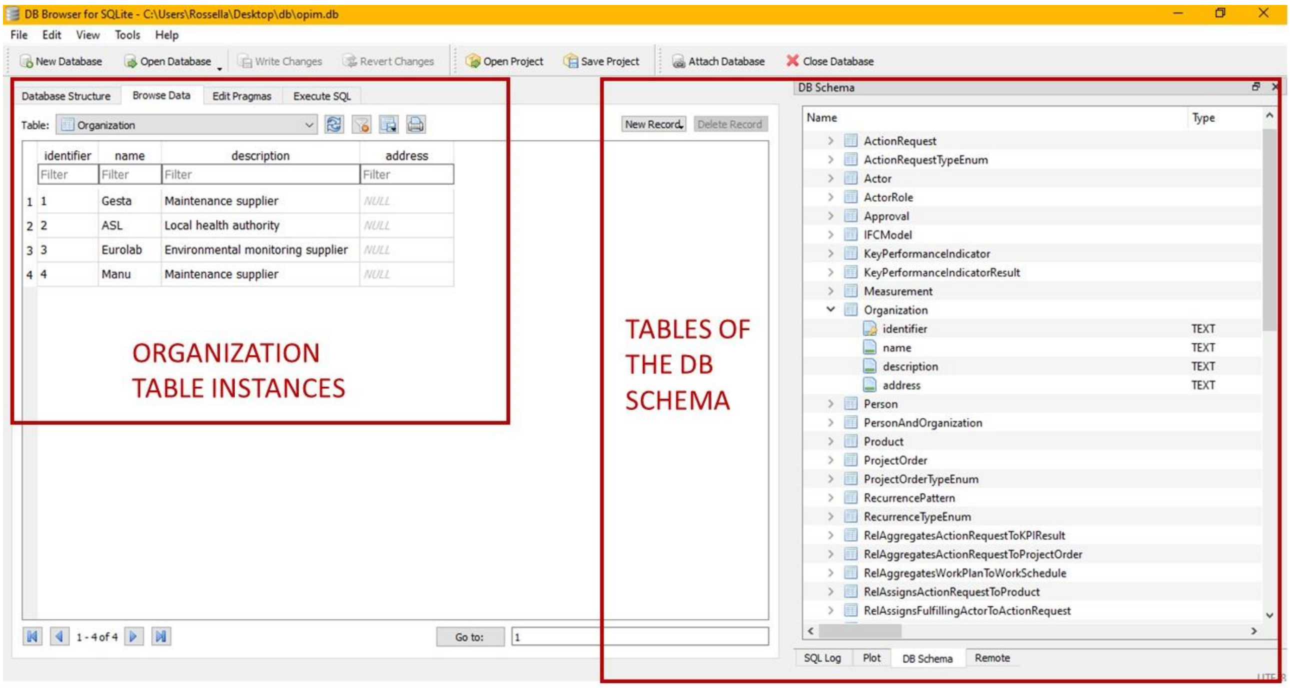



***Figure 59.*** *DB Browser Version 3.11.2 for SQLite database file.*

# 5. Implementation cases

The applicability of the undertaken research methodology has been demonstrated in the hospital buildings field. Databases used in this research protect patient's privacy. They regard only maintenance and monitoring activities and patient-related information were not collected. Analysed data are the outcome of maintenance activities carried out according to the Italian regulation, furthermore analysed processes and environments were not modified for the scope of this study.

This section presents case studies results and the discussion of main findings. The section 5.1 discusses a first attempt of PIM implementation tested on a 'native' BIM model linked to Excel spreadsheets. The application regards one public hospital. The section 5.2 presents openPIMs integrated with a customized database. This application regards three public hospitals, the first case study is the extension of the PIM implementation discussed in section 5.1, the rest has been developed from scratch. In both cases the tool selected to integrate information systems is *Dynamo*. Dynamo is a visual programming environment developed by the Autodesk software house that enables to perform parametric design and automate tasks (Dynamo Studio, 2019). Dynamo extends the building information modelling with the logic environment of a graphical algorithm editor (Explore Dynamo, 2019). Dynamo provides for a canvas as a basic workspace. Here the functions (*nodes*) can be arranged and linked to each other by directed edges (also denoted as *wires*) (Preidel et al., 2017). The different functions are usually offered in a library that can be expanded through several packages (**Figure 60**).

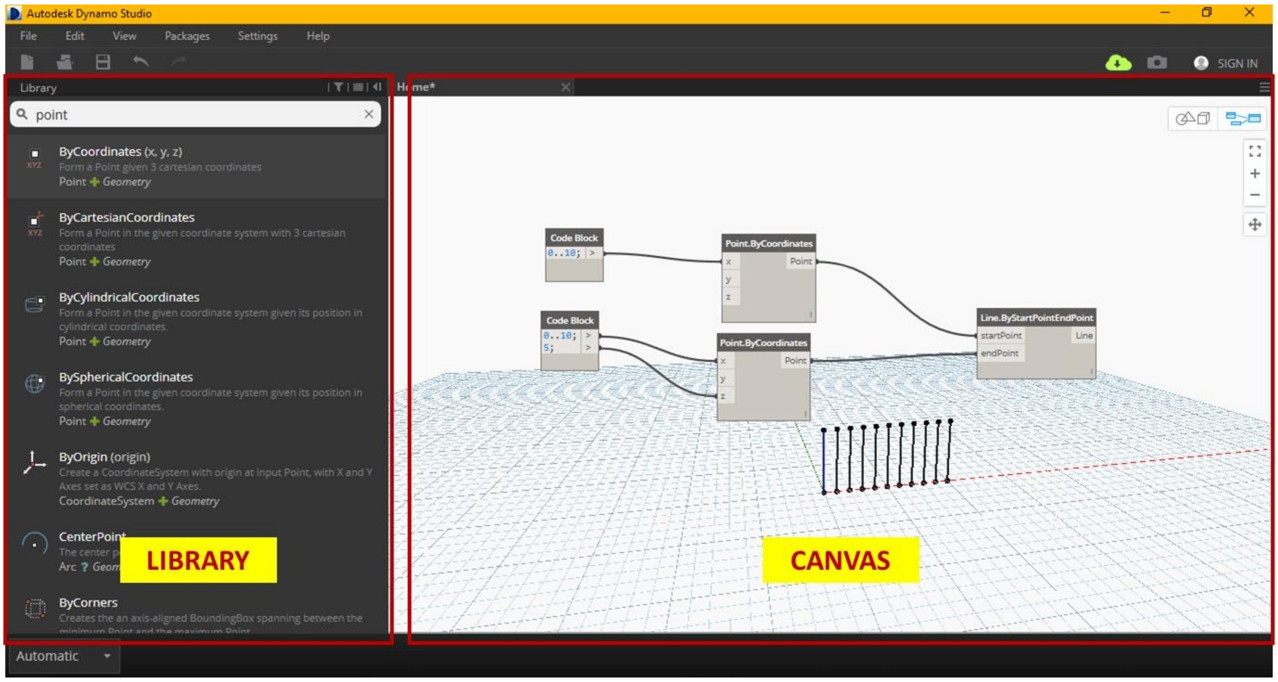



***Figure 60.*** *Typical environment of a Visual Programming Language: library containing nodes and the work-space canvas.*

## 5.1 PIM case study

The methodology presented in the section 3 has been implemented first on a public hospital in the province of Salerno, South of Italy (**Figure 61**). The results have been published in (Marmo et al., 2019a).

The Local Health Authority of Salerno has recently provided new contractors for FM and Prevention and Safety activities for hospitals under its responsibility. No existing BIM models are held by the authority or the FM contractors, and the processes currently in use among them are not BIM-oriented. This is a common situation within the Italian built environment. Therefore, recent laws and regulations regarding the digitalization of the information process in the construction sector require to face the digitalization of existing buildings and related services. In such context this case-study constitutes the first step taken to a BIM-aided FM.

In this case study BIM is used to gather information related to the environmental control, to communicate the monitoring results, and to analyze the condition assessment in terms of maintenance interventions required.

The controls discussed in this study concern the risk management associated with surgery rooms activities. We accessed the database containing the surgery units' environmental controls, which regard air quality. Other factors and engineering devices were not monitored. The methods used to perform those tests respect the Italian regulations and are based on the Italian guidelines regarding the assessment of the efficiency of the preventive measures adopted by the prevention and safety department of healthcare organizations.

The PIM described here has a basic geometric development (a BIM model with LOD 200) but contains specific non-graphical information for facility management. The geometric model was created in Autodesk Revit 2019, starting from 2D CAD plans regarding the architectural and HVAC systems.

The case study is focused on the environmental systems management, so it was enriched by the definition of rooms and related properties (i.e., environmental condition index). The examined hospital has no BAS, but the quality control is performed according to a planned schedule of activities.

The analyzed database regard the monitoring results related to one semester of activities (last semester of 2018 year) carried out in three operating rooms. In this database the results were not grouped by operating room, but they were reported for each type of test separately. They were translated in a summarized Excel sheet to make them easier to read by Dynamo (**Table 19**). The monitoring results were translated to Boolean values to define the failure (1) or the fulfillment (0) of each control in each room.

***Table 19.*** *Monitoring results associated to each surgery rooms presented as Boolean values.*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Orthopedic Surgery Room | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| General Surgery Room | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| Pediatric Surgery Room | 1 | 0 | 0 | 0 | 0 | 0 | 1 |

The input data in Excel sheets (**Figure 62**) can be easily updated when BPA activities are conducted. The data concern all the results enabling to calculate the ECI for each surgery room (i.e., the value of control parameters, their respective weights, and the value of the resulted ECI). Dynamo was used to create bidirectional links between the model and external data, as systems integration tool.

The *Excel.ReadFromFile* node was used to connect the BPA results spreadsheet-based with the model parameters. The 'If' statement was used to check the needs of intervention according to the monitoring activities results. The 'If' statement contains a Boolean statement so that the 'true' condition was associated with the failure of environmental controls. The results of the performance assessment were transposed in the model through the node *Element.SetParameterByName* (**Figure 63**).

The BPA results and maintenance tasks needed are visualized in the model in the form of shared parameters, furthermore it is possible to visualize the performance assessment by thematic drawings.

The **Figure 64** shows the thematic plan of three surgery rooms and the properties associated to them, in terms of ECI, controls (I1, I2, etc.) and interventions required (1.1, 1.2, etc.). In this case, which regards the general surgery room, the controls I1, I4, and I7 are not fulfilled, so the corresponding required interventions are reported in the model (1.1 HEPA filters inspection, 1.2 HVAC pipes inspection; 3.1 Project condition check, 3.2 ATU supplied power control; 7.1 Air-cooled inspection, 7.2 HVAC ducts inspection, 7.3 ATU inspection).


***Figure 61.*** *Location of the case study: building and surrounding.*

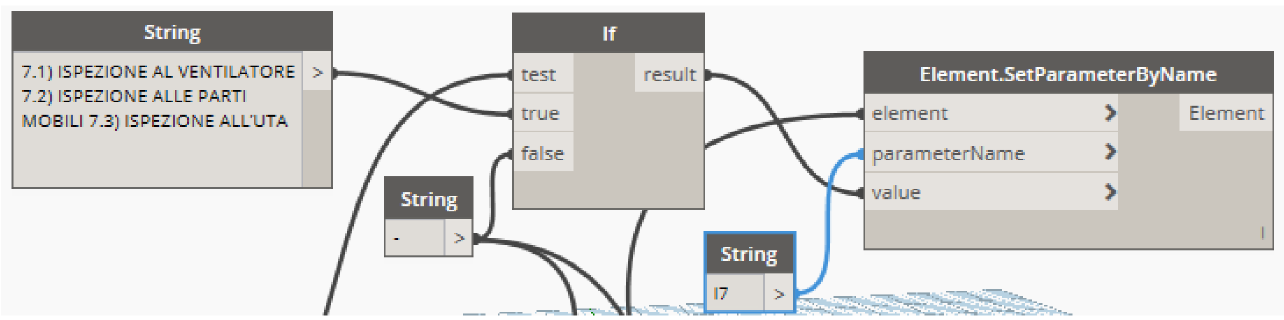



***Figure 62.*** *Conditional logic in Dynamo.*

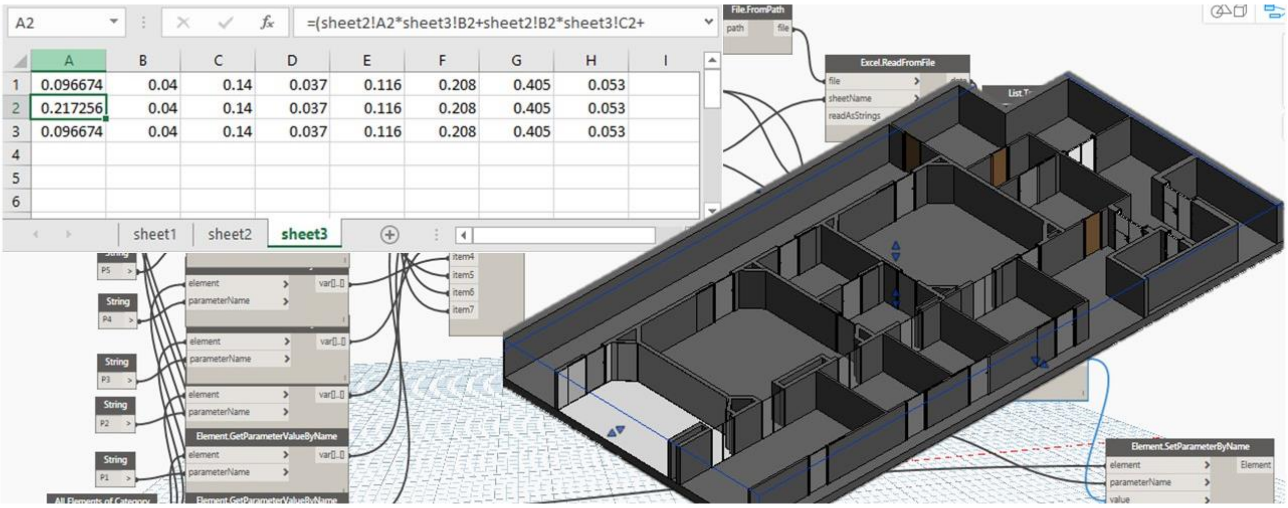



***Figure 63.*** *Excel-Dynamo-Revit links.*

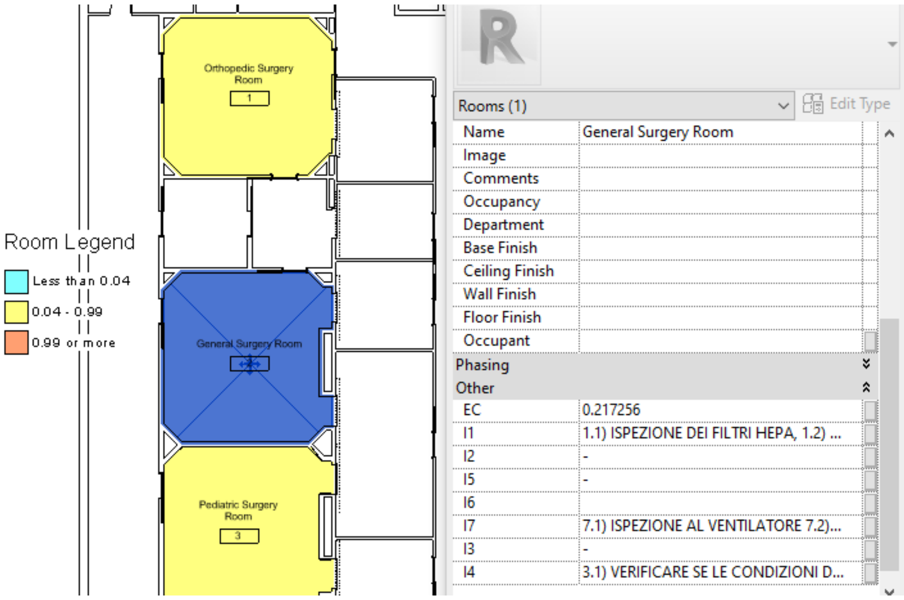



***Figure 64.*** *Thematic plans of orthopedic, pediatric and general surgery rooms. ECIndex and inspections required are reported in the model as rooms properties.*

## 5.2 OpenPIM case studies

The implementation of the openPIM approach presented in the section 4 is discussed here. Three case studies have been developed and they concern:

- One hospital located in the province of Salerno, Italy (case study A);
- One hospital located in Verona, Italy (case study B);
- One hospital located in Ljubljana, Slovenia (case study C).

The openPIM database has been filled with information retrieved from those organisations. In particular the following sources have been considered:

- Tenders' specifications about monitoring activities and O&M management for identifying contractors and managers involved in those processes. In this way the tables *RoleEnum*, *Person*, *Organization*, *PersonAndOrganization*, *ActorRole*, *Actor* were filled;

- Maintenance plans, reports of corrective maintenance activities and project orders records were examined to fill *WorkPlan, WorkPlanTypeEnum, WorkSchedule, WorkScheduleTypeEnum, Task, TaskTimeRecurring*, *TaskTypeEnum*, *ProjectOrder*, *ProjectorderTypeEnum*, *Product* tables;

- Results of environmental condition and evaluation of the Environmental Condition Index were used for *Measurement*, *KeyPerformanceIndicator, KeyPerformanceIndicatorResult* tables.

The implementation of the openPIM regards surgery units. An Environmental Condition Index (ECI) has been used to quantify and evaluate the environmental quality of surgery rooms of A and B case studies. The case study A was used also to validate the openPIM framework related to corrective and preventive maintenance management, while the case study C aimed at testing the openPIM framework for the planned maintenance management. Filling the database implies following its structure. As an example, to define an instance of an actor it is necessary to fill *RoleEnum*, *ActorRole*, *Person*, *Organization*, *PersonAndOrganization* tables first. Each actor instance is identified by a unique id. The **Figure 65** reports the example of the environmental monitoring supplier, to whom the id=6 in the *Actor* table is associated.

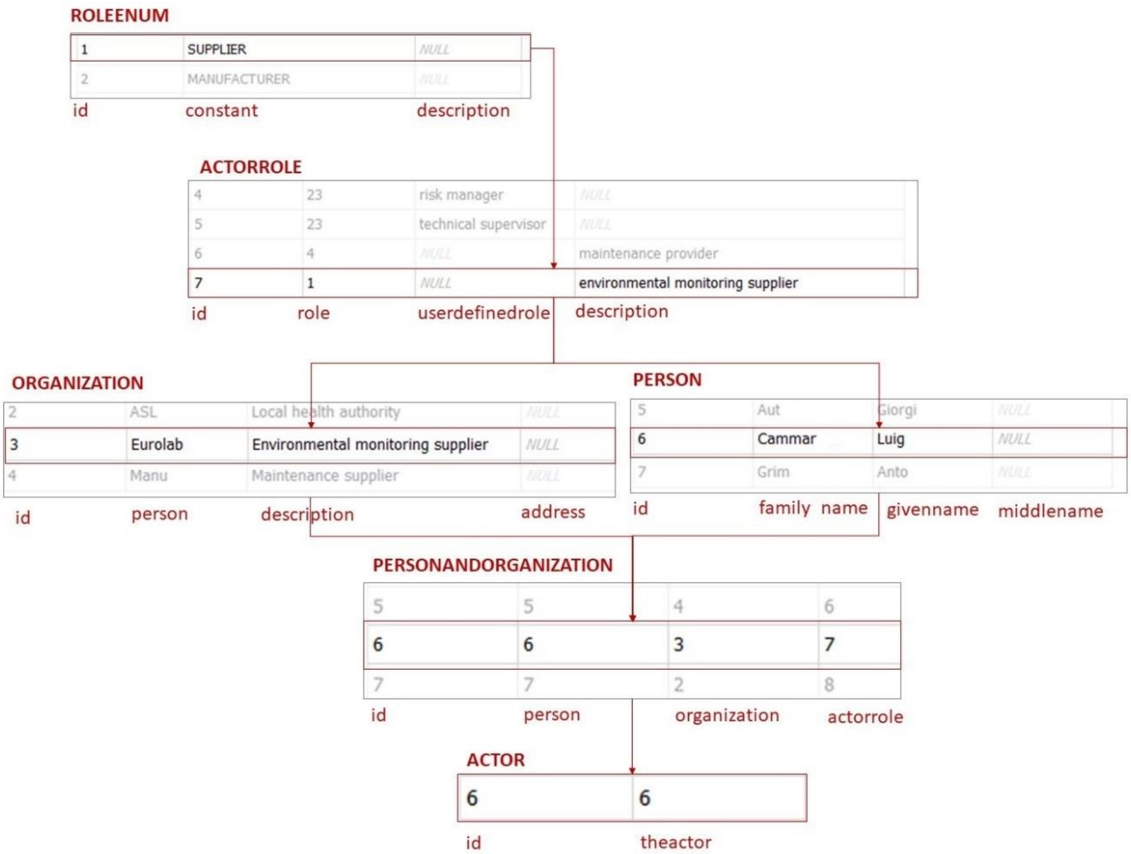



***Figure 65.*** *Example of database filling process.*

Autodesk Revit 2019 was used to create native models. This modelling software allows to export IFC models in different versions, including IFC4 Reference View and IFC4 Design Transfer View. The re-importation of such IFC models in the modelling platform (Revit 2019) was affected by a certain grade of loss of information. For this reason, the IFC 2x3 Coordination View version, correctly and comprehensively exported and re-imported, was chosen to implement the BIM-FM-BPA integration (**Figure 66**). During the exportation the IFC GUID was stored as element parameter, the level of detail for element geometry was settled as low.

After the exportation, the IFC was opened in Revit and managed by Dynamo. In order to establish a connection between the model and the database, the *Slingshot!* Dynamo package was used. It contains a group of nodes for utilizing relational database management system (Slingshot! For Dynamo, 2019). The SQLite engine database was chosen among others (i.e. PostgreSQL and MySQL) as it is commonly used all over the world (What is SQLite, 2019) and above all, it is file-based, so that possible connection issues can be avoided (Issues with Dynamo-MySQL connection, 2019) (**Figure 67**). The database was created and edited in DB Browser for SQLite.

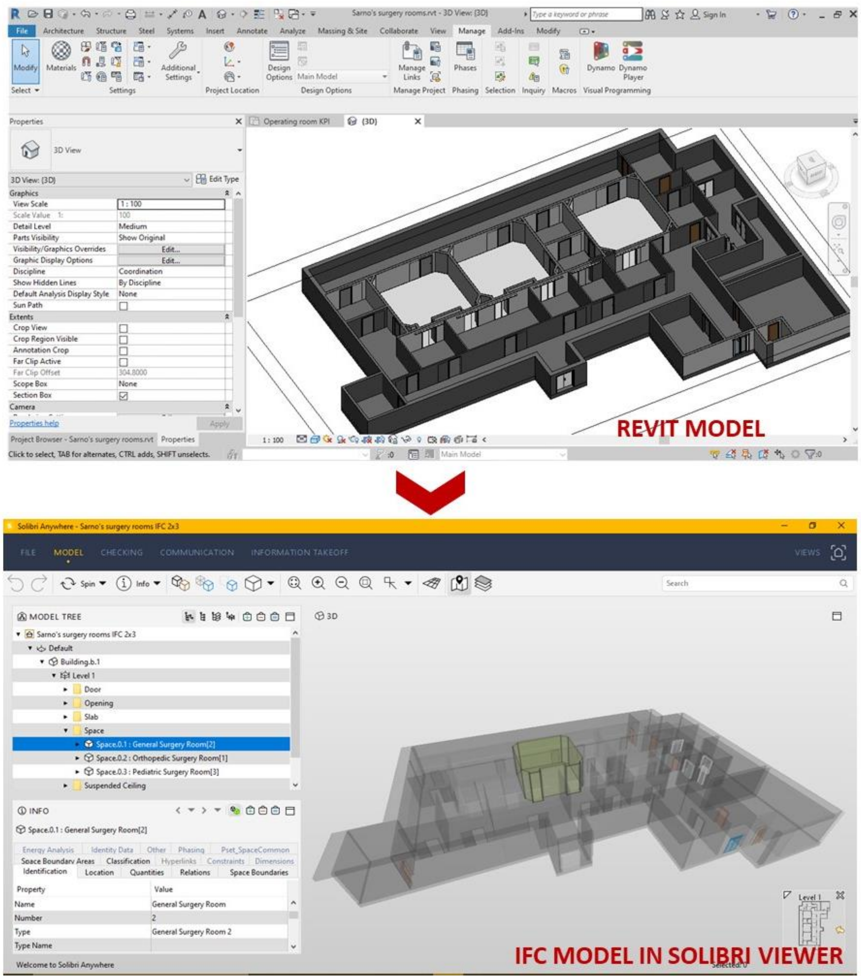



***Figure 66.*** *The BIM model was created using Autodesk Revit 2019. The IFC model has been exported and visualized on Solibri viewer.*


***Figure 67.*** *Integration process between FM systems and BIM model. Revit has been used for creating native models and exporting them in the IFC data format, the relational database integrates the IFC model through a Dynamo application.*

The **case study A** regards the same hospital discussed in the section 5.1, therefore the existing PIM was used. The *SelectModelElement* node has been used to identify id elements directly from the view in use on Revit. This is the starting point for querying the database about further information related to that element. As an example, it is possible to extract the environmental performance assessment results for the general surgery room. Retrieving the *localId* and the associated *globalId* from the element model it is possible to deduct the measurements related to it. These measurements are linked to one or more KPI results through the *RelAssignsToMeasurement* relationship. From the *KeyPerformanceIndicatorResult* table it is possible to retrieve the KPI value and other attributes (interpretation, comment, etc.). Furthermore, the *Element.SetParameterByName* node can be used to update the IFC model with data from the database (**Figure 68**). The results can be also visualised in a thematic plan (**Figure 69**). It must be noticed that user-defined parameters are not exported in IFC model by default. To store customised parameters, such as 'EC' that stands for Environmental Condition Index value, the Revit property set has been exported too.

The same information can be obtained from the DBMS itself (**Figure 70**). An SQL *JOIN* clause can query columns from several tables to obtain combined results. A *JOIN* combines columns from one or more tables by using common values. Some condition can be used to identify the specific required KPI value. As an example, to differ one KPI from another when they are about the same product, the *timestamp* attribute can be used as specifier. The SQL statement used to retrieve the KPI value associated to a determined element *localID* is reported below:

```
SELECT globalId, localID, RelAssignsToMeasurement.relatedMeasurement,
valueNumerical FROM Product

INNER JOIN RelAssignsProductToMeasurement

ON RelAssignsProductToMeasurement.relatingProduct = Product.globalId

INNER JOIN RelAssignsToMeasurement

ON RelAssignsToMeasurement.relatedMeasurement=
RelAssignsProductToMeasurement.relatedMeasurement

INNER JOIN KeyPerformanceIndicatorResult

ON KeyPerformanceIndicatorResult.id =
RelAssignsToMeasurement.relatingResult

WHERE timestamp='2019-03-20 00:00:00' AND localId= '137211'.
```

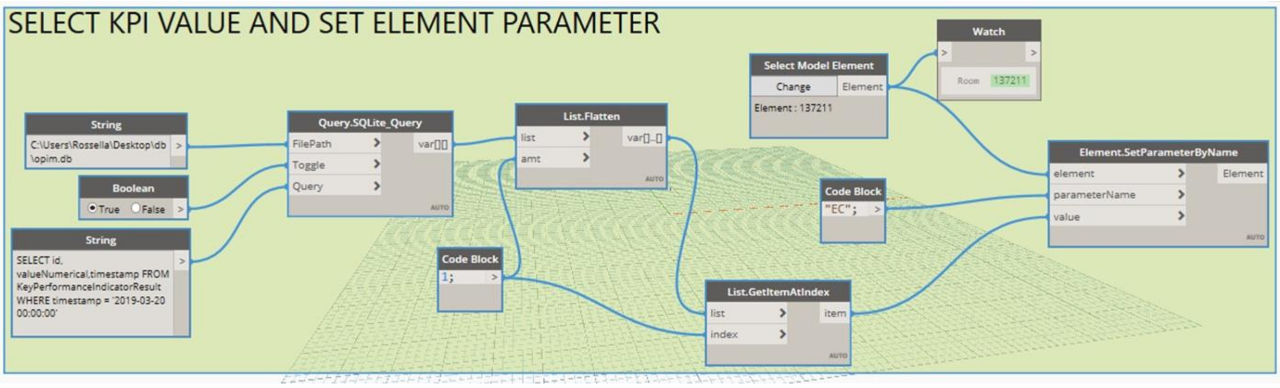



***Figure 68.*** *The picture shows the database query performed on Dynamo and the element parameter setting.*

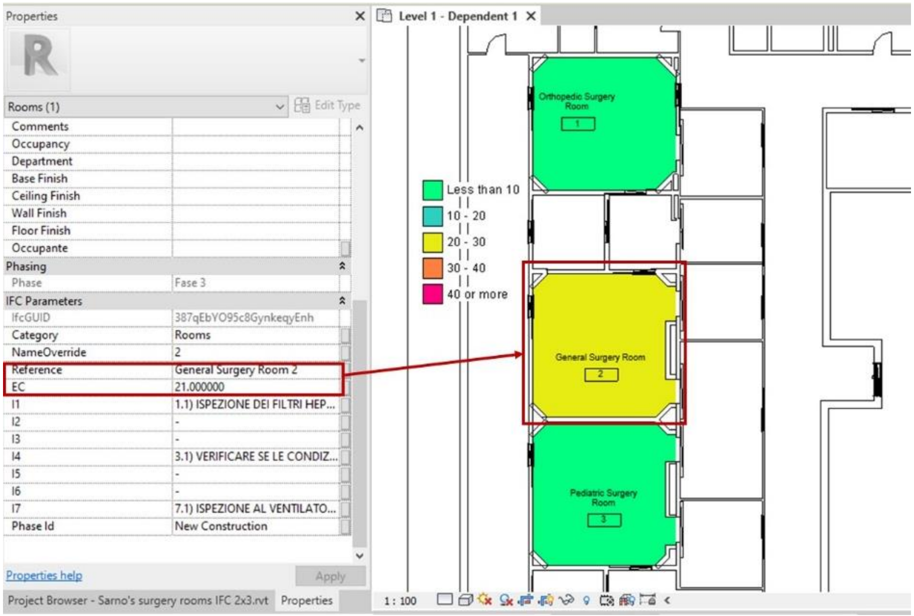



***Figure 69.*** *Thematic plan for surgery rooms. The legend has illustrative purposes. The value 21 stands for 21%.*

```sql
SELECT globalId, localID, RelAssignsToMeasurement.relatedMeasurement, valueNumerical,shortName FROM
INNER JOIN RelAssignsProductToMeasurement
ON RelAssignsProductToMeasurement.relatingProduct = Product.globalId
INNER JOIN RelAssignsToMeasurement
ON RelAssignsToMeasurement.relatedMeasurement= RelAssignsProductToMeasurement.relatedMeasurement
INNER JOIN KeyPerformanceIndicatorResult
ON KeyPerformanceIndicatorResult.id = RelAssignsToMeasurement.relatingResult
INNER JOIN keyPerformanceIndicator
ON keyPerformanceIndicator.id = KeyPerformanceIndicatorResult.keyPerformanceIndicator
```

| | globalId | localId | relatedMeasurement | valueNumerical | shortName |
|---|---|---|---|---|---|
| 1 | 387qEbYO95c8GynkeqyEnh | 137211 | 1 | 0.21 | ECI |
| 2 | 387qEbYO95c8GynkeqyEnh | 137211 | 2 | 0.21 | ECI |
| 3 | 387qEbYO95c8GynkeqyEnh | 137211 | 3 | 0.21 | ECI |
| 4 | 387qEbYO95c8GynkeqyEnh | 137211 | 4 | 0.21 | ECI |
| 5 | 387qEbYO95c8GynkeqyEnh | 137211 | 5 | 0.21 | ECI |
| 6 | 387qEbYO95c8GynkeqyEnh | 137211 | 6 | 0.21 | ECI |

***Figure 70.*** *SQL statement executed in the DBMS for retrieving the KPI value associated to a given object.*

Through the database it is possible to get information about planned or corrective maintenance activities associated to an object, both done or waiting to be performed. For example, from the *ActionRequest* table it is possible to retrieve the request for corrective intervention regarding a door. The *localId* and/or the *globalId* permits to identify univocally the object, the *RelAssignsActionRequestToProduct* relationship gives the request for intervention related to that object, the *ActionRequest* table contains information about such a request. The SQL statement in this case is:

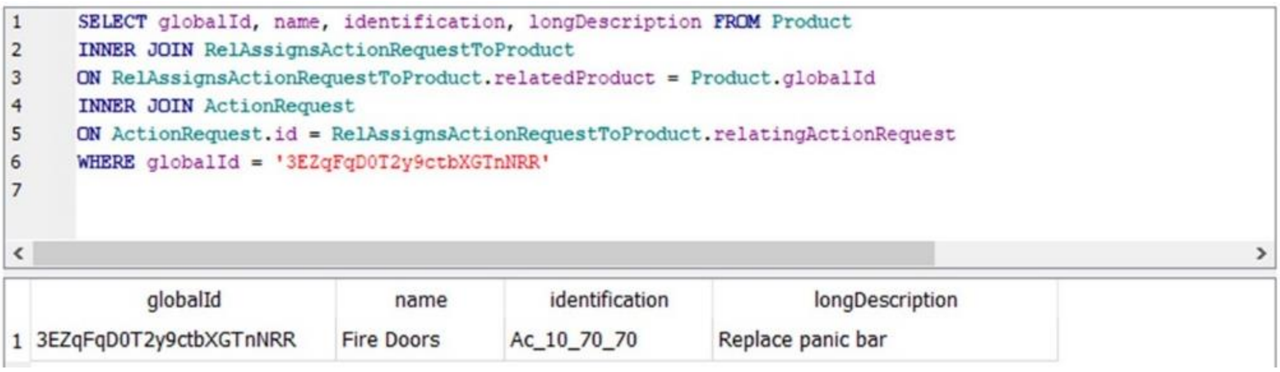
```
SELECT globalId, name, identification, longDescription
FROM Product
INNER JOIN RelAssignsActionRequestToProduct
ON RelAssignsActionRequestToProduct.relatedProduct = Product.globalId
INNER JOIN ActionRequest
ON ActionRequest.id =
RelAssignsActionRequestToProduct.relatingActionRequest
WHERE globalId = '3EZqFqD0T2y9ctbXGTnNRR'
```

The results of this query are showed in the **Figure 71**. The *identification* attribute of the *ActionRequest* table has been defined considering the **Uniclass** classification system. Uniclass is a consistent classification structure for all disciplines in the construction industry. It is based on a set of tables which allow information about a project to be defined from the broadest view to the most detailed view (Uniclass 2015, 2019).

The *Ac* table of the Uniclass system contains a list of activities. The Ac_10_70 code is related to a group of remediation, repair and renovation activities as reported in **Table 20**.

***Table 20.*** *Extract of Uniclass Ac table.*

| | | | | |
|---|---|---|---|---|
| Ac_10_70 | 10 | 70 | | Remediation, repair and renovation |
| Ac_10_70_65 | 10 | 70 | 65 | Remediation |
| Ac_10_70_70 | 10 | 70 | 70 | Renovation |
| Ac_10_70_75 | 10 | 70 | 75 | Repair |



```
SELECT globalId, name, identification, longDescription FROM Product
INNER JOIN RelAssignsActionRequestToProduct
ON RelAssignsActionRequestToProduct.relatedProduct = Product.globalId
INNER JOIN ActionRequest
ON ActionRequest.id = RelAssignsActionRequestToProduct.relatingActionRequest
WHERE globalId = '3EZqFqD0T2y9ctbXGTnNRR'
```

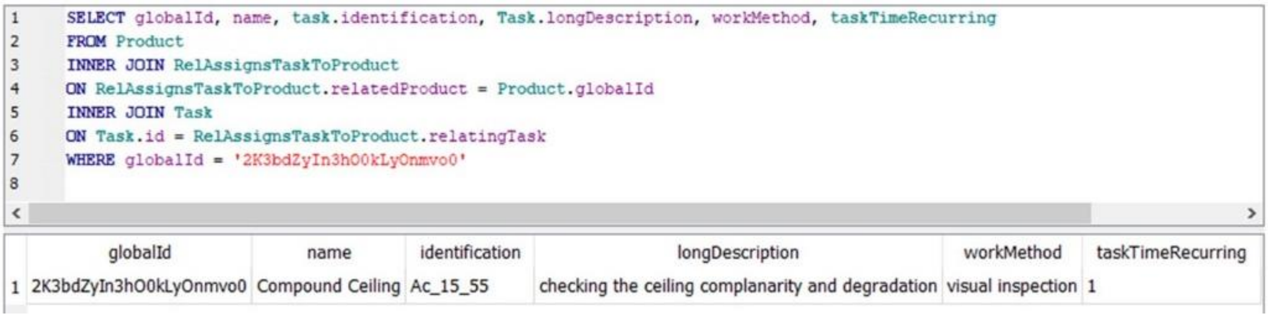
| | globalId | name | identification | longDescription |
|---|---|---|---|---|
| 1 | 3EZqFqD0T2y9ctbXGTnNRR | Fire Doors | Ac_10_70_70 | Replace panic bar |

***Figure 71.*** *SQL statement results viewed in the DBMS. The action request regards replacing the panic bar.*

Finally, it is possible to keep track of planned preventive maintenance activities. The example reported below is related to the visual inspection of the ceiling (**Figure 72**). Such a task is contained in the *Task* table, the *RelAssignsTaskToProduct* relationship link the *Task* table to the *Product* table. Further information about the task, as the frequency and the related work schedule, can be retrieved from other task-related tables. The SQL statement to get product global id, product name, task identification, task work method, task description and task time is:

```
SELECT globalId, name, task.identification, Task.longDescription,
workMethod, taskTimeRecurring
FROM Product
INNER JOIN RelAssignsTaskToProduct
ON RelAssignsTaskToProduct.relatedProduct = Product.globalId
INNER JOIN Task
ON Task.id = RelAssignsTaskToProduct.relatingTask
WHERE globalId = '2K3bdZyIn3hO0kLyOnmvo0'
```

The identification code in this case is Ac_15_55 which stands for 'Performance surveying' according to the Uniclass classification system.



```
SELECT globalId, name, task.identification, Task.longDescription, workMethod, taskTimeRecurring
FROM Product
INNER JOIN RelAssignsTaskToProduct
ON RelAssignsTaskToProduct.relatedProduct = Product.globalId
INNER JOIN Task
ON Task.id = RelAssignsTaskToProduct.relatingTask
WHERE globalId = '2K3bdZyIn3hO0kLyOnmvo0'
```

| | globalId | name | identification | longDescription | workMethod | taskTimeRecurring |
|---|---|---|---|---|---|---|
| 1 | 2K3bdZyIn3hO0kLyOnmvo0 | Compound Ceiling | Ac_15_55 | checking the ceiling complanarity and degradation | visual inspection | 1 |

**Figure 72.** *SQL statement results viewed in the DBMS. The task is about preventive maintenance of ceilings.*

**Case study B** regards a big surgery unit of a Verona's hospital containing 33 operating rooms (**Figure 73**).

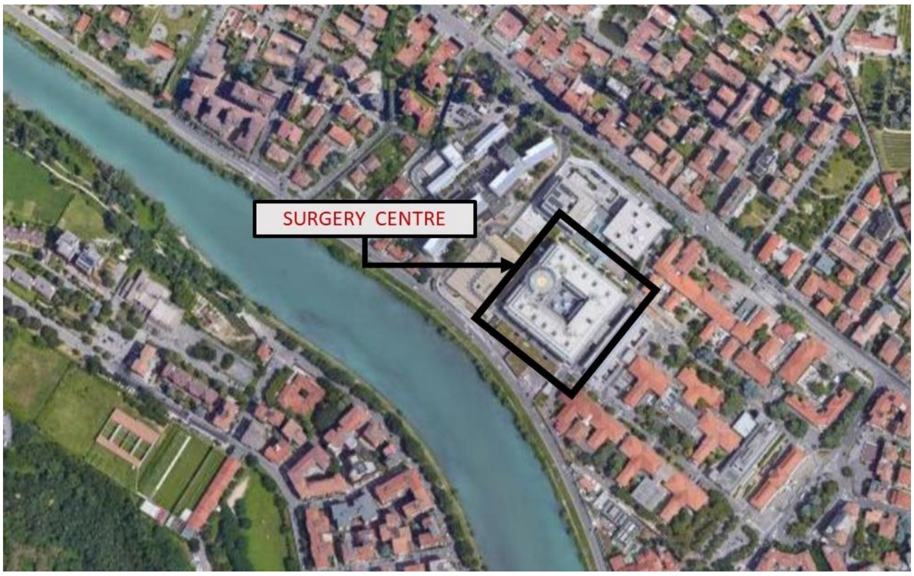



***Figure 73.*** *Case study B area.*

The healthcare facilities management is not BIM-oriented and no BIM models were available. For this reason, the openPIM was modelled from scratch. References for creating the native BIM model were architectural and mechanical plans. The model is used here to gather information regarding environmental controls and to visualise the corresponding results. The healthcare maintenance department provided sources for developing this case study. Collected data consist of anesthetic gases concentration, air particles concentration and microclimatic condition. Other parameters were not analyzed as they are evaluated from time to time according to the requirements of the health and safety department and the healthcare director.

Anesthetic gases concentration and air particles contamination were related to 31 surgery rooms. The microclimatic condition report was available only for 2 rooms out 31. These three quality factors are monitored by sensors which collect data continuously.

Air contamination values were collected each two minutes in 31 different rooms. For each surgery room, the maximum daily value was compared to the threshold limit to check the acceptability of the contamination. The threshold limit is provided by the UNI EN ISO 14644-1: 2016, considered as reference also by the ISPESL guidelines (ISPESL, 2009) to which the Verona's organization refers.

A monthly-based report regarding 31 surgery rooms was used for the analysis of an aesthetic gases concentration, it contained measured values and conformity evaluation in terms of fulfilled or failed controls.

Microclimatic condition were considered to establish the acceptance of temperature and relative humidity values. The temperature data are collected each minute, while the relative humidity is calculated each 15 minutes. The maximum daily value was used to perform the acceptance control. The reference limits are provided by ISPESL guidelines (ISPESL, 2009) and by the DPR 14/01/1997 (President of Italian Republic, 1997).

These data filled and updated the openPIM database. Similarly to the case study A, the measurement results were used to fill the *Measurement* table, calculated KPIs values were inserted in the *KeyPerofrmanceIndicatorsResul*t table and relationships between the aforementioned tables were defined in the *RelAssignsToMeasurement* table.

In this case a Python application was developed and tested to automatically update the IFC model with data from the database. The advantage of using Python consists of creating a unique node for connecting and querying the database. Furthermore, Python nodes support long and complex queries (i.e., 'inner join' statements and clauses) so that the efficiency both of the database and of Dynamo application can be improved. An application for retrieving KPI results associated to a determined product (i.e., cardiac surgery room) has been developed. The application establishes a connection with the database and carries out queries for retrieving the ECI value of an element starting from its localId (**Figure 74**). These results have been used to set ECI parameter values in the IFC model through the Element.SetParameterByName node
Due to the complexity of the BIM model, only the common IFC property set has been exported from the Revit model. Nevertheless, the IFC exportation retrieved the 'EC' parameter as IfcSpace attribute, among the IfcPropertySet of the product. To do so a user defined property set has been defined, as follows:

```
PropertySet:    Environmental Condition Index I    IfcSpace
    ECI    Real    EC
```

Environmental condition results are visualised in a thematic plan through a color scheme as shown in **Figure 75**.

Maintenance plans and corrective maintenance reports were considered to fill the corresponding tables in the openPIM database. As this data are not geometry-related, they cannot be visualized as IFC model attributes unless user-defined attributes are intentionally added. Current IFC viewer applications do not support to store or manage this kind of attributes yet.

Into the IFC file it is possible to locate the fragment which shows an example of the customised IfcPropertySet ‘Environmental Condition Index’ for the use case:

```
#447= IFCSPACE('3mEKxmRXn5YBf4tDclS4iG',#42,'031',$,$,#398,#444,'Day
surgery',.ELEMENT.,.INTERNAL.,$);
#450= IFCSPACETYPE('3rrERpHI50kvrYrU2u60vu',#42,'031',$,$,$,$,'137314',$,.NOTDEFINED.);
#451= IFCPROPERTYSINGLEVALUE('Name',$,IFCLABEL('Day surgery'),$);
#452= IFCPROPERTYSET('0Q7fpz7ib9Z8Cf0YZgDdAl',#42,'Pset_AirSideSystemInformation',$,(#451));
#454= IFCPROPERTYSINGLEVALUE('Name',$,IFCLABEL('Day surgery'),$);
#455= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Rooms'),$);
#456= IFCPROPERTYSET('2RyRNFL9bDB8glpvxIVjk0',#42,'Pset_ProductRequirements',$,(#454,#455));
#458= IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Day surgery 031'),$);
#459= IFCPROPERTYSINGLEVALUE('Category',$,IFCLABEL('Rooms'),$);
#460= IFCPROPERTYSET('2w_jp04SPE6vV6wf7F5hgw',#42,'Pset_SpaceCommon',$,(#458,#459));
#462= IFCPROPERTYSINGLEVALUE('ECI',$,IFCREAL(69.),$);
#463= IFCPROPERTYSET('0I4OvQlk5AegzZ07gFx4CV',#42,'Environmental Condition Index','',(#462));
```


***Figure 74***. *Thematic plan reporting ECIndex for 31 surgery rooms. The values 21.00 and 0.00 stands for 21% and 0%.*

**Case study C** includes an operating unit, located in Ljubljana, concerning five oncological surgery rooms (**Figure 75**).

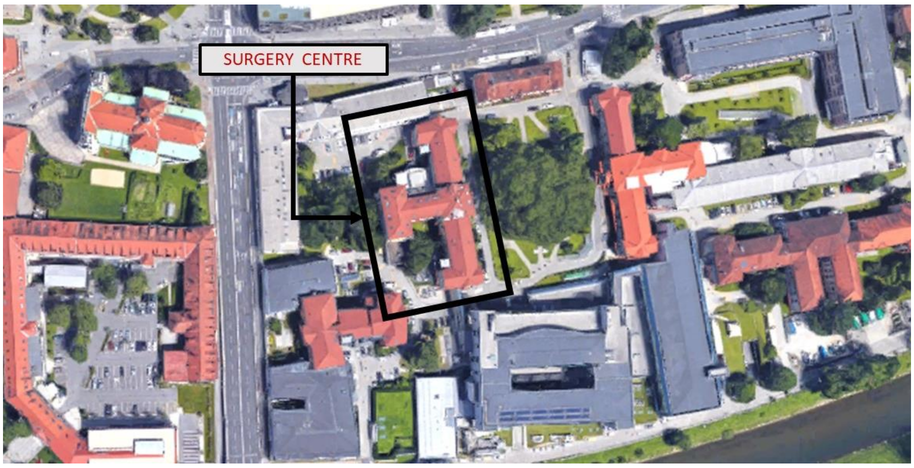



***Figure 75***. *Case study C area.*

It has been developed for testing the openPIM database capability in supporting planned maintenance management. In this case the environmental monitoring report was not available. By the way, the healthcare authority performs monitoring and ordinary maintenance activities of the surgery unit once per year.

The maintenance plan used for developing this pilot implementation contained all checking, reparation and cleaning activities to be performed in the 2019. WorkPlan, WorkSchedule, Task, TaskTimeRecurring, Product and related tables were filled with data retrieved from the maintenance plan.  The identification attribute of the Task table has been defined considering the Uniclass classification system (Uniclass 2015, 2019). Detailed tasks information (time resources, start date, end date, long description, involved elements, etc.) can be gathered from the database.

An IFC model was created based on CAD architectural plans. Starting from the *globalId* of an IFC product it is possible to get planned maintenance information associated with it. The SQL query performed on the DBMS and related results are reported in **Table 21**. As this information is not geometry-related, it cannot be visualized into the IFC model (**Figure 76**).

***Table 21.*** *SQL statement for retrieving data about planned maintenance tasks.*

| SQL query | | | |
|---|---|---|---|
| SELECT globalId, Task.identification, task.longDescription, task.workMethod FROM Product<br>INNER JOIN RelAssignsTaskToProduct<br>ON RelAssignsTaskToProduct.relatedProduct=Product.globalId<br>INNER JOIN Task<br>ON Task.id=RelAssignsTaskToProduct.relatingTask<br>WHERE globalId='23yv66nlP8wA5vCN9xEVBe' | | | |
| Results | | | |
| globalId | identification | longDescription | workMethod |
| 23yv66nlP8wA5vCN9xEVBe | Ac_15_55 | General inspection and reparation of wood and steel furnitures | visual inspection and manual work |

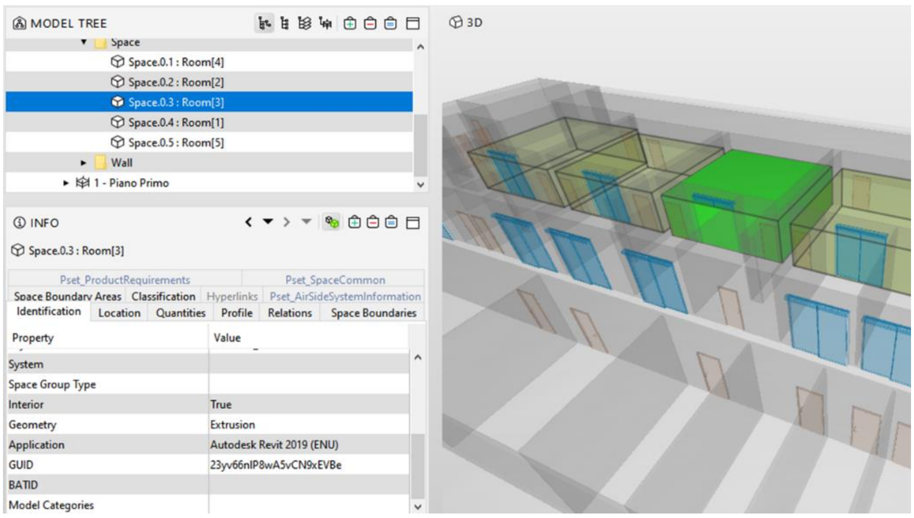



***Figure 76.*** *Case study C, IFC model in Solibri application.*

## 5.3 Analysis and discussion

In this section, a synthesis of findings and their analysis is presented.

The exposed case studies differ in dimensions, collected and analyzed data (**Figure 77**), while they share the methodological approach for the model development which consists of three main steps: (1) analyzing the organization's information requirements; (2) developing the model according to these needs; (3) integrating FM systems and BIM models.

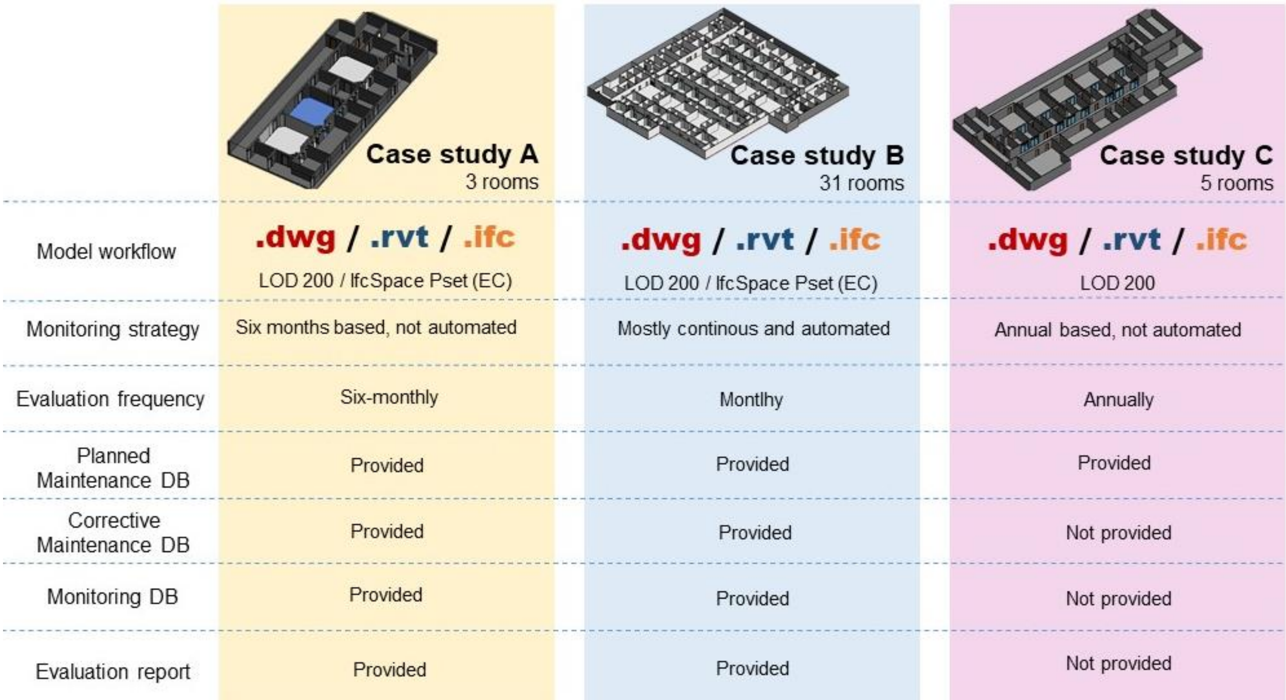



***Figure 77.*** *Case studies comparative analysis.*

The PIM implementation case provides for:

1. Proposing a workflow for PIM implementation based on BPMN model (**Figure 41**);
2. Listing maintenance related information which can inform the BIM model as element properties (**Table 9**);
3. Defining a new KPI for surgery rooms, measuring the environmental and functional performances (Formula (1));
4. Correlating the measured performances to required maintenance intervention in terms of inspections and controls (**Table 17**);
5. Implementing a conditional logic and the information systems integration (**Figure 62, 63**).

The PIM application demonstrates the positive impact that BIM can have on FM and BPA processes. A Performance Information Model facilitates the analysis of building performances and the information exchange process among different stakeholders. **Figure 78** shows the instance of PIM implementation, starting from the already developed model (referring to the **Figure 41**). The requests for intervention and related approvals are omitted in order to simplify the diagram interpretation.

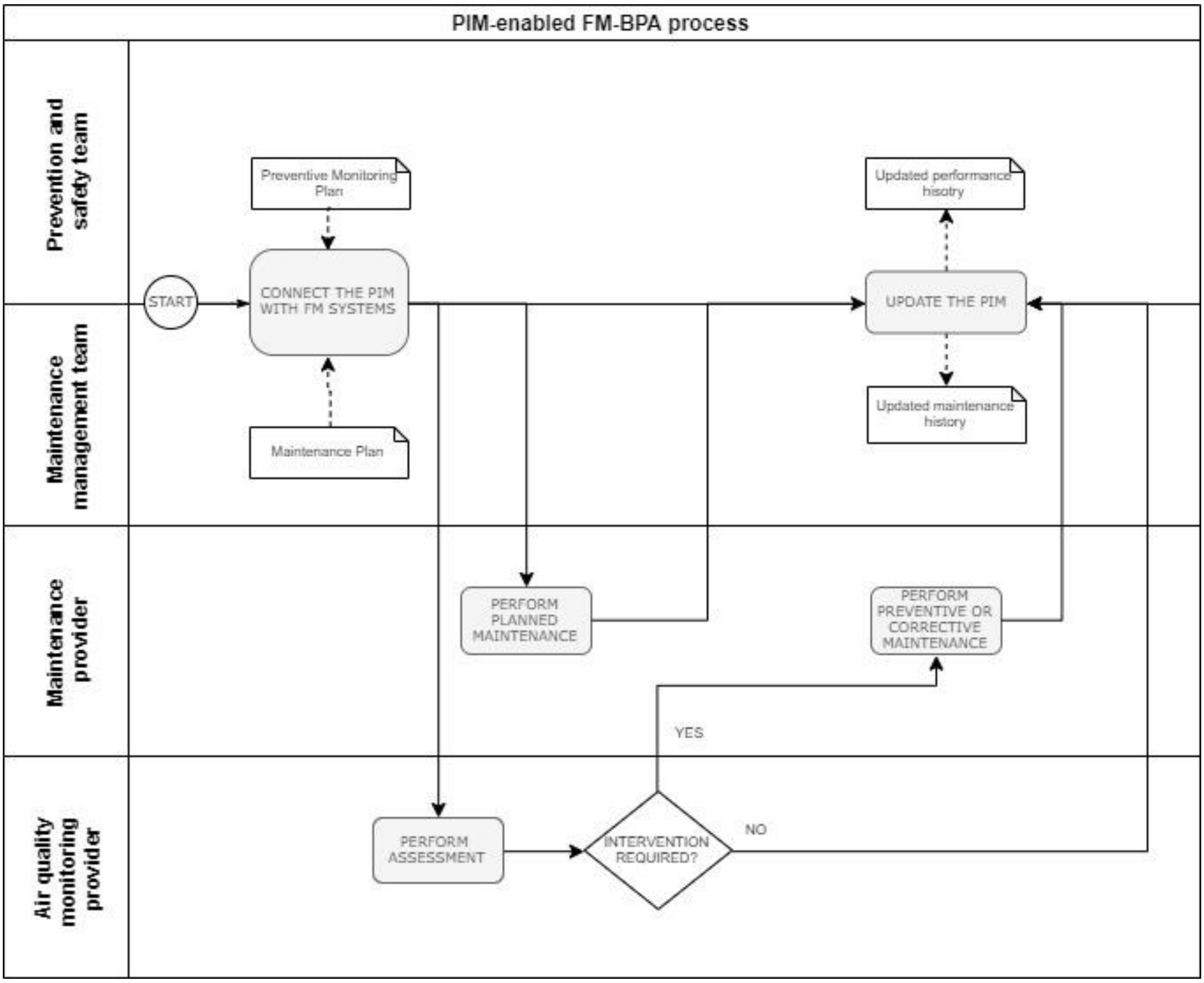



***Figure 78.*** *Instance of the PIM application process (Marmo et al, 2019a).*

The integration of a relational database with a BIM model has been proved and offers great potentialities. It allows users to efficiently store and examine building information for any kind of purposes (e.g. facility management). BIM data are presented in a standardised form, they can be queried and they are easily accessible using SQL statements.

It should be mentioned that other ways to link different data sources exist and their expected benefits are great. Recent research initiatives regard the use of Semantic Web for construction data management within BIM environments. This is a technology enabling data integration and complex searches in multiple sources (Shen and Chua, 2011), providing improvements in information exchange (Aziz et al., 2006, Pauwels et al, 2015). Building data can be understood by machines, improving efficiency and accuracy of information management. As an example, Semantic Web has been applied to facilitate the maintenance management starting from linking a BIM knowledge base and a product manufacturer knowledge base (Niknam et al., 2019).

Nevertheless, an external database allows to (1) connect several users; (2) offer a friendly system to store life cycle data and information; (3) integrate data, so to make comparative analysis.

The openPIM approach can support the management of historical data through maintenance works record, assessment activities record, performance assessment results, information that are rarely captured in BIM models nowadays.

Furthermore, openPIM case studies results prove that:

- The openPIM database is ahead of time because it is based on entities that are not geometry-based (as task, actor, project order, etc.) and are not visible in IFC viewer software currently available;
- Even though many researchers have proposed extension of existing IFC data schema to gather maintenance related information, this thesis proves that the latest IFC 4.2 schema supports BIM workflows in the FM domain in a comprehensive manner. It provides a wide amount of entities to define maintenance and performance assessment processes;
- The proposed openPIM can be referred to as an expansion of the FM handover MVD. It adds entities such as IfcActionRequest, IfcProjectOrders, IfcTask, IfcWorlPlan, IfcWorkSchedule, IfcApproval, IfcKeyPerformanceIndicator, IfcKeyPerformanceIndicatorsResult, IfcMeasurement which support maintenance management, monitoring activities planning and implementation, and performance assessment analysis.

# 6. Conclusion

Current research trends reveal that there is a continuously growing interest in facilities information management using BIM, which offers a good opportunity for integrating various data sources needed for daily O&M activities. Even though such an integration process has promising potential benefits, for example relating performance thresholds to maintenance planning, in very few cases the benchmarking of performance has been tested. Current BIM applications in the operational phase regard mostly the opportunity to release a comprehensive inventory about the asset to be managed. Visualisation is the key benefit. Nevertheless, a seamless information process between BIM and FM systems is hard to obtain. For this purpose, open standard data models improve data mapping and data integration between BIM models and FM systems.

Surveys aiming at developing the common BIM data requirements for O&M are limited and more focused surveys for specific building types and for specific O&M tasks must be conducted.

Literature findings demonstrate that digital models hardly become digital twins of real assets, that is to say these models unlikely are updated during the asset lifecycle.

Within this context, this thesis argued for developing a methodological approach to integrate BIM, BPA and FM systems, supporting organisational, environmental and technical requirements achievement during the asset lifecycle. To do so a novel Performance Information Model is presented. It is meant to be a decision-making support tool, based on the use of KPIs as relevant summarized knowledge vehicles which keep the model beneficial to FM and maintenance scopes.

The thesis, focused on the healthcare sector, contributes to the body of knowledge by outlining benefits and challenges encountered using BIM for the assets operational phase; identifying a set of measurable control parameters and a novel Key Performance Indicators for the environmental quality assessment of operating units; proposing an efficient and original approach for achieving the FM-BPA-BIM systems integration though a novel Performance Information Model.

A standardized tool to keep track of FM information has been designed, in form of relational database. A framework for BIM-FM-BPA integration has been developed and implemented. Three international case studies tested and validated the openPIM framework for managing corrective maintenance, for performance assessment purposes, and for planned maintenance management.

The openPIM framework allows the creation of a client-oriented model which will be kept more likely updated. Stakeholders' information requirements lead the model and related database design; an IFC model is created according to this set of information; many applications and technologies (through visual programming language, python programming language, structured query language, semantic web, etc.) can be developed to integrate sources of data. The openPIM directly supports performances reports, and, as a consequence, several analyses (as financial, technical, environmental, sustainability, etc.) which can target future interventions.

The research is currently limited to a specific application field. This means that the Environmental Condition Index here presented is suitable for operating units but it will not fit requirements of other facilities. On one hand, the list of environmental control parameters and their criticality weights are specific for operating units. On the other hand, the focus on the environmental system management required the development of model enriched only by environmental-related attributes and elements (i.e., user-defined parameters for IfcSpace elements). Neverthless, the openPIM database demonstrated its value in supporting maintenance and monitoring activities management on a more general level.

It is evident that different application areas might lead to Performance Information Models focused on other systems which will address other information requirements.

Following the methodological approach here used (analysis of organization's information requirements; development of Performance Information Models; integration of sources useful for the operational phase), new case studies will require the identification and/or the definition of new KPIs and related measurable control parameters and they will result into new asset information requirements, that is to say different PIMs. Those case studies will implement the openPIM database in a way that its structure will be respected but the measurements and related KPI results will differ for scopes.

Further researches serve to test on more comprehensive as-built models the PIM and openPIM applicability and related benefits. Technical and financial aspect of facilities management must be considered to obtain a fully integrated Performance Information Model supporting FM ad BPA activities. A comprehensive Performance Information Model has at least the following application benefits:

1. Improved performances assessment;
2. Integrated and updated visualization of the operating condition of building and its elements;
3. Inventory management of building components, spaces, furniture and documents;
4. Automation of the quantity take-off;
5. Supported maintenance history management;
6. Supported scheduling of future maintenance interventions;
7. Integrated sources of knowledge.

In the domain of condition-based, preventive or predictive maintenance, complex analysis (affordability, sustainability, obsolescence, actual service life, etc.) should be performed through PIM development. These analyses will involve not only the element scale, but also technological and environmental systems and at the end, the building itself. The use of KPIs (financial, technical, organisational) will address different scales of decision making and will enable benchmarking activities.

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# List of tables

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# List of acronyms

| | |
|---|---|
| AEC | Architecture, Engineering and Construction |
| AHP | Analytical Hierarchy Process |
| BAS | Building Automation Systems |
| BEMS | Building Energy Management Systems |
| BIM | Building Information Modeling |
| BPA | Building Performance Assessment |
| BPE | Building Performance Evaluation |
| BPMN | Business Process Modelling Notation |
| BREEAM | Building Research Establishment Environmental Assessment Method |
| CAD | Computer-Aided Design |
| CAFM | Computer Aided Facility Management |
| CDE | Common Data Environment |
| CMMS | Computerized Maintenance Management System |
| COBie | Construction Operations Building Information Exchange |
| CSFs | Critical Success Factors |
| DDL | Data Definition language |
| DML | Data Manipulation Language |
| DMS | Document Management System |
| ECI | Environmental Condition Index |
| ER model | Entity-Relationship model |
| FM | Facility Management |
| HSE | Health and Safety Environment |
| ICT | Information Communication Technologies |
| IFC | Industry Foundation Classes |
| KPI | Key Performance Indicator |

| | |
|---|---|
| LEED | Leadership in Energy and Environmental Design |
| LOD | Level Of Development |
| LOG | Level of Geometry |
| LOI | Level of Information |
| MVD | Model View Definition |
| O&M | Operation and Maintenance |
| PDCA | Plan-Do-Check-Act |
| PIM | Performance Information Model |
| POE | Post Occupancy Evaluation |
| SLA | Service Level Agreement |
| SQL | Structured Query Language |
| VPL | Visual Programming Language |

# List of annexes

**Annex 1.** Delphi questionnaire.

UNIVERSITÀ DEGLI STUDI DI NAPOLI 'FEDERICO II'

## QUESTIONARIO

Il presente questionario si inserisce in una tesi di dottorato svolta presso l'Università degli Studi di Napoli 'Federico II' riguardante la gestione della manutenzione. Con il presente questionario si vogliono definire i pesi dei parametri misurabili caratterizzanti la qualità ambientale di un blocco operatorio, al fine di migliorare il controllo delle prestazioni ambientali e la priorizzazione degli interventi manutentivi.

Il parere di un esperto rappresenta un contributo prezioso alla ricerca, la preghiamo dunque di rispondere ai quesiti ivi presenti.

Informazioni aggiuntive:

LA COMPILAZIONE DEL QUESTIONARIO È ANONIMA.

Gli intervistati formano un **panel di esperti**, l'analisi dei giudizi da loro espressi è gestita da un 'amministratore' che curerà il corretto svolgimento dell'indagine.

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**INTRODUZIONE**

Obiettivi specifici del questionario:
- determinazione dei pesi da attribuire ai parametri di controllo ambientale (ad esempio *ricambi d'aria, contaminazione particellare* etc.) nel blocco operatorio di una struttura sanitaria,
- determinazione dei pesi delle sub-aree funzionali (ad esempio *sub-area operatoria*) ai fini del corretto funzionamento del blocco operatorio.

Il questionario è impostato in maniera da richiedere un giudizio fondato sul confronto diretto tra parametri e tra sub-aree funzionali individuati preliminarmente.

Il presente documento è diviso in due sezioni:

- Sezione preliminare, comprende il glossario dei termini ricorrenti e la scomposizione gerarchica del sistema ambientale di una struttura ospedaliera
- Il questionario vero e proprio, suddiviso in quattro parti riguardanti rispettivamente i dati generali dell'intervistato, i confronti tra parametri ambientali, i confronti tra elementi del sistema ambientale, il giudizio sul grado di confidenza del parere fornito.

## SEZIONE PRELIMINARE

- **GLOSSARIO:**

**Sistema ambientale dell'organismo edilizio**: insieme strutturato delle unità ambientali e degli elementi spaziali definiti nelle loro prestazioni e nelle loro relazioni
**Qualità ambientale:** insieme delle prestazioni ambientali degli elementi spaziali di un organismo edilizio
**Prestazione ambientale**: prestazione di un elemento spaziale relativa a un requisito ambientale
**Requisito ambientale**: traduzione di un'esigenza in fattori fisico-ambientali e in richieste di servizi tecnologici atti a individuarne le condizioni di soddisfacimento da parte di un'unità ambientale
**Elemento spaziale:** porzione di spazio destinata allo svolgimento delle attività di un'unità ambientale
**Settore funzionale:** insieme di aree funzionali caratterizzate da elementi di omogeneità relativamente alle funzioni complesse che esse stesse rappresentano, finalizzato a definire il raggruppamento di specifiche macro-funzioni articolate (es. il settore Diagnosi e Terapia in cui sono raggruppati il blocco operatorio, il pronto soccorso etc.)
**Area funzionale:** insieme delle unità ambientali necessarie, tra loro relazionate, per lo svolgimento di una funzione complessa, generata da diverse attività elementari che concorrono a garantire la funzionalità complessiva e autonoma (es. il blocco operatorio, il pronto soccorso etc.)
**Unità ambientale:** insieme delle attività omogenee, compatibili tra loro, al fine di definire uno spazio fruibile per lo *svolgimento di tali attività (es. sala operatoria).*

- **SCOMPOSIZIONE GERARCHICA DEL SISTEMA AMBIENTALE DI UNA STRUTTURA OSPEDALIERA**

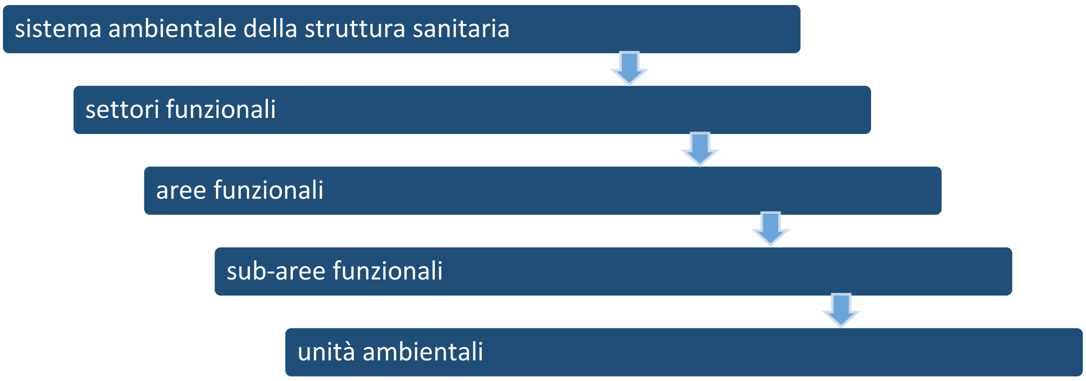


*Figura 1. Una struttura ospedaliera si intende formata da: settori funzionali (ad esempio il settore di diagnosi e cura), aree funzionali (ad esempio il blocco operatorio), sub-aree funzionali (ad esempio l'area operatoria), unità ambientali (ad esempio la sala operatoria).*

*Tabella 2. Rappresentazione tabellare della scomposizione gerarchica del sistema ambientale di una struttura ospedaliera.*

| Settori funzionali | Aree funzionali | Sub-aree funzionali | Unità Ambientali |
|---|---|---|---|
| **Degenza** | Riabilitazione | | |
| | Day Hospital | | |
| | Degenza ordinaria | | |
| | Degenza specialistica | | |
| | Degenza intensiva/subintensiva | | |
| **Diagnosi e cura** | Emergenza | | |
| | Rianimazione | | |
| | Poliambulatorio | | |
| | Esami funzionali ed endoscopici | | |
| | Diagnostica per immagini | | |
| | Ricerca anatomo patologica | | |
| | Laboratorio | | |
| | Riabilitazione | | |
| | Radioterapia | | |
| | Dialisi | | |
| | Day Hospital | | |
| | **Blocco operatorio** | Sub-area accoglienza | ---- |
| | | **Sub-area operatoria** | Corridoi puliti |
| | | | Corridoi sporchi |
| | | | **Sale operatorie** |
| | | | Spogliatoi |
| | | | Preparazione e risveglio pazienti |
| | | | Zone Filtro |
| | | | Substerilizzazione |
| | | | Vuotatoio sala operatoria |
| | | Sub-area servizi personale | Stanza personale |
| | | | Riposo personale |
| | | | Sevizi igienici personale |
| | | Sub-area supporto | Deposito sporco |
| | | | Deposito pulito |
| | | | Deposito materiale sterile |
| | Sterilizzazione | | |
| | Blocco parto | | |
| | Emoteca | | |
| | Centro transfusionale | | |
| | Farmacia | | |
| **Servizi generali** | Dispensa | | |
| | Mensa | | |
| | Distribuzione | | |
| | Lavanderia | | |
| | Polizia | | |
| | Manutenzione | | |
| | Magazzini | | |
| | Impianti tecnologici | | |
| | Spogliatoio | | |
| | Morgue | | |
| **Management** | Direzione sanitaria | | |
| | Uffici amministrativi | | |
| | Accettazione | | |
| | Sistema informativo sanitario | | |
| | Ufficio studi e ricerche | | |

- **ELENCO DEI PARAMETRI MISURABILI PER IL CONTROLLO DELLE PRESTAZIONI AMBIENTALI DI UNA DT 2.2.3 SALA OPERATORIA**

Elenco (A):

1) Contaminazione particellare e microbiologica at rest
2) Contaminazione particellare e microbiologica in operational
3) Caratteristiche microclimatiche at rest
4) Caratteristiche microclimatiche in operational
5) Volumi d’aria immessi/ Ricambi d’aria/ Recovery time
6) Inquinamento da agenti anestetici
7) Rumore

**QUESTIONARIO**

- **Dati generali dell'intervistato:**

1) Titolo di studio (ad esempio 'Laurea in Medicina e Chirurgia'):

……………………………………………………………………………………………………………………………………………………………

2) Organizzazione Aziendale di appartenenza (ad esempio 'ASL Salerno'):

……………………………………………………………………………………………………………………………………………………………

3) Struttura di appartenenza (ad esempio 'Servizio di Prevenzione e Protezione'):

……………………………………………………………………………………………………………………………………………………………

4) Ruolo professionale svolto nella struttura di appartenenza (ad esempio 'Responsabile del Servizio di Prevenzione e Protezione'):

……………………………………………………………………………………………………………………………………………………………

- **Confronto tra <u>parametri</u> per l'unità ambientale '<u>DT 2.2.3 SALA OPERATORIA</u>'**

Si chiede di esprimere un giudizio relativo al confronto tra parametri misurabili riguardanti le condizioni ambientali di una sala operatoria. Il giudizio richiesto concerne il peso che ciascun parametro ha al momento della valutazione della qualità ambientale della sala operatoria.

Il giudizio deve essere espresso tramite la scala di valutazione di Saaty, di seguito descritta:

*Tabella 1. La scala di valutazione di Saaty*

| Valore $a_{ij}$ | Interpretazione |
|---|---|
| 1/9 | i è **assolutamente meno importante** di j |
| 1/7 | i è **molto meno importante** di j |
| 1/5 | i è **meno importante** di j |
| 1/3 | i è **leggermente meno importante** di j |
| 1 | i e j sono **equamente importanti** |
| 3 | i è **leggermente più importante** di j |
| 5 | i è **più importante** di j |
| 7 | i è **molto più importante** di j |
| 9 | i è **assolutamente più importante** di j |

I parametri da confrontare sono stati organizzati in righe e colonne, in modo da formare *una matrice dei confronti a coppie*.

Una matrice siffatta è <u>reciproca</u>, ovvero gli elementi presenti sulla diagonale principale sono tutti unitari:

$$a_{ii} = 1 \text{ per ogni i}$$

e vale che:

$$a_{ij} = \frac{1}{a_{ji}} \text{ per ogni i, j}$$

Il valore presente in ogni singola cella rappresenta l'importanza che il parametro della riga i-esima ha rispetto al parametro della colonna j-esima. Vanno riempite solo le celle che appaiono bianche e vuote.

Di seguito si riporta un esempio che possa facilitare la compilazione della matrice.

**Esempio**

| Esempio di confronto tra PARAMETRI MISURABILI che determinano la QUALITA' AMBIENTALE di un SOGGIORNO in una RESIDENZA PRIVATA | | | | | |
|---|---|---|---|---|---|
| | Grado di illuminamento | Rumore | Temperatura | Umidità | Ricambi d'aria |
| Grado di illuminamento | **1** | | | | |
| Rumore | **1/3** | **1** | | | |
| Temperatura | ... | ... | **1** | | |
| Umidità | ... | ... | **3** | **1** | |
| Ricambi d'aria | ... | ... | ... | ... | **1** |

Nella valutazione della qualità ambientale di un soggiorno in una residenza privata si ritiene che il parametro ***rumore* sia leggermente meno importante** del parametro ***grado di illuminamento*.** Allo stesso modo risulta che il parametro ***umidità* sia leggermente più importante** del parametro ***temperatura*** ai fini della qualità ambientale del soggiorno.

Allo stesso modo **si chiede di esprimere il proprio giudizio comparativo tra i seguenti parametri misurabili che determinano la qualità ambientale di una 'DT 2.2.3 SALA OPERATORIA'**. I parametri da confrontare corrispondo a quelli dell'elenco (A) presente a pag. 5 e riproposto di seguito:

1) Contaminazione particellare e microbiologica at rest
2) Contaminazione particellare e microbiologica in operational
3) Caratteristiche microclimatiche at rest
4) Caratteristiche microclimatiche in operational
5) Volumi d'aria immessi/ Ricambi d'aria/ Recovery time
6) Inquinamento da agenti anestetici
7) Rumore

| MATRICE DEI CONFRONTI A COPPIE TRA PARAMETRI AMBIENTALI MISURABILI IN UNA SALA OPERATORIA | | | | | | | |
|---|---|---|---|---|---|---|---|
| | (1) Contaminazione at rest | (2) Contaminazione in operational | (3) Microclima at rest | (4) Microclima in operational | (5) Volumi e Ricambi d'aria/Recovery time | (6) Inquinamento da gas anestetici | (7) Rumore |
| (1) Contaminazione at rest | **1** | | | | | | |
| (2) Contaminazione in operational | | **1** | | | | | |
| (3) Microclima at rest | | | **1** | | | | |
| (4) Microclima in operational | | | | **1** | | | |
| (5) Volumi e Ricambi d'aria/Recovery time | | | | | **1** | | |
| (6) Inquinamento da gas anestetici | | | | | | **1** | |
| (7) Rumore | | | | | | | **1** |

- **Confronto tra <u>sub-aree funzionali</u> nell'area funzionale ' <u>DT2 BLOCCO OPERATORIO</u>'**

Si chiede di esprimere un giudizio relativo al confronto tra sub-aree funzionali che formano un blocco operatorio.

Il giudizio richiesto riguarda il peso che ciascuna sub-area funzionale ha al momento di valutare le prestazioni ambientali di un blocco operatorio, per poter priorizzare gli interventi manutentivi.

Anche in questo caso il giudizio espresso si basa sulla scala di valutazione di Saaty.

Si chiede di compilare la matrice dei confronti a coppie tenendo presente le indicazioni di compilazione già date precedentemente.

Di seguito si riporta un esempio che possa facilitare la compilazione della matrice.

**Esempio**

Esempio di confronto tra AMBIENTI DI UNA RESIDENZA PRIVATA in base al peso che esse hanno nella determinazione delle prestazioni della residenza stessa.

| | Cucina | Bagno | Soggiorno | Camera da letto | Corridoio |
|---|---|---|---|---|---|
| Cucina | **1** | | | | |
| Bagno | **1** | **1** | | | |
| Soggiorno | … | … | **1** | | |
| Camera da letto | … | … | … | **1** | |
| Corridoio | … | … | **1/7** | … | **1** |

Nella valutazione delle prestazioni ambientali di una residenza privata si ritiene che l'ambiente ***bagno* sia equamente importante** rispetto alla ***cucina*.** Allo stesso modo risulta che l'ambiente ***corridoio* sia molto meno importante** rispetto all'ambiente ***soggiorno***.

Allo stesso modo si chiede di esprimere il proprio giudizio comparativo tra le seguenti sub-aree funzionali che compongono un BLOCCO OPERATORIO. Le aree da confrontare corrispondo a quelle dell'elenco (B) presente a pag. 5 e riportato di seguito:

1) **DT 2.1 Sub-area accoglienza/orientamento.**
2) **DT 2.2 Sub-area interventistico/operatoria**. Elenco delle Unità Ambientali:
   - DT 2.2.1 CORRIDOI PULITI
   - DT 2.2.2 CORRIDOI SPORCHI
   - <u>DT 2.2.3 SALE OPERATORIE</u>
   - DT 2.2.4. SPOGLIATOI
   - DT 2.2.5 PREPARAZIONE PERSONALE
   - DT 2.2.6 ZONE FILTRO
   - DT 2.2.7 SUBSTERILIZZAZIONE
   - DT 2.2.8 VUOTATOIO SALA OPERATORIA
3) **DT 2.3 Sub-area servizi personale**. Elenco Unità Ambientali:
   - DT 2.3.1 STANZE PERSONALE

- DT 2.3.2 RIPOSO PERSONALE
- DT 2.3.3 SERVIZI IGIENICI PERSONALE

4) **DT 2.4 Sub-area servizi di supporto all’area**. Elenco Unità Ambientali:
   - DT 2.4.1 DEPOSITO SPORCO
   - DT 2.4.2 DEPOSITO PULITO
   - DT 2.4.3 DEPOSITO MATERIALE STERILE

| **MATRICE DEI CONFRONTI A COPPIE TRA SUB-AREE FUNZIONALI DI UN BLOCCO OPERATORIO** | | | | |
|---|---|---|---|---|
| | (1) Accoglienza/ orientamento | (2) Interventistico/ Operatoria | (3) Servizi al personale | (4) Servizi di supporto all’area |
| (1) Accoglienza orientamento | **1** | | | |
| (2) Interventistica/ Operatoria | | **1** | | |
| (3) Servizi al personale | | | **1** | |
| (4) Servizi di supporto all’area | | | | **1** |

- **Giudizio sul grado di incertezza del parere fornito**

In una scala di valori in cui:

**1 = completamente incerto**

**10 = completamente certo**

| Come valuta il grado di incertezza delle opinioni fornite in questo questionario? |
|---|
| (Esprimere il proprio giudizio mediante un numero intero compreso tra 1 e 10): |

**Annex 2.** Vector of weights calculation on MATLAB.

```
>> a = [1 0.15 0.25 0.37; 6.69 1 1.83 1.37; 3.97 0.55 1 0.59; 2.70 0.73 1.69 1]

a =

    1.0000    0.1500    0.2500    0.3700
    6.6900    1.0000    1.8300    1.3700
    3.9700    0.5500    1.0000    0.5900
    2.7000    0.7300    1.6900    1.0000


avec =

  -0.1305 + 0.0000i  -0.0745 - 0.1836i  -0.0745 + 0.1836i   0.0478 + 0.0000i
  -0.7490 + 0.0000i  -0.2720 + 0.2925i  -0.2720 - 0.2925i  -0.9501 + 0.0000i
  -0.4001 + 0.0000i  -0.2295 + 0.4205i  -0.2295 - 0.4205i   0.3039 + 0.0000i
  -0.5117 + 0.0000i   0.7562 + 0.0000i   0.7562 + 0.0000i   0.0512 + 0.0000i


aval =

   4.0787 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i
   0.0000 + 0.0000i  -0.0415 + 0.5666i   0.0000 + 0.0000i   0.0000 + 0.0000i
   0.0000 + 0.0000i   0.0000 + 0.0000i  -0.0415 - 0.5666i   0.0000 + 0.0000i
   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0000 + 0.0000i   0.0043 + 0.0000i

>> [max,pos] = max(diag(aval))

max =

    4.0787


pos =

     1

>> x = avec(:,1)

x =

   -0.1305
   -0.7490
   -0.4001
   -0.5117

>> norm = x/sum(avec(:,1))

norm =

    0.0728
    0.4182
    0.2234
    0.2856
```

**Annex 3.** Overall ER diagram.


WorkPlanTypeEnum
id int
constant str
description str
workPlans WorkPlan
WorkPlan
id int
workPlanTypeEnum WorkPlanTypeEnum
creationDate date
purpose str
startTime datetime
relAggregates RelAggregatesWorkPlanToWorkSchedule
WorkScheduleTypeEnum
id int
constant str
description str
workSchedules WorkSchedule
RelAggregatesWorkPlanToWorkSchedule
id int
workSchedule WorkSchedule
workPlan WorkPlan
WorkSchedule
id int
workScheduleTypeEnum WorkScheduleTypeEnum
relAssignToTask RelAssignsWorkScheduleToTask
relAggregates RelAggregatesWorkPlanToWorkSchedule
RelAssignsWorkScheduleToTask
id int
relatedtask Task
relatingSchedule WorkSchedule
RecurrenceTypeEnum
id int
constant str
description str
recurrencePatterns RecurrencePattern
RecurrencePattern
id int
recurrenceTypeEnum RecurrenceTypeEnum
dayComponent int
dayInWeekNumber int
monthComponent int
interval int
occurrences int
task_time_recurrings TaskTimeRecurring
TaskTimeRecurring
id int
recurrencePattern RecurrencePattern
tasks Task
Task
id int
taskTypeEnum TaskTypeEnum
identification str
longDescription str
workMethod str
isMilestone bool
priority str
relAssignsProducts RelAssignsTaskToProduct
relAssignTask RelAssignsWorkScheduleToTask
relAssignActionRequest RelAssignsTaskToActionRequest
taskTimeRecurring TaskTimeRecurring
TaskTypeEnum
id int
constant str
description str
tasks Task
RelAssignsTaskToProduct
id int
relatingTask Task
relatedProduct Product
Person
identifier str
familyName str
givenName str
middleNames str
personAndOrganization PersonAndOrganization
Organization
identifier str
name str
description str
address str
personAndOrganization PersonAndOrganization
RoleEnum
id int
constant str
description str
actorRole ActorRole
ActorRole
id int
role RoleEnum
userDefinedRole str
description str
personAndOrganization PersonAndOrganization
PersonAndOrganization
id int
person Person
organization Organization
roles ActorRole
actor Actor
Actor
id int
theactor PersonAndOrganization
relIssuingActorToActionRequest RelAssignsIssuingActorToActionRequest
relFullfillingActorToActionRequest RelAssignsFulfillingActorToActionRequest
relIssuingActorToProjectOrder RelAssignsIssuingActorToProjectOrder
relFullfillingActorToProjectOrder RelAssignsFulfillingActorToProjectOrder
IFCModel
id int
modelContent str
relProduct RelAssignsProductToModel
RelAssignsProductToModel
id int
relatedIFCModel IFCModel
relatingProduct Product
Product
globalId str
name str
description str
objectType str
relIFCModel RelAssignsProductToModel
relMeasurement RelAssignsProductToMeasurement
relActionRequest RelAssignsActionRequestToProduct
relTask RelAssignsTaskToProduct
RelAssignsProductToMeasurement
id int
relatingProduct Product
relatedMeasurement Measurement
RelAssignsTaskToActionRequest
id int
relatingTask Task
relatedActionRequest ActionRequest
RelAssignsActionRequestToProduct
id int
relatedProduct Product
relatingActionRequest ActionRequest
RelAssignsIssuingActorToActionRequest
id int
relatingActor Actor
relatedActionRequest ActionRequest
RelAssignsFulfillingActorToActionRequest
id int
relatingActor Actor
relatedActionRequest ActionRequest
ActionRequestTypeEnum
id int
constant str
description str
actionRequest ActionRequest
ActionRequest
id int
identification str
actionRequestTypeEnum ActionRequestTypeEnum
status str
longDescription str
relProduct RelAssignsActionRequestToProduct
relIssuingTask RelAssignsTaskToActionRequest
relIssuingActor RelAssignsIssuingActorToActionRequest
relFulfillingActor RelAssignsFulfillingActorToActionRequest
relKPIResult RelAggregatesActionRequestToKPIResult
relProjectOrder RelAggregatesActionRequestToProjectOrder
RelAggregatesActionRequestToProjectOrder
id int
relatingActionRequest ActionRequest
relatedProjectOrder ProjectOrder
RelAggregatesActionRequestToKPIResult
id int
relatingActionRequest ActionRequest
relatedKPIResult KeyPerformanceIndicatorResult
Measurement
id int
timestamp datetime
valueNumerical float
valueDescriptive str
description str
relProduct RelAssignsProductToMeasurement
relResult RelAssignsToMeasurement
KeyPerformanceIndicator
id int
name str
shortName str
description str
keyPerformanceIndicators KeyPerformanceIndicatorResult
KeyPerformanceIndicatorResult
id int
keyPerformanceIndicator KeyPerformanceIndicator
valueNumerical int
valueDescriptive str
timestamp datetime
comment str
interpretation str
relMeasurement RelAssignsToMeasurement
relActionRequest RelAggregatesActionRequestToKPIResult
RelAssignsToMeasurement
id int
relatingResult KeyPerformanceIndicatorResult
relatedMeasurement Measurement
interpretation str
acceptance bool
ProjectOrderTypeEnum
id int
constant str
description str
projectOrders ProjectOrder
RelAssociatesApproval
id int
relatingApproval Approval
relatedProjectOrder ProjectOrder
Approval
id int
name str
description str
timeOfApproval datetime
status str
RequestingApproval str
GivingApproval str
approvedObjects RelAssociatesApproval
RelAssignsIssuingActorToProjectOrder
id int
relatingActor Actor
relatedProjectOrder ProjectOrder
RelAssignsFulfillingActorToProjectOrder
id int
relatingActor Actor
relatedProjectOrder ProjectOrder
ProjectOrder
id int
projectOrderTypeEnum ProjectOrderTypeEnum
status str
longDescription str
relActionRequest RelAggregatesActionRequestToProjectOrder
relApproval RelAssociatesApproval
relIssuingActor RelAssignsIssuingActorToProjectOrder
relFulfillingActor RelAssignsFulfillingActorToProjectOrder

**Annex 4.** PostgreSQL statements.

```sql
CREATE TABLE "actionrequesttypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "actionrequest" (
  "id" INTEGER PRIMARY KEY,
  "identification" TEXT,
  "actionrequesttypeenum" INTEGER NOT NULL,
  "status" TEXT,
  "longdescription" TEXT
);

CREATE INDEX "idx_actionrequest__actionrequesttypeenum" ON
"actionrequest" ("actionrequesttypeenum");

ALTER TABLE "actionrequest" ADD CONSTRAINT
"fk_actionrequest__actionrequesttypeenum" FOREIGN KEY
("actionrequesttypeenum") REFERENCES "actionrequesttypeenum" ("id")
ON DELETE CASCADE;

CREATE TABLE "approval" (
  "id" SERIAL PRIMARY KEY,
  "name" TEXT,
  "description" TEXT,
  "timeofapproval" TIMESTAMP,
  "status" TEXT,
  "requestingapproval" TEXT,
  "givingapproval" TEXT
);

CREATE TABLE "ifcmodel" (
  "id" SERIAL PRIMARY KEY,
  "modelcontent" TEXT
);

CREATE TABLE "keyperformanceindicator" (
  "id" SERIAL PRIMARY KEY,
  "name" TEXT NOT NULL,
  "shortname" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "keyperformanceindicatorresult" (
  "id" SERIAL PRIMARY KEY,
  "keyperformanceindicator" INTEGER NOT NULL,
  "valuenumerical" INTEGER,
  "valuedescriptive" TEXT,
  "timestamp" TIMESTAMP,
  "comment" TEXT,
  "interpretation" TEXT
);
```

```sql
CREATE INDEX
"idx_keyperformanceindicatorresult__keyperformanceindicator" ON
"keyperformanceindicatorresult" ("keyperformanceindicator");

ALTER TABLE "keyperformanceindicatorresult" ADD CONSTRAINT
"fk_keyperformanceindicatorresult__keyperformanceindicator" FOREIGN
KEY ("keyperformanceindicator") REFERENCES "keyperformanceindicator"
("id") ON DELETE CASCADE;

CREATE TABLE "measurement" (
  "id" INTEGER PRIMARY KEY,
  "timestamp" TIMESTAMP NOT NULL,
  "valuenumerical" DOUBLE PRECISION,
  "valuedescriptive" TEXT,
  "description" TEXT
);

CREATE TABLE "organization" (
  "identifier" TEXT PRIMARY KEY,
  "name" TEXT NOT NULL,
  "description" TEXT,
  "address" TEXT
);

CREATE TABLE "person" (
  "identifier" TEXT PRIMARY KEY,
  "familyname" TEXT NOT NULL,
  "givenname" TEXT NOT NULL,
  "middlenames" TEXT
);

CREATE TABLE "product" (
  "globalid" TEXT PRIMARY KEY,
  "name" TEXT,
  "description" TEXT,
  "objecttype" TEXT
);

CREATE TABLE "projectordertypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "projectorder" (
  "id" SERIAL PRIMARY KEY,
  "projectordertypeenum" INTEGER NOT NULL,
  "status" TEXT,
  "longdescription" TEXT
);

CREATE INDEX "idx_projectorder__projectordertypeenum" ON
"projectorder" ("projectordertypeenum");
```

```sql
ALTER TABLE "projectorder" ADD CONSTRAINT
"fk_projectorder__projectordertypeenum" FOREIGN KEY
("projectordertypeenum") REFERENCES "projectordertypeenum" ("id") ON
DELETE CASCADE;

CREATE TABLE "recurrencetypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "recurrencepattern" (
  "id" SERIAL PRIMARY KEY,
  "recurrencetypeenum" INTEGER NOT NULL,
  "daycomponent" INTEGER,
  "dayinweeknumber" INTEGER,
  "monthcomponent" INTEGER,
  "interval" INTEGER,
  "occurrences" INTEGER
);

CREATE INDEX "idx_recurrencepattern__recurrencetypeenum" ON
"recurrencepattern" ("recurrencetypeenum");

ALTER TABLE "recurrencepattern" ADD CONSTRAINT
"fk_recurrencepattern__recurrencetypeenum" FOREIGN KEY
("recurrencetypeenum") REFERENCES "recurrencetypeenum" ("id") ON
DELETE CASCADE;

CREATE TABLE "relaggregatesactionrequesttokpiresult" (
  "id" SERIAL PRIMARY KEY,
  "relatingactionrequest" INTEGER NOT NULL,
  "relatedkpiresult" INTEGER NOT NULL
);

CREATE INDEX
"idx_relaggregatesactionrequesttokpiresult__relatedkpiresult" ON
"relaggregatesactionrequesttokpiresult" ("relatedkpiresult");

CREATE INDEX
"idx_relaggregatesactionrequesttokpiresult__relatingactionreques" ON
"relaggregatesactionrequesttokpiresult" ("relatingactionrequest");

ALTER TABLE "relaggregatesactionrequesttokpiresult" ADD CONSTRAINT
"fk_relaggregatesactionrequesttokpiresult__relatedkpiresult" FOREIGN
KEY ("relatedkpiresult") REFERENCES "keyperformanceindicatorresult"
("id") ON DELETE CASCADE;

ALTER TABLE "relaggregatesactionrequesttokpiresult" ADD CONSTRAINT
"fk_relaggregatesactionrequesttokpiresult__relatingactionrequest"
FOREIGN KEY ("relatingactionrequest") REFERENCES "actionrequest"
("id") ON DELETE CASCADE;

CREATE TABLE "relaggregatesactionrequesttoprojectorder" (
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  "id" SERIAL PRIMARY KEY,
  "relatingactionrequest" INTEGER NOT NULL,
  "relatedprojectorder" INTEGER NOT NULL
);

CREATE INDEX
"idx_relaggregatesactionrequesttoprojectorder__relatedprojectord" ON
"relaggregatesactionrequesttoprojectorder" ("relatedprojectorder");

CREATE INDEX
"idx_relaggregatesactionrequesttoprojectorder__relatingactionreq" ON
"relaggregatesactionrequesttoprojectorder" ("relatingactionrequest");

ALTER TABLE "relaggregatesactionrequesttoprojectorder" ADD CONSTRAINT
"fk_relaggregatesactionrequesttoprojectorder__relatedprojectorde"
FOREIGN KEY ("relatedprojectorder") REFERENCES "projectorder" ("id")
ON DELETE CASCADE;

ALTER TABLE "relaggregatesactionrequesttoprojectorder" ADD CONSTRAINT
"fk_relaggregatesactionrequesttoprojectorder__relatingactionrequ"
FOREIGN KEY ("relatingactionrequest") REFERENCES "actionrequest"
("id") ON DELETE CASCADE;

CREATE TABLE "relassignsactionrequesttoproduct" (
  "id" SERIAL PRIMARY KEY,
  "relatedproduct" TEXT NOT NULL,
  "relatingactionrequest" INTEGER NOT NULL
);

CREATE INDEX "idx_relassignsactionrequesttoproduct__relatedproduct"
ON "relassignsactionrequesttoproduct" ("relatedproduct");

CREATE INDEX
"idx_relassignsactionrequesttoproduct__relatingactionrequest" ON
"relassignsactionrequesttoproduct" ("relatingactionrequest");

ALTER TABLE "relassignsactionrequesttoproduct" ADD CONSTRAINT
"fk_relassignsactionrequesttoproduct__relatedproduct" FOREIGN KEY
("relatedproduct") REFERENCES "product" ("globalid") ON DELETE
CASCADE;

ALTER TABLE "relassignsactionrequesttoproduct" ADD CONSTRAINT
"fk_relassignsactionrequesttoproduct__relatingactionrequest" FOREIGN
KEY ("relatingactionrequest") REFERENCES "actionrequest" ("id") ON
DELETE CASCADE;

CREATE TABLE "relassignsproducttomeasurement" (
  "id" SERIAL PRIMARY KEY,
  "relatingproduct" TEXT NOT NULL,
  "relatedmeasurement" INTEGER NOT NULL
);

CREATE INDEX "idx_relassignsproducttomeasurement__relatedmeasurement"
ON "relassignsproducttomeasurement" ("relatedmeasurement");
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CREATE INDEX "idx_relassignsproducttomeasurement__relatingproduct" ON
"relassignsproducttomeasurement" ("relatingproduct");

ALTER TABLE "relassignsproducttomeasurement" ADD CONSTRAINT
"fk_relassignsproducttomeasurement__relatedmeasurement" FOREIGN KEY
("relatedmeasurement") REFERENCES "measurement" ("id") ON DELETE
CASCADE;

ALTER TABLE "relassignsproducttomeasurement" ADD CONSTRAINT
"fk_relassignsproducttomeasurement__relatingproduct" FOREIGN KEY
("relatingproduct") REFERENCES "product" ("globalid") ON DELETE
CASCADE;

CREATE TABLE "relassignsproducttomodel" (
  "id" SERIAL PRIMARY KEY,
  "relatedifcmodel" INTEGER NOT NULL,
  "relatingproduct" TEXT NOT NULL
);

CREATE INDEX "idx_relassignsproducttomodel__relatedifcmodel" ON
"relassignsproducttomodel" ("relatedifcmodel");

CREATE INDEX "idx_relassignsproducttomodel__relatingproduct" ON
"relassignsproducttomodel" ("relatingproduct");

ALTER TABLE "relassignsproducttomodel" ADD CONSTRAINT
"fk_relassignsproducttomodel__relatedifcmodel" FOREIGN KEY
("relatedifcmodel") REFERENCES "ifcmodel" ("id") ON DELETE CASCADE;

ALTER TABLE "relassignsproducttomodel" ADD CONSTRAINT
"fk_relassignsproducttomodel__relatingproduct" FOREIGN KEY
("relatingproduct") REFERENCES "product" ("globalid") ON DELETE
CASCADE;

CREATE TABLE "relassignstomeasurement" (
  "id" SERIAL PRIMARY KEY,
  "relatingresult" INTEGER NOT NULL,
  "relatedmeasurement" INTEGER NOT NULL,
  "interpretation" TEXT,
  "acceptance" BOOLEAN
);

CREATE INDEX "idx_relassignstomeasurement__relatedmeasurement" ON
"relassignstomeasurement" ("relatedmeasurement");

CREATE INDEX "idx_relassignstomeasurement__relatingresult" ON
"relassignstomeasurement" ("relatingresult");

ALTER TABLE "relassignstomeasurement" ADD CONSTRAINT
"fk_relassignstomeasurement__relatedmeasurement" FOREIGN KEY
("relatedmeasurement") REFERENCES "measurement" ("id") ON DELETE
CASCADE;
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ALTER TABLE "relassignstomeasurement" ADD CONSTRAINT
"fk_relassignstomeasurement__relatingresult" FOREIGN KEY
("relatingresult") REFERENCES "keyperformanceindicatorresult" ("id")
ON DELETE CASCADE;

CREATE TABLE "relassociatesapproval" (
  "id" SERIAL PRIMARY KEY,
  "relatingapproval" INTEGER NOT NULL,
  "relatedprojectorder" INTEGER NOT NULL
);

CREATE INDEX "idx_relassociatesapproval__relatedprojectorder" ON
"relassociatesapproval" ("relatedprojectorder");

CREATE INDEX "idx_relassociatesapproval__relatingapproval" ON
"relassociatesapproval" ("relatingapproval");

ALTER TABLE "relassociatesapproval" ADD CONSTRAINT
"fk_relassociatesapproval__relatedprojectorder" FOREIGN KEY
("relatedprojectorder") REFERENCES "projectorder" ("id") ON DELETE
CASCADE;

ALTER TABLE "relassociatesapproval" ADD CONSTRAINT
"fk_relassociatesapproval__relatingapproval" FOREIGN KEY
("relatingapproval") REFERENCES "approval" ("id") ON DELETE CASCADE;

CREATE TABLE "roleenum" (
  "id" INTEGER PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "actorrole" (
  "id" SERIAL PRIMARY KEY,
  "role" INTEGER NOT NULL,
  "userdefinedrole" TEXT,
  "description" TEXT
);

CREATE INDEX "idx_actorrole__role" ON "actorrole" ("role");

ALTER TABLE "actorrole" ADD CONSTRAINT "fk_actorrole__role" FOREIGN
KEY ("role") REFERENCES "roleenum" ("id") ON DELETE CASCADE;

CREATE TABLE "personandorganization" (
  "id" SERIAL PRIMARY KEY,
  "person" TEXT NOT NULL,
  "organization" TEXT NOT NULL,
  "roles" INTEGER NOT NULL
);

CREATE INDEX "idx_personandorganization__organization" ON
"personandorganization" ("organization");
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CREATE INDEX "idx_personandorganization__person" ON
"personandorganization" ("person");

CREATE INDEX "idx_personandorganization__roles" ON
"personandorganization" ("roles");

ALTER TABLE "personandorganization" ADD CONSTRAINT
"fk_personandorganization__organization" FOREIGN KEY ("organization")
REFERENCES "organization" ("identifier") ON DELETE CASCADE;

ALTER TABLE "personandorganization" ADD CONSTRAINT
"fk_personandorganization__person" FOREIGN KEY ("person") REFERENCES
"person" ("identifier") ON DELETE CASCADE;

ALTER TABLE "personandorganization" ADD CONSTRAINT
"fk_personandorganization__roles" FOREIGN KEY ("roles") REFERENCES
"actorrole" ("id") ON DELETE CASCADE;

CREATE TABLE "actor" (
  "id" INTEGER PRIMARY KEY,
  "theactor" INTEGER NOT NULL
);

CREATE INDEX "idx_actor__theactor" ON "actor" ("theactor");

ALTER TABLE "actor" ADD CONSTRAINT "fk_actor__theactor" FOREIGN KEY
("theactor") REFERENCES "personandorganization" ("id");

CREATE TABLE "relassignsfulfillingactortoactionrequest" (
  "id" INTEGER PRIMARY KEY,
  "relatingactor" INTEGER NOT NULL,
  "relatedactionrequest" INTEGER NOT NULL
);

CREATE INDEX
"idx_relassignsfulfillingactortoactionrequest__relatedactionrequ" ON
"relassignsfulfillingactortoactionrequest" ("relatedactionrequest");

CREATE INDEX
"idx_relassignsfulfillingactortoactionrequest__relatingactor" ON
"relassignsfulfillingactortoactionrequest" ("relatingactor");

ALTER TABLE "relassignsfulfillingactortoactionrequest" ADD CONSTRAINT
"fk_relassignsfulfillingactortoactionrequest__relatedactionreque"
FOREIGN KEY ("relatedactionrequest") REFERENCES "actionrequest"
("id") ON DELETE CASCADE;

ALTER TABLE "relassignsfulfillingactortoactionrequest" ADD CONSTRAINT
"fk_relassignsfulfillingactortoactionrequest__relatingactor" FOREIGN
KEY ("relatingactor") REFERENCES "actor" ("id") ON DELETE CASCADE;

CREATE TABLE "relassignsfulfillingactortoprojectorder" (
  "id" SERIAL PRIMARY KEY,
  "relatingactor" INTEGER NOT NULL,
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  "relatedprojectorder" INTEGER NOT NULL
);

CREATE INDEX
"idx_relassignsfulfillingactortoprojectorder__relatedprojectorde" ON
"relassignsfulfillingactortoprojectorder" ("relatedprojectorder");

CREATE INDEX
"idx_relassignsfulfillingactortoprojectorder__relatingactor" ON
"relassignsfulfillingactortoprojectorder" ("relatingactor");

ALTER TABLE "relassignsfulfillingactortoprojectorder" ADD CONSTRAINT
"fk_relassignsfulfillingactortoprojectorder__relatedprojectorder"
FOREIGN KEY ("relatedprojectorder") REFERENCES "projectorder" ("id")
ON DELETE CASCADE;

ALTER TABLE "relassignsfulfillingactortoprojectorder" ADD CONSTRAINT
"fk_relassignsfulfillingactortoprojectorder__relatingactor" FOREIGN
KEY ("relatingactor") REFERENCES "actor" ("id") ON DELETE CASCADE;

CREATE TABLE "relassignsissuingactortoactionrequest" (
  "id" SERIAL PRIMARY KEY,
  "relatingactor" INTEGER NOT NULL,
  "relatedactionrequest" INTEGER NOT NULL
);

CREATE INDEX
"idx_relassignsissuingactortoactionrequest__relatedactionrequest" ON
"relassignsissuingactortoactionrequest" ("relatedactionrequest");

CREATE INDEX
"idx_relassignsissuingactortoactionrequest__relatingactor" ON
"relassignsissuingactortoactionrequest" ("relatingactor");

ALTER TABLE "relassignsissuingactortoactionrequest" ADD CONSTRAINT
"fk_relassignsissuingactortoactionrequest__relatedactionrequest"
FOREIGN KEY ("relatedactionrequest") REFERENCES "actionrequest"
("id") ON DELETE CASCADE;

ALTER TABLE "relassignsissuingactortoactionrequest" ADD CONSTRAINT
"fk_relassignsissuingactortoactionrequest__relatingactor" FOREIGN KEY
("relatingactor") REFERENCES "actor" ("id") ON DELETE CASCADE;

CREATE TABLE "relassignsissuingactortoprojectorder" (
  "id" SERIAL PRIMARY KEY,
  "relatingactor" INTEGER NOT NULL,
  "relatedprojectorder" INTEGER NOT NULL
);

CREATE INDEX
"idx_relassignsissuingactortoprojectorder__relatedprojectorder" ON
"relassignsissuingactortoprojectorder" ("relatedprojectorder");
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CREATE INDEX
"idx_relassignsissuingactortoprojectorder__relatingactor" ON
"relassignsissuingactortoprojectorder" ("relatingactor");

ALTER TABLE "relassignsissuingactortoprojectorder" ADD CONSTRAINT
"fk_relassignsissuingactortoprojectorder__relatedprojectorder"
FOREIGN KEY ("relatedprojectorder") REFERENCES "projectorder" ("id")
ON DELETE CASCADE;

ALTER TABLE "relassignsissuingactortoprojectorder" ADD CONSTRAINT
"fk_relassignsissuingactortoprojectorder__relatingactor" FOREIGN KEY
("relatingactor") REFERENCES "actor" ("id") ON DELETE CASCADE;

CREATE TABLE "tasktimerecurring" (
  "id" SERIAL PRIMARY KEY,
  "recurrencepattern" INTEGER NOT NULL
);

CREATE INDEX "idx_tasktimerecurring__recurrencepattern" ON
"tasktimerecurring" ("recurrencepattern");

ALTER TABLE "tasktimerecurring" ADD CONSTRAINT
"fk_tasktimerecurring__recurrencepattern" FOREIGN KEY
("recurrencepattern") REFERENCES "recurrencepattern" ("id") ON DELETE
CASCADE;

CREATE TABLE "tasktypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "task" (
  "id" SERIAL PRIMARY KEY,
  "tasktypeenum" INTEGER NOT NULL,
  "identification" TEXT,
  "longdescription" TEXT,
  "workmethod" TEXT,
  "ismilestone" BOOLEAN NOT NULL,
  "priority" TEXT,
  "tasktimerecurring" INTEGER
);

CREATE INDEX "idx_task__tasktimerecurring" ON "task"
("tasktimerecurring");

CREATE INDEX "idx_task__tasktypeenum" ON "task" ("tasktypeenum");

ALTER TABLE "task" ADD CONSTRAINT "fk_task__tasktimerecurring"
FOREIGN KEY ("tasktimerecurring") REFERENCES "tasktimerecurring"
("id") ON DELETE SET NULL;

ALTER TABLE "task" ADD CONSTRAINT "fk_task__tasktypeenum" FOREIGN KEY
("tasktypeenum") REFERENCES "tasktypeenum" ("id") ON DELETE CASCADE;
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CREATE TABLE "relassignstasktoactionrequest" (
  "id" SERIAL PRIMARY KEY,
  "relatingtask" INTEGER NOT NULL,
  "relatedactionrequest" INTEGER NOT NULL
);

CREATE INDEX
"idx_relassignstasktoactionrequest__relatedactionrequest" ON
"relassignstasktoactionrequest" ("relatedactionrequest");

CREATE INDEX "idx_relassignstasktoactionrequest__relatingtask" ON
"relassignstasktoactionrequest" ("relatingtask");

ALTER TABLE "relassignstasktoactionrequest" ADD CONSTRAINT
"fk_relassignstasktoactionrequest__relatedactionrequest" FOREIGN KEY
("relatedactionrequest") REFERENCES "actionrequest" ("id") ON DELETE
CASCADE;

ALTER TABLE "relassignstasktoactionrequest" ADD CONSTRAINT
"fk_relassignstasktoactionrequest__relatingtask" FOREIGN KEY
("relatingtask") REFERENCES "task" ("id") ON DELETE CASCADE;

CREATE TABLE "relassignstasktoproduct" (
  "id" SERIAL PRIMARY KEY,
  "relatingtask" INTEGER NOT NULL,
  "relatedproduct" TEXT NOT NULL
);

CREATE INDEX "idx_relassignstasktoproduct__relatedproduct" ON
"relassignstasktoproduct" ("relatedproduct");

CREATE INDEX "idx_relassignstasktoproduct__relatingtask" ON
"relassignstasktoproduct" ("relatingtask");

ALTER TABLE "relassignstasktoproduct" ADD CONSTRAINT
"fk_relassignstasktoproduct__relatedproduct" FOREIGN KEY
("relatedproduct") REFERENCES "product" ("globalid") ON DELETE
CASCADE;

ALTER TABLE "relassignstasktoproduct" ADD CONSTRAINT
"fk_relassignstasktoproduct__relatingtask" FOREIGN KEY
("relatingtask") REFERENCES "task" ("id") ON DELETE CASCADE;

CREATE TABLE "workplantypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "workplan" (
  "id" SERIAL PRIMARY KEY,
  "workplantypeenum" INTEGER NOT NULL,
  "creationdate" DATE,
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  "purpose" TEXT,
  "starttime" TIMESTAMP
);

CREATE INDEX "idx_workplan__workplantypeenum" ON "workplan"
("workplantypeenum");

ALTER TABLE "workplan" ADD CONSTRAINT "fk_workplan__workplantypeenum"
FOREIGN KEY ("workplantypeenum") REFERENCES "workplantypeenum" ("id")
ON DELETE CASCADE;

CREATE TABLE "workscheduletypeenum" (
  "id" SERIAL PRIMARY KEY,
  "constant" TEXT NOT NULL,
  "description" TEXT
);

CREATE TABLE "workschedule" (
  "id" SERIAL PRIMARY KEY,
  "workscheduletypeenum" INTEGER NOT NULL
);

CREATE INDEX "idx_workschedule__workscheduletypeenum" ON
"workschedule" ("workscheduletypeenum");

ALTER TABLE "workschedule" ADD CONSTRAINT
"fk_workschedule__workscheduletypeenum" FOREIGN KEY
("workscheduletypeenum") REFERENCES "workscheduletypeenum" ("id") ON
DELETE CASCADE;

CREATE TABLE "relaggregatesworkplantoworkschedule" (
  "id" SERIAL PRIMARY KEY,
  "workschedule" INTEGER NOT NULL,
  "workplan" INTEGER NOT NULL
);

CREATE INDEX "idx_relaggregatesworkplantoworkschedule__workplan" ON
"relaggregatesworkplantoworkschedule" ("workplan");

CREATE INDEX "idx_relaggregatesworkplantoworkschedule__workschedule"
ON "relaggregatesworkplantoworkschedule" ("workschedule");

ALTER TABLE "relaggregatesworkplantoworkschedule" ADD CONSTRAINT
"fk_relaggregatesworkplantoworkschedule__workplan" FOREIGN KEY
("workplan") REFERENCES "workplan" ("id") ON DELETE CASCADE;

ALTER TABLE "relaggregatesworkplantoworkschedule" ADD CONSTRAINT
"fk_relaggregatesworkplantoworkschedule__workschedule" FOREIGN KEY
("workschedule") REFERENCES "workschedule" ("id") ON DELETE CASCADE;

CREATE TABLE "relassignsworkscheduletotask" (
  "id" SERIAL PRIMARY KEY,
  "relatedtask" INTEGER NOT NULL,
  "relatingschedule" INTEGER NOT NULL
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);

CREATE INDEX "idx_relassignsworkscheduletotask__relatedtask" ON
"relassignsworkscheduletotask" ("relatedtask");

CREATE INDEX "idx_relassignsworkscheduletotask__relatingschedule" ON
"relassignsworkscheduletotask" ("relatingschedule");

ALTER TABLE "relassignsworkscheduletotask" ADD CONSTRAINT
"fk_relassignsworkscheduletotask__relatedtask" FOREIGN KEY
("relatedtask") REFERENCES "task" ("id") ON DELETE CASCADE;

ALTER TABLE "relassignsworkscheduletotask" ADD CONSTRAINT
"fk_relassignsworkscheduletotask__relatingschedule" FOREIGN KEY
("relatingschedule") REFERENCES "workschedule" ("id") ON DELETE
CASCADE
```