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# Sustainability of linear infrastructure domain-specific data sets in open BIM asset centric workflows

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**ABSTRACT**

The digitalization of linear infrastructure projects can be nowadays supported by workflows that improve not only the quality of the deliverables but also the efficiency of the way they are developed, cultivating communication between project participants. Technology, tools, equipment and procedures aid in accomplishing these objectives and the construction industry is becoming more and more digital-oriented and receptive to approaches as Building Information Modelling (BIM). Amongst the advantages of BIM implementation, one can count increased productivity, earlier exposure of project errors, earlier detection of omissions, communication procedures streamlined, project costs optimization and control, more informed scheduling, building simulation and analysis, and many others. However, since it is of recent adoption in the infrastructure field, to fully make the most of the listed benefits, there are still significant developments and adaptations to be made due to the nature of this sector.

The infrastructure domain is vast, encompassing assets related to the economy and social domains of society. The focus of the present dissertation is on the transportation category, where linear infrastructures assets such as roads, railways and airport runways occupy an emphasized role. As networks of longitudinal structures with large territory interaction, their intervention area must be subject to multiple analysis at an earlier planning stage, before and beyond simple plano-altimetric decisions. They present a very specific nature, both structure and component-wise as related to the terminology and modelling methodology. Like any complex built asset, linear infrastructures are multidisciplinary (in terms of specialized areas and teams involved), and their projects present very particular challenges, namely the high dependence on existing structures, infrastructures and the surrounding environment.

There is now no argument that BIM is and has to be applied and viewed as something beyond just the 3D model. Even though it can be considered as the central core of any project, the part that provides the most return to professionals in terms of investment has to be considered the organizational one related to data. The initial investment in training and resources is later compensated by the increased quality of project deliverables and especially improved control and management of the assets in their operation life. Project participants should encourage in an early stage the adoption and implementation of open standards, since if they remain connected to proprietary software the full potentialities of BIM will never be attained.

One of the major demands when it comes to linear infrastructure projects is related to the organization of all the data associated and its conveyance between all project participants (interoperability of information) in a streamlined way. These projects encompass a great amount of information (big datasets) that originates from manifold sources, often not properly organized and stored, leading to lack of organization.

The present dissertation focuses on a new methodology for sustainability of datasets, created since the early project stages up to the operation and maintenance, and how they can be gathered, accessed and retrieved in an open standardized manner. As part of the methodology a technical framework is proposed that connects big datasets to the digital BIM

model of the asset. The development of these data connections contributes additionally to the sustainability of projects, minimizing paper-based deliverables, improving the communication between different teams involved (leading to better and timely decisions), aiding in cost savings and general improvement of all operation, maintenance and rehabilitation procedures and activities.

Therefore, the main deliverable of the present dissertation is a methodology that proposes a technical framework consisting of different software applications that integrates domain-specific data, connecting and integrating open infrastructure BIM (IFC) models with big datasets through a relational database. The methodology also proposes a new BIM workflow that enables the integration of IFC 4.3 files, with collections of infrastructure domain-specific data (e.g. spreadsheet data, images, pdf documents).

The proposed framework called InfraGOTdata can be regarded as an innovative Common Data Environment (CDE), which is a well-known concept for BIM workflows. The relational database InfraGOTdb is inherent to the IFC schema and upgraded to support big datasets coming from multiple static or dynamic sources. The user application InfraGOTapp enhances professional user experience, streamlining the integration of domain specific data, benefiting from a clear connection with data from multiple sources can be organized, referenced and queried according to the interests and needs of the professionals.

Future developments of the presented work can extend it by integrating prediction models (e.g. performance-wise, climate changes impact analysis) and establishing the connection to technologies related to the smart city concept, where the Internet of Things (IoT) solutions further improve the efficiency and sustainability of the infrastructure assets' management.

**Keywords:** Building Information Modelling (BIM), Linear infrastructure, Interoperability, Sustainability, Industry Foundation Classes (IFC), Big datasets.

# 1. Introduction

## 1.1. Background and rationale

The full digitalization of construction projects presents itself as a reality nowadays, allowing all participants to improve the productivity and efficiency in their work. The established designation for what can be simplistically referred to as the digitalization of all project-related data is Building Information Modelling (BIM). Initially developed to assist the architectural field, BIM has naturally caught the attention of the infrastructural field and has been adopted with success by professionals worldwide. The origins of the BIM as a concept can be reported to the 1970s, namely to Charles M. Eastman article “The use of computers instead of drawings in building design” [1], where it is specifically suggested the coupling between a quantity and geometric analysis with its complete description, as well as the automatization of data preparation (including cost estimation or material quantities). The first appearance of the term “BIM” is assigned to the article by Nederveen and Tolman entitled “Modelling multiple views on buildings” [2].

Such is its importance that countries began to create laws demanding the implementation of the digitalization of public projects. The Scandinavian countries are amongst the first ones to require BIM technologies and methodologies to be used in construction projects. Finland started in 2001 and later on, in 2007, decided that all software had to be IFC certified, boosting the adoption of open standards in the industry. In Denmark, BIM has been mandatory since 2007 for all public projects, Norway since 2016. In Sweden, the government is establishing plans to mandate BIM, the public Transportation Association requires BIM since 2015. The United Kingdom is a leader when it comes to BIM adoption, in 2016 BIM level 2 (where collaborative work practices are central) was made mandatory for public projects [3].

Some countries opted for a gradual introduction of BIM, based on the projects’ value. One such introduction takes place in Italy where, with the Ministerial Decree 560 of 2017, the timeline for the mandatory but gradual introduction of the use of digital modelling methods and tools for the Construction Sector based on the asset’s tender value is set. From January 2019, public works with a tender value starting from 100 million euros are compelled to use approaches as Building Information Modelling (BIM), in 2025 this will be extended to all public works [4].

BIM supports innovative workflows applied to built asset projects, which accompany them throughout its lifecycle, design, construction and operation phases, offering the possibility to access and oversee all related information (Figure 1). The International Organization for Standardization (ISO) defines asset as “item, thing or entity that has potential or actual value to an organization” [5], clarifying also that they can be divided in physical and non-physical (e.g. digital assets, licences, intellectual property rights). In the PAS 1192-5:2015 Specification for security-minded building information modelling, digital built environments and smart asset management [6], a built asset is defined as a building or infrastructure subject to a construction project or where the related information is held digitally. Borrmann et al. [7] defines BIM as comprising the “methods and tools for the continuous digital support of the planning, construction and operation phases of the lifecycle of built facility based on a digital building model.”, highlighting the continuous support provided throughout all project phases and replacing "building“ for “built facility”, encompassing also infrastructure assets.

| PROJECT LIFECYCLE | | |
|---|---|---|
| 1. DESIGN | 2. CONSTRUCTION | 3. OPERATION |
| Concept<br>Briefing<br>Programming<br>Planning<br>Concept Design<br>Detailed Design<br>Final Design<br>Analysis | Bidding<br>Tendering<br>Planning<br>Detailing<br>Manufacturing<br>Procurement<br>Commissioning<br>Handover | Management<br>Maintenance<br>Decommissioning<br>Reprogramming |

Figure 1 – Project lifecycle phases, adapted from [8].

The operation phase is one that profits most from the proper adoption of BIM, where maintenance and management activities are enhanced and more consistent, when properly supported by updated easily accessed and reliable data. Roads, highways and airport runways are examples of linear infrastructures where the operation phase is extremely connected to the pavement condition, in fact, the projects usually include a Pavement Management System (PMS) [4].

Regarding in particular the infrastructural field, terms like Civil Information Modelling (CIM), “Horizontal BIM” and “Heavy BIM” [9] or the direct notation Infrastructure Building Information Modelling (I-BIM) are often applied. For simplicity purposes, the present document will continue to use the acronym BIM. The introduction of BIM for infrastructure generates a change of paradigm in terms of process [10]. It requires innovation concerning all the organizations and stakeholders involved (internal and external), such as clients, designers, companies, components and software companies, managers, universities, public and private research centres.

Research in the BIM field is crucial, as its inherent technological nature is in constant development along with the innovations on the construction field in terms of new procedures, methodologies, equipment, etc. Widespread academic research on the digitalization of the built environment has been present since the transition from the “traditional” paper to CAD-based project development. Automation in the AECO (Architecture, Engineering, Construction and Operation/Ownership) has since then expanded with advancements in the fields like Internet of Things (IoT), Artificial Intelligence (AI) and Machine Learning, Predictive Analytics, Virtual Reality and Autonomous Equipment. BIM presented itself as the core model-based solution where all these advancements could be integrated, upgrading projects’ efficiency and sustainability. Furthermore, the infrastructural field is now in need of solutions to hasten the appropriate adoption of BIM, making the most of its benefits.

The topics highlighted in the section , namely BIM and its widespread implementation, BIM-workflows, BIM for infrastructure and big datasets collected in the operation phase of the infrastructure lifecycle along with integration of automation technologies, are in the core of the research.

## 1.2. The research problem

Linear infrastructure projects combine many parts, for example, a roadway project contains data regarding geometric design, location data, drainage, geotechnics, earthworks, pavement design, signalling and safety, lighting and telecommunications, risks and impacts assessment. Each part comprises information (graphical and non-graphical) formalized in plans, studies, reports, standards, etc. Prior to the digitalization of projects, all this data was often predisposed to be lost, difficult to be updated and the information exchange between project participants was not ideal. Moreover, data was not systematically organized and stored, not facilitating its access, modification and retrieval. The advent of Computer-Aided Design (CAD), gave projects the next evolution in terms of quality, time and cost-saving in the production of the graphical parts of the project, and CAD even evolved to 3D, allowing the creation of complex models. Still, this improvement did not prevent all the previously referred issues, the formats were still very connected to the commercial tools used and the communication between the different teams remained mostly paper-based.

Since projects are obviously not composed of geometric and location data only, as previously stated, the connected information, which Teicholz [11] designates as attribute data, has to be also efficiently available. The importance, quantity and necessity of non-graphical information increases from the inception of the project where graphics usually do play the main role up to the operating stages (Figure 2). One can argue that all project data derives from non-graphical data, for example, derives from information requirements, still the support given by geometric detailed models is indisputable and needed from the get-go. The BIM model can then be used also as a map for the information, especially after the design and construction periods.

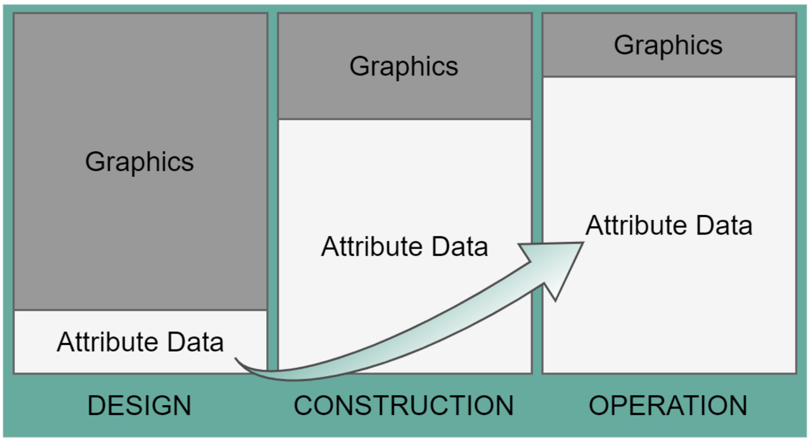



Figure 2 – Importance of attribute data throughout the project, adapted from [11].

BIM aids in the organization of all lifecycle project data, offering a systematic organization, improving the deliverables quality, communication between different teams and reducing costs. The economic advantage of the adoption of BIM workflows is a direct consequence of reduced rework, reduced errors and omissions on documentation (teams are more involved and have easier access to them, detecting and correcting issues at an earlier stage), contractors have a stronger insight on the overall project, scheduling can be linked directly to the 3D model, suppliers benefit from an early awareness on the specifications on the products or services requested, among many others.

The Infrastructure Asset Managers BIM Requirements Report [12] clarifies the meaning of asset as an object with value for the owner or managing organization. It is important to understand also that assets are not only physical (real) but also digital (virtual). From this perspective, and directly connected to the present research, a digital twin of any linear infrastructure must be itself defined as an asset. Digital twins can be defined as digital representations created using integrated simulations and service data [13].

When discussing physical infrastructure assets and their importance, they should be viewed as part of a big system, providing to the population energy, mobility, water, waste, communication and social facilities, connected and embodying a major system. The digital twins of these assets, either prepared before their construction or after it (through the use of reverse engineering processes), can be fundamentally viewed as tools that enable, in addition to location and functionality purposes, decisions to be made. The quality of these virtual assets is directly connected to the adoption of data digitization and of BIM workflows. When a physical infrastructure asset is connected to the respective digital asset the advantages range from the improved knowledge of their current state (enabling prompt and better decisions on their management/maintenance and efficient interventions) to a better insight on their connection to the surrounding environment and other systems, contributing to the creation of what can be designated as a smart infrastructure.

Notwithstanding BIM is now adopted successfully in infrastructure projects, full interoperability and the early adoption of open standards still presents challenges, especially when the specificities of these projects find limited support. For this motive, the insights on the latest developments of the BuildingSMART's standardization [14] solutions for infrastructure projects, and involvement on the Infrastructure Room Expert Panel meetings, allowed for a better understanding on how their proposals can be integrated on the proposed methodology. These projects can benefit from a structured platform that conveys information without overloading the digital models, which in combination with the adoption of BIM workflows proves advantageous for all professionals.

The problematic issue of establishing a reliable connection between graphics and attribute data is still not properly addressed, especially when the importance of the assets require an amount of essential data to be accessible to all stakeholders connected and interested entities at any given time, from a reliable and complete source, constituting the core base of the research problem of the present dissertation. Moreover, the importance of doing so resourcing to open standardization throughout has not yet been the object of extensive research.

## 1.3. Aim and hypothesis

With focus on linear infrastructure projects and their proper robust and reliable digitalization, the purposes of the present dissertation were defined as follows:

- Attaining a documented insight on the benefits and difficulties present when BIM is applied to linear infrastructure projects.
- The study of the latest buildingSMART International (bSI) open standards (IFC) for linear infrastructure and its requirements for integration in the design, construction and asset-centric project stages.
- The study of data sets, obtained for example from pavement assessments, that can be recorded to an asset database.
- Enabling the consultation, visualization, retrieval, modification and update of all data connected to a linear infrastructure project.
- The development of an IFC model-view profile with a subset of classes to support the connection to the asset database.
- The development of an innovative BIM workflow and a new framework for linking the asset database to IFC models.
- Validate the new BIM workflow with use cases.

Hypothesis definition:

Since linear infrastructure projects are very demanding in terms of information (quantity and quality-wise), a platform connecting big datasets to the digital BIM model of the asset, obtained from an open standard IFC file improves the federated organization of big datasets (including dynamic), and the connection of data from multiple sources in an organized and referenced way which can be queried according to the interests and needs of the professionals.

## 1.4. Research methodology adopted

The research methodology adopted began with a literature review of what has been done and is currently being developed in the field (BIM and infrastructure), with special attention given to linear infrastructure projects and the adoption of open standards. Therefore, the state of the art review and the initial assessment on how such projects are being developed by professionals, namely in terms of common tools and workflows adopted, justified the importance and highlighted the innovation needed in terms of gathering all information, conveying it properly and making the most of the applicable open standards.

The core work required an extensive study of the BIM workflows, of the type of big data usually associated and required for linear infrastructure projects and of the open standards used and how can they be implemented to the advantage of the professionals.

The new proposed methodology to enhance project sustainability and how data can be gathered, accessed and retrieved using open standards is constituted by a technical framework connecting big datasets to the digital BIM model of the asset.

As the present dissertation focuses on the infrastructural field, transportation domain, the proposal involves an innovative methodology that connects BIM to asset data management in the lifecycle of a digital construction project: an asset-centric BIM workflow that extends perception of BIM-models beyond physical and functional representation of an infrastructure facility and links them to external data sources (big, dynamic data). The framework presented as the main deliverable of the present work opens up a new and extendable approach for what can be defined as a reliable source of information for linear infrastructure projects, using the latest developments of the dedicated open standards, namely the IFC, therefore the IFC data model was also focus of study.

The framework is materialized through a relational database, named InfraGOTdb, and a user application InfraGOTapp. For the database development, which constitutes the connection between the file and the big data, Entity-relationship and Object-oriented database models were studied and applied. The main aspects of these topics used for the development of the proposed framework are detailed throughout the present document.

The supportive case study used for the application of the BIM workflow and validation of the results was Lamezia Terme's International Airport main runway (detailed in the Appendix). The case study supported the validation of one of the still challenging aspects when connecting semantic data to a BIM model is concerned, the precise location of measurements resulting from inspection tests and surveys. Although proprietary tools allow this feature, conveying that information in an open standardized way was not possible. The tools do allow the exportation of the model in open standard type files, however, these files are incomplete and don't reflect all the data included. The reason for that is that even though the standards could be complete and ready for application, the major software houses obviously need time to upgrade their tools import/export capabilities, a process that involves extensive resources, namely workforce wise. This case study also allowed to validate how the geometric characteristics of a linear asset can be specified properly, using IFC entities, some from the current official released schema, others adapted from the latest developments of the buildingSMART's project IFCRoad. Although the chosen case study is an airport runway, the principles of defining the pavement structure focus of the IFCRoad project are applicable, therefore used in the present proposed framework.

Proprietary tools, specific to the field, were used, namely Autodesk's Civil 3D 2020 and Bentley's OpenRoads Designer, because of their diffusion and application worldwide. This implied becoming proficient in the use of both, especially in the design stage. For the visualization and quality verification of the exported IFC files, the tool BIM Collab ZOOM was used.

Being that the airport runway is an existing built asset, reverse engineering procedures, sometimes referred to as back engineering, were applied to replicate the geometry of the runway and detail its pavement structure. The basis for that work were CAD drawings of the airside runway project. It is relevant to point out the importance of developing BIM models of built assets, as they prove advantageous especially in the operation phase. In this particular case study moreover, as the airside of airports ise strictly controlled in terms of regular inspections (e.g. analysis of the pavement structural condition, detection of pathologies), because of their need to always operate in ideal conditions.

## 1.5. Contribution to the body of knowledge

In accordance with the established aims, the present thesis will deliver as contributions to the body of knowledge:

- A description of BIM related core concepts and tools dedicated especially to linear infrastructure projects;
- A detailed analysis of one of the most robust and established open standards, Industry Foundation Classes (IFC) from the perspective of what it offers to linear infrastructure projects;
- An overview of the information that is required especially when an asset-centric BIM-workflow is analysed, and how can this big data be organized and connected to a BIM model in an open standardized manner.

The major contribution of the present thesis to the academic community and construction industry professionals is an innovative platform for connecting pavement big data to the projects IFC file.

- Gathering all the project parts under a unique data interface easily accessed and of simplified comprehension for all project members, which will prove advantageous to all academic researchers that can further improve it as well as professionals in the field that can pick it up and integrate it on their projects workflow.
- The second major contribution is to programmatically update IFC files to be compatible with the latest released version of the schema IFC 4.2.

# 2. State of the art in infrastructure information modelling

In order to further understand the application of BIM to infrastructural projects and the different approaches taken by other researchers when confronting data interoperability, a state of the art review was carried out. Initially, the infrastructure domains and categories are described and the focus of the review refined. The systematic literature review provided a more extended vision on BIM in general and its application to linear infrastructure projects.

## 2.1. Infrastructure domains and categories

Weber et al. [15] divides infrastructure into two main domains: economic and social. Social infrastructures are connected to health, education, sports, public administration and security facilities. This particular domain is excluded from the analysis contained in the present thesis. Of utmost value however is the economic infrastructure domain, composed of the transport, energy, water, waste and communication categories. In the transportation category, land, water, air and multimodal, define the types of assets that can be enumerated. Costin et al. [7] present a similar division of the infrastructural field divided into domains and categories, as presented in the following Figure.

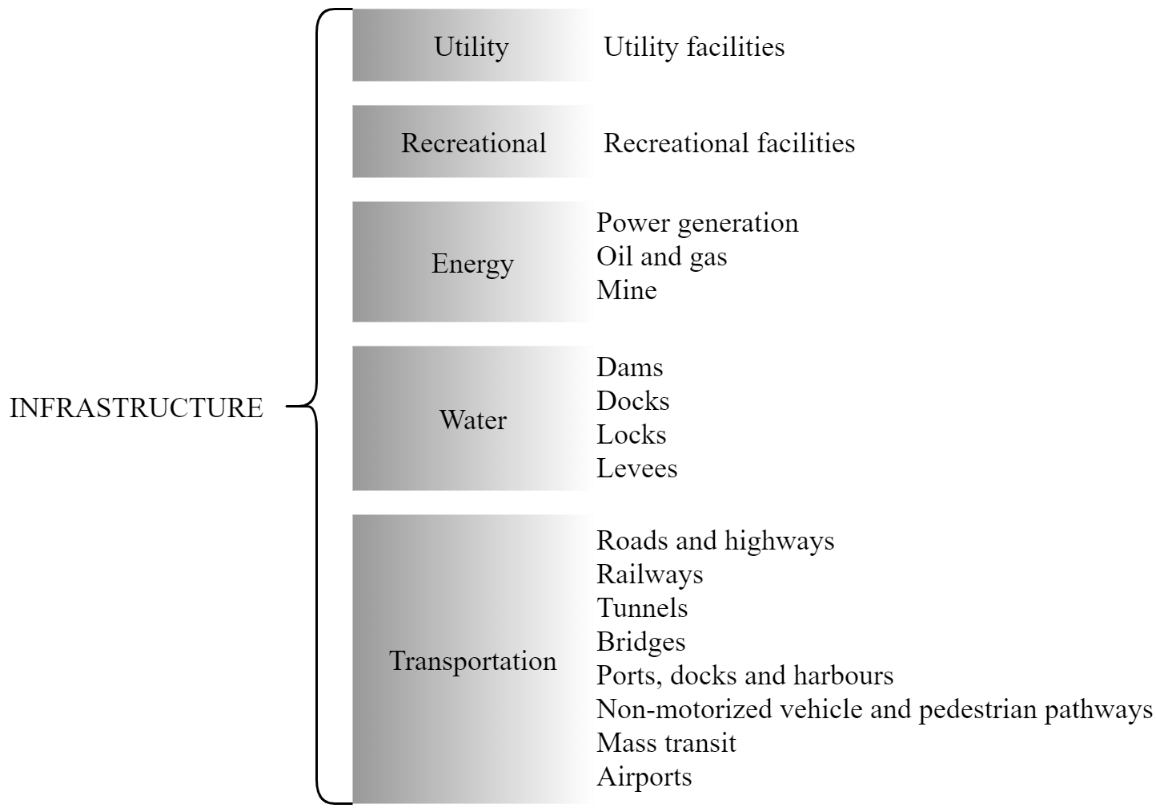



Figure 3 – Infrastructure domains and categories, adapted from [15].

The transportation linear infrastructures, (roadways, railways, tunnels, bridges and runways) and the development of their projects using BIM, as well as the status of adoption of neutral standards for exchange for data (geometric and semantic), were the major focus of the literature review.

## 2.2. Methodology for literature review

The process for the systematic literature review consisted in the development of a review protocol, the definition of the scope including keyword identification and the successive data collection from academic databases, namely Scopus, ScienceDirect, IEEE Xplore and ASCE Library. Technical papers/research articles, as well as conference proceedings and review papers, were included in the literature review. The state of the art review followed the guidelines presented in Figure 4.

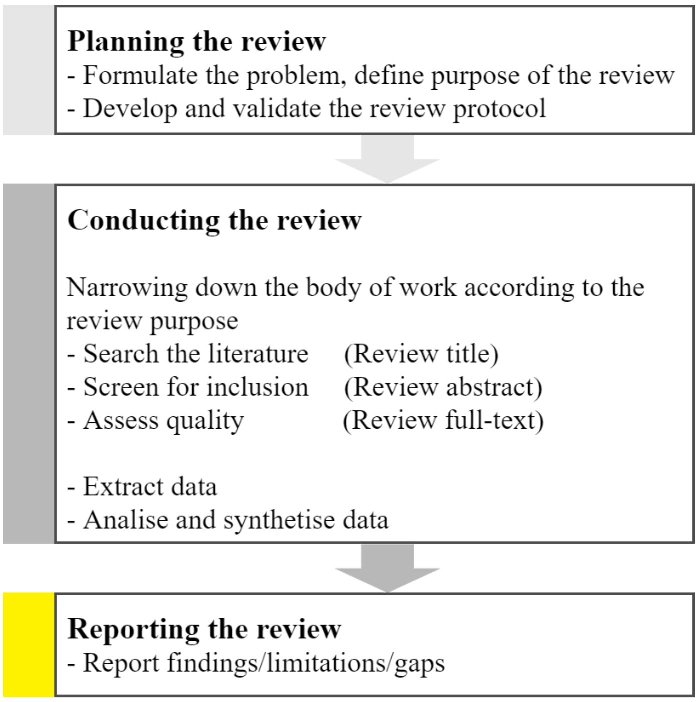



Figure 4: Systematic literature review steps, adapted from [16].

Planning the review, (the first step), was supported by the need of understanding what has been done, research and industry-wise, in the digitalization of linear infrastructure projects area, integration of big data (including visual) and which standards are being accepted and applied when BIM workflows are adopted. So accordingly, the following research questions are the base for the definition of the search query:

- How advanced are infrastructure projects in terms of the digitalization of all data required to be included in them?
- How are BIM workflows being applied to linear infrastructure projects and are the participants retrieving the utmost of their advantages?
- Which open standards are being adopted in linear infrastructure projects?
- How are infrastructure projects sustaining the associated Big Data?

Another important goal of the review was to identify gaps in research, defining possible innovative research lines which further validate the academic and industry value of the dissertation.

The review protocol described was materialized with the query: ( TITLE-ABS-KEY ( "BIM" AND "infrastructure" AND ( "standards" OR "IFC" OR "big data" OR "project" ) ) ) for all the chosen academic electronic databases, which remain the main source of published literature. The search was not limited to any specific time interval. As previously stated, all retrieved articles, conference papers and review papers were included and “forwarded” to the second step “Conducting the review” (Figure 4), where the narrowing down of the body of work was conducted. The review protocol was validated by peer review.

Although some subject areas are not in the frame of the intended research, more focused on the Engineering and Computer Science fields, it was decided to not exclude any subject area and “allow” all results to be collected and pass on to the next step. The reason for that finds justification on the fact that some relevant papers are often miscategorized, for example the chosen query applied to the academic database Scopus resulted in several articles in the Biochemistry, Genetics and Molecular Biology area, pertinent to the purpose of the review. Figure 5 summarizes the top 20 sources and corresponding number of papers collected, included in the first phase of the systematic review.

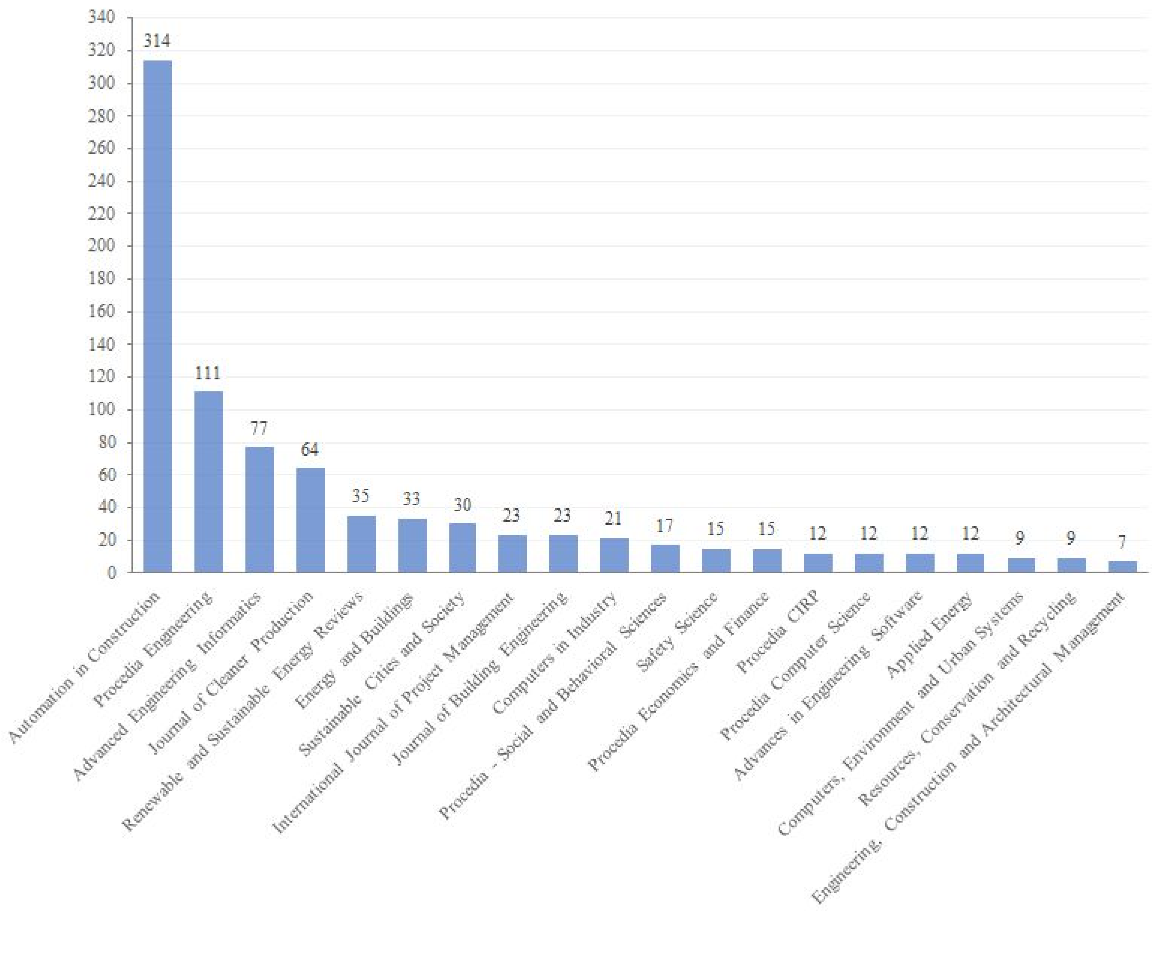



Figure 5: Systematic literature review, top 20 publication sources.

### 2.3. Literature review results

The body of work which resulted from the defined query was narrowed down based on the title and abstract revision.

For systematization purposes the chosen papers were organized according to specific categories: General, roads and highways, railways, bridges, tunnels and airports, and according to specific fields of research, namely, the use of open standards, the application of BIM workflows and Big Data connection, according to the purposes and goals of the present dissertation.

Some detailed insights taken from the analysis of the resulting documents, which lead to a better insight of the defined research questions are detailed in the present chapter.

Table 1. Summary and categorization of reviewed publications.

| **Category** | **Open standards** | **BIM workflow** | **Big Data** | **Technologies** |
|---|---|---|---|---|
| **Roads and highways** | 18, 26, 84 | 17, 20, 21, 23, 24, 25, 27, 29 | 28 | 19, 22 |
| **Railways** | 33, 37, 39, 42, 43, 44, 47 | 30, 31, 32, 34, 35, 36, 37, 38, 39, 40, 41, 45, 46, 47, 48, 49 | | 46 |
| **Bridges** | 52, 59, 60 | 50, 51, 52, 53, 54, 55, 56, 57, 58, 61 | 50 | 53 |
| **Tunnels** | 62, 67, 73, 74, 75, 76, 78, 85 | 64, 65, 66, 68, 69, 70, 71, 72, 73, 78 | | 63, 77 |
| **Airport** | 4 | 79, 80, 81 | | |
| **General** | 82, 84, 86 | | 81, 82, 83, 87, 88, 89, 90 | |

Tomek and Vitásek [17] analyze the economic efficiency of road construction by the integration of a life-cycle cost analysis (LCCA). They refer to BIM application as an assurance that no major contractual changes occur during construction, for when BIM workflows are applied in road projects the produced documentation is more reliable and provides a solid base for improved economic decisions.

The authors also refer to the importance of “incorporating maximal standardization” to achieve optimal control of the economic assessment of these projects.

In 2011, Lee and Kim [18] recognized the need for specific entities in terms of road design and proposed the introduction of entities to improve the schema, namely, IfcRoadSpatialElement (spatial element), IfcRoadServiceElement and IfcRoadElement (physical elements), as entities of abstract super type. Although some of the proposed entities never made it to the official released IFC schemas, it is important to highlight that researchers were timely aware of the lack of entities to cover all the specific elements on a road project.

The adoption of lean construction in Small Medium Enterprises (SMEs) devoted to highway projects is studied by Tezel et al. [20]. One of the proposed future directions recommended, at the Process level was to increase the adoption of BIM to improve the information conveyance between all project participants. Although BIM is becoming an imperative solution for linear infrastructure projects development, SMEs can struggle with the initial required investment, in terms of tools and training required.

Sankaran et al. [21] use the term Civil Integrated Management (CIM), and establish it as more specific than BIM for infrastructure projects due to their inherent specificities and requirements. In the paper, a survey is conducted on forty-two American State Transportation Agencies (STAs) to clarify the state of CIM adoption and integration into their workflows.

A clear perspective on how CIM can be implemented and integrated during the asset lifecycle is given (Scope & surveying, Design, Construction and operation and Management). The survey analysis returned some interesting findings, such as that all agencies agreed that 2D plans continue to be a core component of the information workflow, recognizing however the importance and benefits when deliverables from 3D modelling tools are used are superior. Only 6 of the 42 agencies reported using BIM for construction sequencing (also designated 4D BIM) purposes and only 2 reported expert knowledge when cost related information is connected to the project (5D BIM).

The fact that National STAs are not fully embracing CIM workflows as common and established practices is surprising as it is clear that the transition towards a total digital workflow is getting more and more on demand. However, it serves as an indicator that the transition presents challenges which have to be gradually addressed.

There are many technologies connected and that can benefit from their integration with BIM. Such an example was found on [22], where terrestrial laser scanners are used for the detection of highway retaining walls displacements.

The paper proposes a fully automated framework for feature extraction from point clouds to monitor the displacements. 3D models were in this case used to validate the extraction of geometric data from point clouds, and both sensor parameters and 3D models were imported into a simulation environment for assessment of their accuracy. From this research, it is clear that the connection of innovative and in constant development equipment and technologies to 3D models of the assets will always prove advantageous for analysis purposes, and that the research of mechanisms to establish those links, in the most reliable manner, is still in need.

Chong et al. [23] analyse the adoption and use of BIM in road infrastructure projects through two exploratory case studies, where the main uses where identified: visualization, quantity-take off, clash detention, transportation management, traffic impact simulations, conduction and preparation of surveys during the construction phase and structural analysis. There was no opportunity to identify the BIM uses during the operation and maintenance phases. Of interest also was the distinction of the applications directly connected within the BIM model: clash analysis, construction progress visualization, cost analysis, structural analysis, and those with indirect integration: transportation management, deviation detection and on-site tracking of construction progress. Since the case studies were road construction projects from two different countries, Australia and the People's Republic of China, an interesting comparison between the adoption and use of BIM was made. The paper concluded that BIM was used for similar purposes, but the managerial strategies applied were different. The reasons can be connected to: the different working cultures, to the fact that in the Australian case the client was a government department and in the Chinese a private transportation company, and to the state of adoption and use of BIM in infrastructure projects of each country.

The acknowledgement that the alignment design and the choice of optimal routes for linear infrastructures using traditional methods is cost and time consuming serves as an incentive for the adoption of BIM. Although the integration of BIM with Geographic Information Systems (GIS) is still a topic requiring the academic and industry's attention, Zhao et al. [26], propose an approach for the management of the alignment contextually integrated with the location planned for the infrastructure. In this paper, semantic web technologies are used for data integration, facilitating the planning process, combining the topographic and geographic data with the design of the alignment. The proposed integration also focuses on interoperability between BIM and GIS, aiding in the process of alignment optimization in a more timely and efficient manner.

The Visual Management (VM) practices in highways construction projects is the focus of Tezel and Aziz [27]. The paper describes how BIM can assist in visualization as a facilitator tool in meetings for example, where BIM models provide a more detailed overview of the projects. BIM models can enhance the quality of design briefings, safety simulations, improve the client's engagement to the project and to the scheduled activities simulation.

A railway project in South Korea was the case study in [31], where the goal was to investigate the benefits of BIM implementation. The study involved surveys to professionals working on the site and the assessment of possible improvements made if BIM was adopted in the early stages of the construction phase, which wasn't the case. One of the most interesting findings of the paper is the identification of 12 project errors that could be avoided, mostly related to dimension changes, miscalculations and dimensions wrongly defined. Authors also calculated and compared the costs associated with BIM implementation and the costs needed to fix the errors found, estimating savings of $38,503 if BIM was adopted.

A good example of open standard application to the modelling of railway bridges is presented by Lee et al. [42]. The paper suggests new IFC entities and IFC user-defined property sets for the modelling of the railway bridge. At the time of the paper publication the IFC released schema didn't contemplate specific elements for these particular infrastructures. The use of property sets was applied for customizing and adding information to the model and it proves advantageous since it doesn't alter the data model.

The insufficiency of open data standards for the information exchange of linear infrastructures still limits the application of full interoperability in these projects. This issue was the object of study in [43], where those limitations were analysed in rail projects. General software interoperability issues and the problematic of CAD based coordinate systems models and GIS were identified as the main issues. The paper refers to the unilateral possibility to exchange a model between 2 different software tools. The integration of object-based, alignment-based and GIS models still requires research and development, however recent standardization efforts, namely from BuildingSMART are improving and extending the IFC schema for infrastructure.

Tunnels are very special infrastructures with specific construction processes, not yet supported fully in terms of open standards. Zhou et al. [62] propose new entities for the IFC schema to accommodate the shield segment assembly construction as well as an algorithm to automatically detect constraints during the tunnel construction. Efforts as the ones made in this particular paper draw attention to the necessity of an almost constant update of the standards, for the inclusion of information on very specific construction processes (and all related entities, objects, equipment) which need to be included and correctly utilized.

In [88] the field of statistics, data mining and warehousing, machine learning and Big Data Analytics are the focus on a review of the potentialities of these recent technologies and techniques for the construction industry. The paper analyses the increased popularity in database solutions for Big Data storage, highlighting that their successful implementation is still missing.

The importance of Big Data management is also the focus in Ng et al. [89] where an infrastructure asset management (IAM) is combined with master data management (MDM) and the preliminary results of the proposed SIAM-MDM solution are presented. One of the conclusions states the benefit of the solution in assisting stakeholders on the process of sharing infrastructure BIM models and therefore contribute for the smart infrastructure initiatives which are becoming more and more common. Once again interoperability is referred to as the main key aspect for data integration in the light of the smart infrastructure concept.

Bilal et al. [90] propose a Big Data architecture and prototype implementation to optimize construction projects. Using Structured Query Language (SQL) commands the suggested approach was mainly for profitability performance purposes.

This paper helped to understand how big data, that can be characterized through quantity, variety of formats and speed of the data income, is so important for construction projects.

## 2.4. Conclusions and research gaps

The analysis of the resulting body of work of the presented state of the art in infrastructure information modelling allowed for the following conclusions to be drawn:

- Throughout the analysed literature, Interoperability is generally considered as one of the most important factors, still in need of research and development, for all professionals to benefit the most of BIM workflows application.
- Full Interoperability maintains a top place in terms of importance from the first project phases up to their operation, from inception onward.

The report of the review and the scrutiny of the resulting literature, called attention to some still present gaps in research, namely:

- Databases are considered to be a good solution for managing Big Data in infrastructure projects, however, in the reviewed body of work, no specific platform linking information in an open standardized way for linear infrastructure projects information was found.
- The connection of Big Data to BIM models, is not yet fully explored as it should, the suggestion of a framework was made only in one reviewed paper, with no implementation or validation though.
- The connection of Big Data and BIM models, through the exclusive use of open standard files, was not found in the presented state of the art. Because of the potentiality of the subject and lack of research on the particular field, this was one of the gaps found that gave motivation for the present thesis development.
- The airport category, especially when the airside pavement assets are concerned, is still not being given the proper attention in terms of research. Although similarities with roads and highways projects are clear, a more detailed attention should be given to these particular infrastructures.

# 3. Core concepts for research

The present chapter details some of the major concepts applied throughout the research for the dissertation. Similar to every other domain, when the foundation knowledge lacks or is not clear, so does the work being developed.

Therefore, the chapter details the most relevant concepts connected to the main research topic, namely sustainability, open information modelling, interoperability, asset centric workflows and databases fundamentals.

## 3.1. Sustainability concept

Sustainability as a concept involves using resources efficiently and effectively in order to eliminate hazardous decisions that can damage systems and prevent them from thriving. Sustainability serves as a principle in all fields of society, and its importance in construction shouldn't be understated, serving as a driver for innovation. When referring to the construction field sustainability presents three interdependent dimensions related to environmental, economic and social concerns. The impacts of all activities connected to the field have increasingly been object of attention, and new approaches on how to optimise efficiency in all the processes involved are constantly being developed.

Sustainability is obviously also connected to goals related to performance and efficiency improvements inside construction enterprises. Chang et al. [91] identified 29 key aspects related to the three dimensions, as follows:

- Economic: Corporate strategy, quality management, supply chain management, innovation system, corporate governance, customer service, communication management, network building, risk management;
- Social: occupational health and safety, education and training, wages and welfare, anti-corruption and fair competition, human rights, supporting community development, obeying laws and regulations, caring for all employees, promoting the development of the industry;
- Environmental: Environmental management, construction waste management, land use efficiency, water conservation and harvesting, materials conservation, energy conservation, managing impacts on biodiversity, emission reduction, green innovation and products, light pollution control, noise control.

It is clear that the identified aspects have to be considered throughout all the construction lifecycle, in all activities and processes that it comprises. Therefore the adoption of workflows that enable the needed feasibility of the sustainability principles should be encouraged. IT connectivity and digitalization play a big role in the achievement of such goals. There are many examples on how data science contributes to sustainability in construction projects, namely innovative computational methods that streamline the management of construction site big visual data [92].

Gatchie [93] proposes a framework for the integration of sustainability in projects, contributing to project success and suggests some concrete measures that can be implemented at the organizational level to integrate the sustainability metric on all phases of the projects development. The recommendations are divided and specific to the three dimensions previously defined.

Keeping an updated economic plan to always improve and allocate in the best way the financial resources, properly allocating project tasks and resources, controlling the quality of the work and actively involving all stakeholders. At the social level, recommendations such as encouraging open communication, setting standards, appointing sub-leaders and incentivizing training were proposed. Environmentally, the recommendations of the framework were mainly: reducing, reusing and recycling materials, regularly performing environmental impact and cost analysis, resort to renewable energy sources and promoting best practices in terms of resources conservation.

Aarseth et al. [94] enlightens that the incorporation of innovative types of technical solutions, systems and standardized practices is one of the most important steps to implement project sustainability.

In conclusion, it can be stated that every measure that contributes to the deliverables improved quality and the efficiency of the processes during their development as well as implementing solutions to enhance the clear exchange of information between all stakeholders involved in a project is a major vehicle for project sustainability.

The construction industry is vast in terms of specialized teams involved, and the project that accompanies the assets lifecycle includes also a strong digital component, therefore, every technological improvement which can potentially aid in the establishment of sustainable policies, practices and workflows should be welcomed and implemented.

## 3.2. Open information modelling standards

Building Information Modelling (BIM) can be nowadays considered as a “buzzword” for it can be summarized quite simplistically as the digitalization of all data included in a construction project and an improved workflow which aids project participants to achieve improved communication, insight and control, throughout its whole lifecycle.

Perhaps a better assumption is even to not limit the application of the term to the construction industry (heavily connected to Architecture and Civil Engineering), but include other related fields as Mechanical, Electrical, Geotechnical, Environmental and Chemical Engineering, which can also benefit from BIM implementation in their specific workflows.

There are many definitions found in the specialized literature, some of which were chosen to be left as reference, as follows:

Sacks et al. [95] defines BIM as a “verb or an adjective phrase to describe tools, processes, and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction, and later its operation. Therefore, BIM describes an activity, not an object. To describe the result of the modeling activity, we use the terms “building information model” in full, “building model,” or most simply, “BIM model”. Even though the definition narrows BIM to buildings in the same document it is mentioned its application to the infrastructural field, in projects related to roads, highways, railways, tunnels, bridges, etc. maintaining the same expected optimal results in terms of design, construction, management and operation, performance, and collaboration.

Jeong and Kim [96] call attention to the importance of the important semantic enrichment possible when a project uses BIM: “BIM is semantically-based and object-oriented; it has 3D modeling capabilities and allows users to retrieve comprehensive design model information represented by objects and their attributes through its authoring tools and standard data schemas such as IFC.” The description given also points out the relevance of retrieving all data contained, from the authoring tools (used to create the actual model and submodels) resourcing to the application of standard data schemas, which are essential for a streamlined exchange of information.

The process of exchanging non-proprietary data, through a methodology that embraces and values collaboration based on open standards and workflows is generically referred to as Open BIM. As a trademark, openBIM is a "universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows. openBIM is an initiative of buildingSMART and several leading software vendors using the open buildingSMART Data Model" [97].

One connected concept is the level of maturity of the BIM adoption, and the previously defined openBIM methodology falls under the highest level of maturity of BIM (defined as Level 3), and interoperability constitutes one of its major drivers, designated Integrated-BIM (iBIM), meaning total collaboration between all parties involved during the entire lifecycle of the asset project (Figure 6).

If theoretically, the concept seems relatively easy to implement, that is still not the case in reality, where released open standards for infrastructure are still not sufficiently robust for this level of maturity to be achieved.

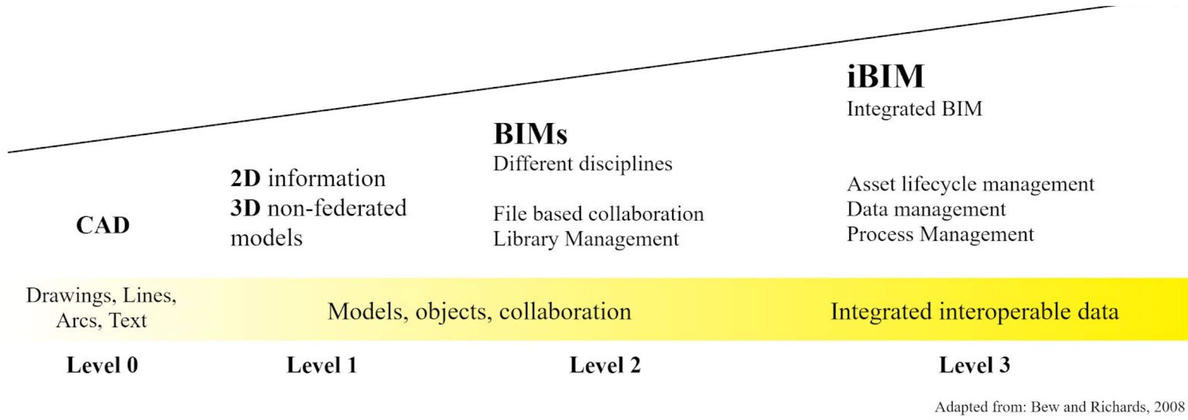



Figure 6: BIM maturity levels.

Level 3, i-BIM extends the use of BIM to the management and maintenance phases, in terms of the asset lifecycle, process and data management.

Specifically for linear infrastructure projects there are currently some options in terms of standards, namely buildingSMART's Industry Foundation Classes (IFC), COINS, INSPIRE Transport Network, ISO TC211, Inframodel (Finnish), NASA/TQ QUDT, SOSI (Norwegian), OGC InfraGML, OKSTRA (German), RWS-OTL (Dutch), W3C SKOS, PROV-O) [98], MVD and IDM, LandXML, CityGML, gbXML, CoBie, BCF and JHDM. The referred standards all find application in the infrastructural field but obviously in characteristically specific ways. Some of them are actively in the development and improvement stages, as is the case of IFC (Figure 7).

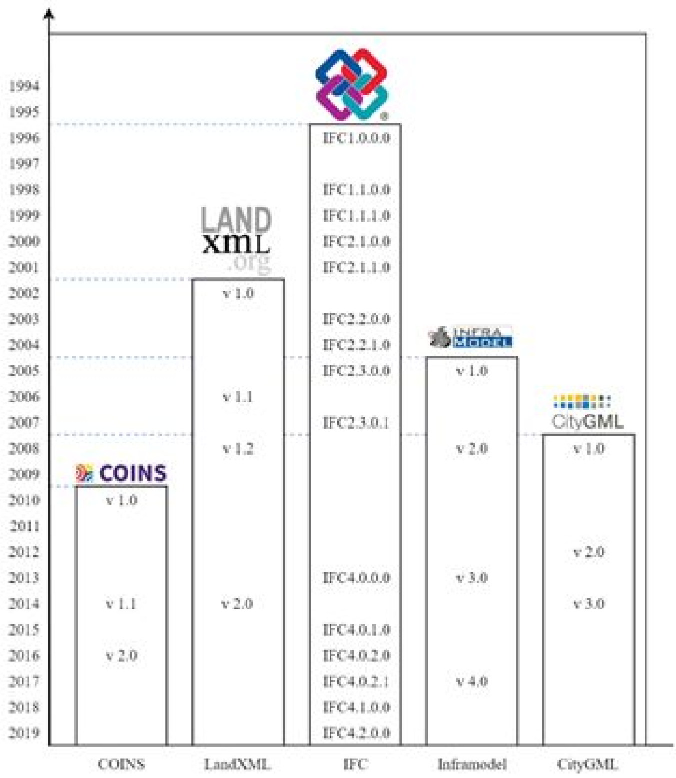



Figure 7: Release dates of standards applicable to the infrastructural field.

### 3.3. Interoperability concept

Many participants and teams are involved throughout the development of linear infrastructure projects, each of them with specific roles, that result into actions and/or deliverables. Communication between them is as important for the projects' success as is the imparting of the deliverables they produce. Usually, each field (e.g. Traffic Engineering and Design) and corresponding actors, resort to specialized tools and equipment, which is perfectly acceptable, since it is, for now, utopic for one tool to excel in all needed tasks. However, there is a required flow of data between project participants, digital data, that has to be conveyed in a reliable way.

For that motive, all information contained in the projects should also be fully interoperable, perhaps one of the more challenging objectives and key goals of BIM application. This implies the interchange of all project's data between all stakeholders, without omissions and errors, so that every intervenient has the utmost confidence in the reliability of the information retrieved. Due to the complexity of linear infrastructure projects there are numerous needed model exchanges from different sources (Figure 8). These exchanges take place during all the lifecycle of the project.

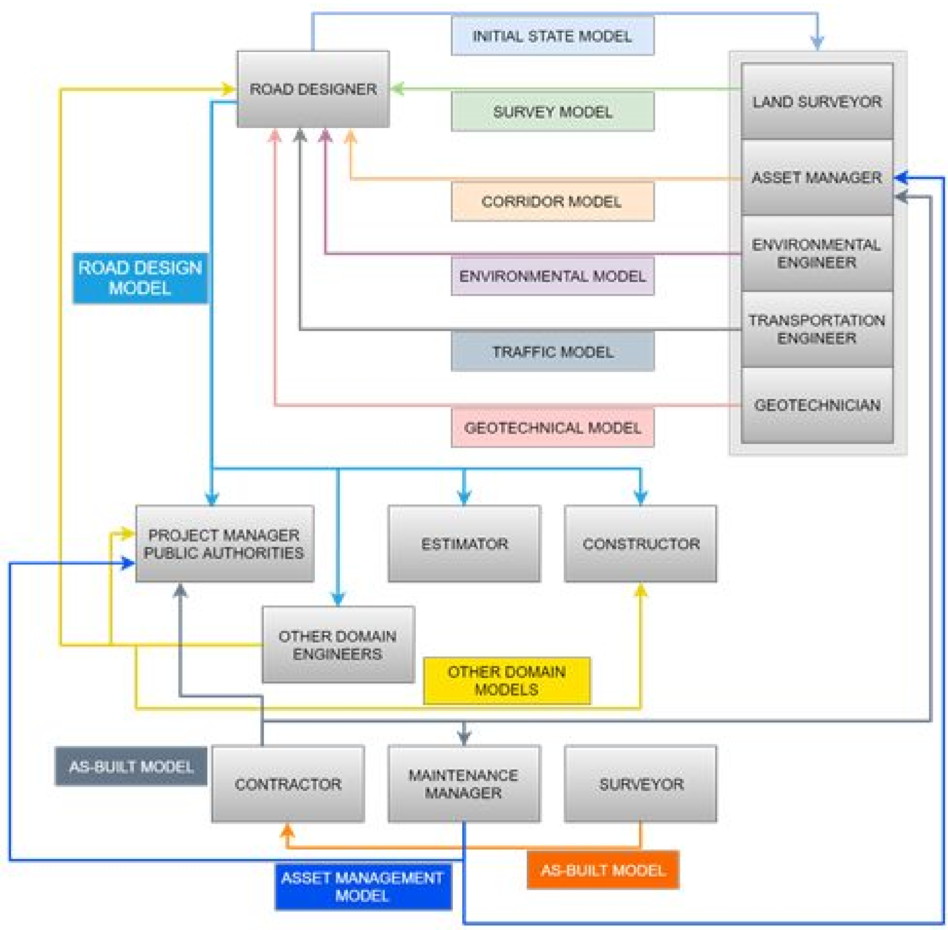



Figure 8: Exchange model scenario of a road project, adapted from [99].

The data-driven exchanges described justify and benefit from an early application of open exchange standards, vehicles for interoperability, which when applied properly allow the information to flow from a native model environment (connected to the tools used from each intervenient part) to a Common Data Environment (CDE).

### 3.4. Asset-centric BIM workflow

The BIM dictionary presents as definition to the term BIM workflow [100], the following: "A workflow identifies major successive activities to perform, decision gates to pass-through, and delivery milestone to reach. A BIM workflow is typically part of larger BIM Processes - aimed at fulfilling strategic/operational objectives - and may include several documented Procedures. There are two major types of BIM Workflows: Internal BIM Workflows and Collaborative BIM Workflows".

The definition distinguishes internal workflows, as the activities related to the model's production within an organization and their internal exchange, and collaborative BIM workflows, where the exchange of project data between all project participants and organizations demands the proper planning of activities, (in terms of type, time and sequence) to best facilitate that share.

Infrastructure projects are complex, in terms of the required information (quantity, type, source, etc.) to serve in the best way throughout all the asset's lifecycle. All activities since the early stages of the project (e.g. concept, planning and design) up to the ones during the construction phase, lead to the production of large amounts of data, which has to be managed and organized in a federated way. Organizations are now starting to realize the importance of the control over the access, retrieval, update of all information that comes from the Design and Construction phases. When BIM workflows are properly adopted in the early stages, the maintenance of these robust sources of information becomes easier to maintain and use, constituting a solid base of reliable data serving the asset up to the end of its operating life.

Basically, the workflows can be divided into those carried up to the end of the construction of the asset and those performed in the operation and maintenance phases, and through all the lifecycle the flow of information should be maintained and streamlined.

It is easy to perceive that when infrastructure projects were not supported by this availability of information, provided through the use of BIM, the lack of information leads to economic and poor scheduling damaging consequences. Although the changes needed for this "upgrade to BIM", in terms of improving the workflows and processes used by all organizations, teams and professionals connected to the projects, are not absent of challenges, the advantages in terms of quality of the deliverables, productivity boost and cost savings, should be sufficient drivers for the needed adjustments.

Figure 9, outlines both the construction and asset centric workflows, their corresponding stages, main purposes and the final resulting deliverables and outcomes.

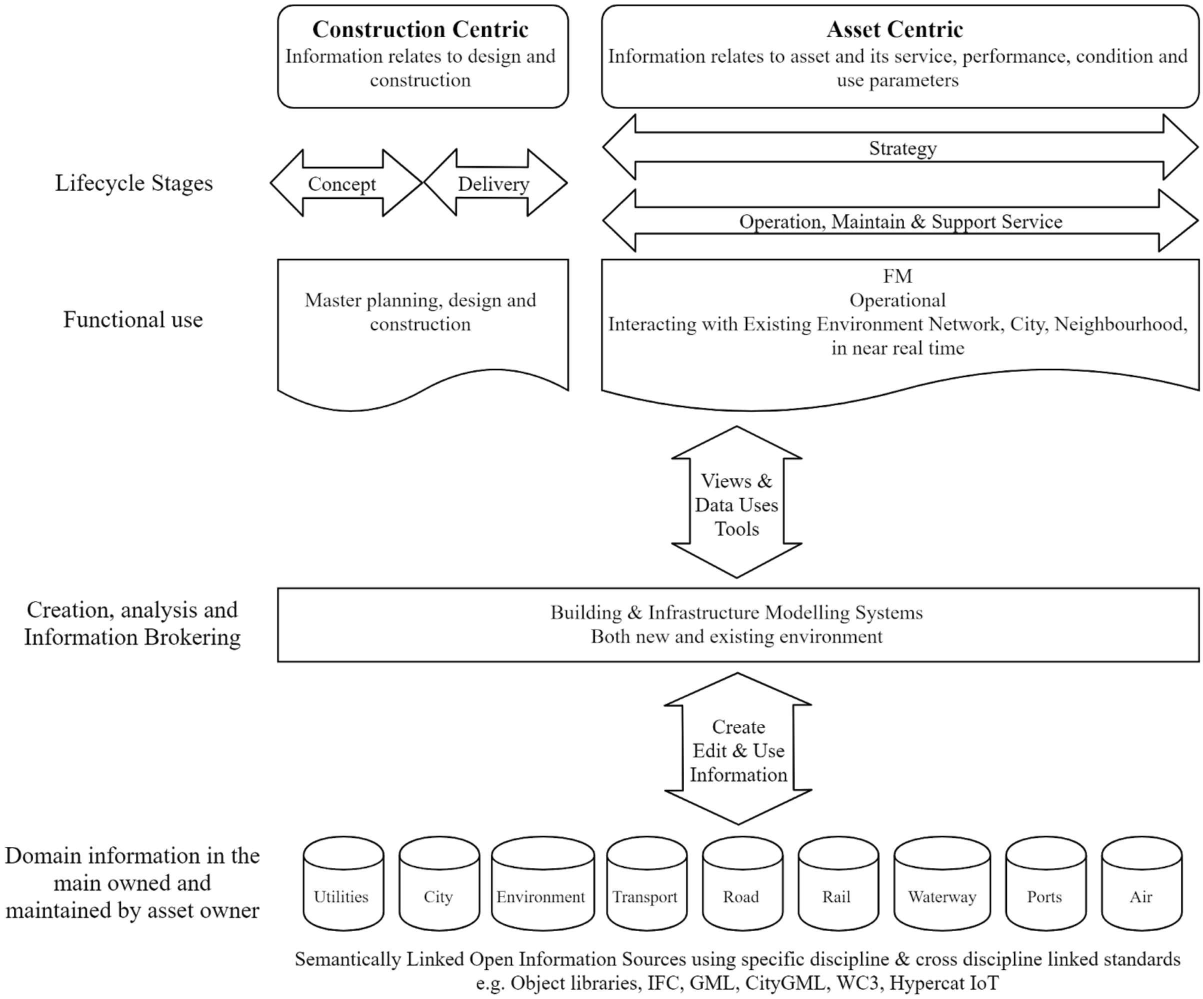



Figure 9: Construction and asset centric, adapted from [5].

The asset centric workflow spans the opportunities to achieve project sustainability, especially when management and maintenance of the asset is considered. Inheriting data from the previous phases, the operation and maintenance are central in asset centric workflows.

The central asset BIM model serves as the core to which all data is linked and the asset owner should explore the best possible and reliable way to establish federated, complete and easy to access information sources.

Databases can be used in a very effective way to establish these needed connections, even when proprietary file formats are being applied, however, when one considers the advantage of retrieving information in a reliable way, open standards have to be applied consistently.

## 3.5. Databases fundamentals

Database modelling is the first step when a structured and operational database is needed to gather under one source all information needed, for example related to a construction project. Database systems were developed in the 70’s as a management solution for organizations to systematically and in a structured system, store information.

Common uses for databases are: enterprise (sales, accounting, human resources), manufacturing, finance (banking, transactions), telecommunication, web-based services (social media, online retailers), documents and navigation related.

Nowadays, databases are commonly used throughout most activities for their capacity of gathering and organizing different types of data from multiple sources and they are designed to manage large bodies of information. And since the beginning of their creation they evolved from the storage of simple structured information to the possible inclusion of data with complex relationships and structure.

To properly design a database some steps have to be followed, as presented in the following Figure.

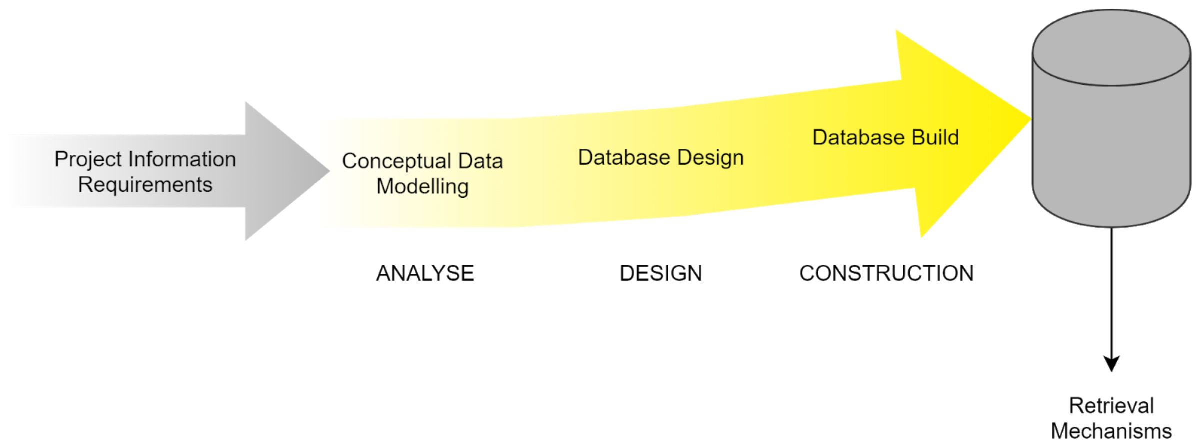



Figure 10: Database creation steps, adapted from [101].

The first step involves the definition of the project requirements, essentially the purposes of the database, and what are the expectations of the users in terms of their necessities. It is in this phase that the data and functional requirements are documented.

The requirements document mainly describe the type of data items and their attributes, defining their constraints and the relationships between them.

Once the outlined goals are established, the process of analysing how the data required by users can be organized conceptually takes place. The conceptual data model is a formal representation of what the system should encompass. In this phase a map of the concepts and how they relate to each other is defined, and the adequate type of database to meet the project’s requirements is chosen.

The design phase establishes the system specifications for the construction of the database and the corresponding schema. The database is then populated. The data is accessed through retrieval mechanisms, that define a set of criteria usually by querying (stating the request for specific information) the database. The Database Management System (DBMS), selects and retrieves the demanded data, which can then be stored and viewed. The domain-specific language Structured Query Language (SQL), is one of the most used to prepare the queries and communicate with the database.

Data models are the base of the database structure, among the different types, the following can be found:

- Hierarchical database model
- Relational model
- Network model
- Object-oriented database model
- Entity-relationship model
- Document model
- Entity-attribute-value model

Because of the entity oriented structure of the IFC file format, an entity-relationship model was chosen as the most adequate. Pony object-relational mapper (ORM) was chosen for the design of the database.

One of the advantages of Pony ORM is the capability to interact with the database using Python, generating functions and expressions which can later be translated into SQL and used for the query of the database.

# 4. Linear Infrastructures design & information modelling

## 4.1. Linear infrastructure design concepts

The geometric design of linear infrastructures is largely influenced by national standards and guidelines. Most countries adopt independent guidelines that provide requirements and conduct the designer to follow certain constraints especially connected with safety concerns, user comfort and sustainability of the final solution. Therefore, it is the role of the designer to follow them in conformity with the project's requirements in terms of fulfilling in the best way possible all the expectations and performance requirements for the specific asset.

The core graphical content of linear infrastructure projects contains the representation of the surface/s, alignments, profiles, cross-sectional elements and corridors and is briefly described as follows:

The nucleus of linear infrastructure projects' geometric design is the definition of the alignment/s (2-dimensional geometric representation of the path) and profile/s (representation of the vertical path). Both of them are also highly dependent and limited by the constraints imposed from the surrounding environment, therefore the surface/terrain where the infrastructure is planned to be constructed and its correct representation serves as the base of the design process.

Digital terrain data is usually collected from remote sensing, photogrammetry, and Global Positioning Systems (GIS) techniques. Nowadays, innovative methods of obtaining terrain data, such as the use of LiDAR equipment, deliver detailed point clouds, usually used for the rigor and precision they provide to the designer. Most software tools dedicated to linear infrastructure projects contain features that allow the creation of terrain data. Terrain models nowadays are often replicated digitally from large collections of points acquired by laser scanners or similar technologies that allow an accurate 3D representation of the surface.

The rendering of these points is commonly processed through Delaunay's triangulation, which calculates the surface geometry, forming a triangulated irregular network (TIN) connecting the points (nodes) that are closest together, as can be seen on the next figure.

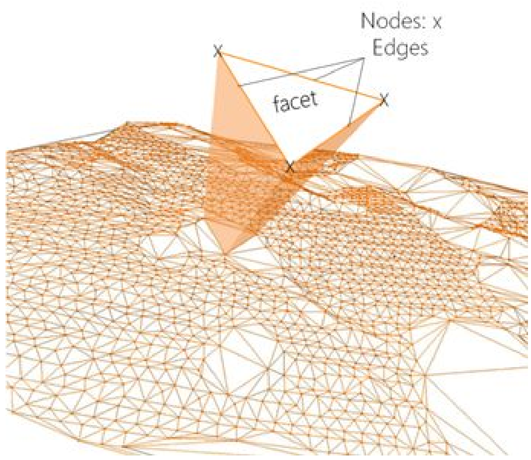



Figure 11: TIN surface.

The horizontal alignment is the 2D representation of the path of the linear infrastructure, often composed of tangents, transition curves (e.g. spirals, clothoids, parabolas) and circular curves (Figure 12).

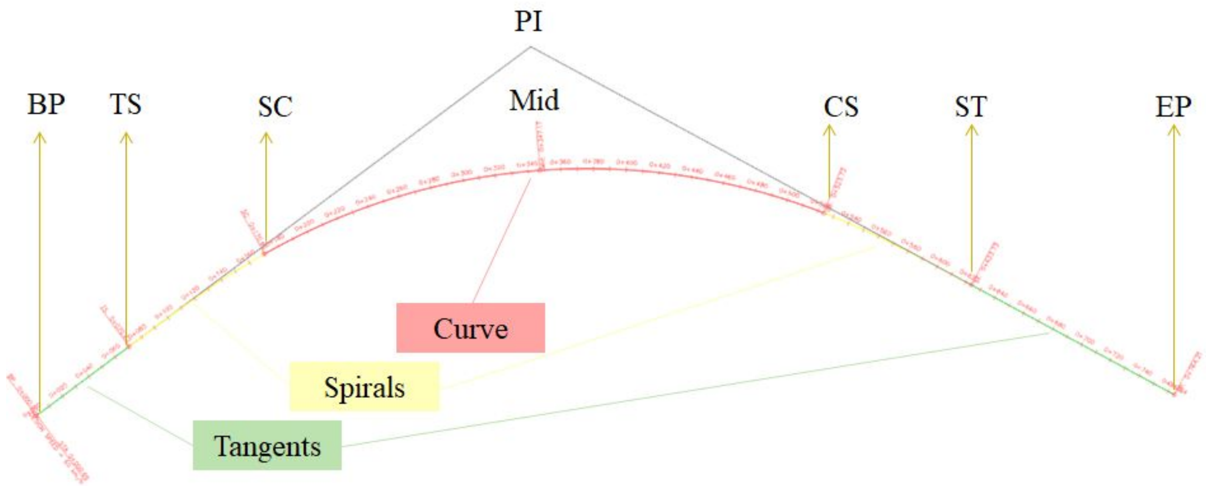



Figure 12: Example of the representation of a horizontal alignment.

The profile, designated also as vertical alignment, provides the vertical path of the asset, and is usually composed of tangents and curves (e.g. circular, parabola, asymmetrical parabolas).

Both horizontal and vertical alignments are designed based on specifications, manuals, protocols and guidelines, often according to national requirements (defining design, comfort and safety) and their final layout is highly interconnected between them as well as with the terrain.

The vertical alignment design relies on information about the terrain, therefore, in the design stage both the surface/terrain profile and the design profile are represented. An example of the representation of both can be viewed on Figure 13.

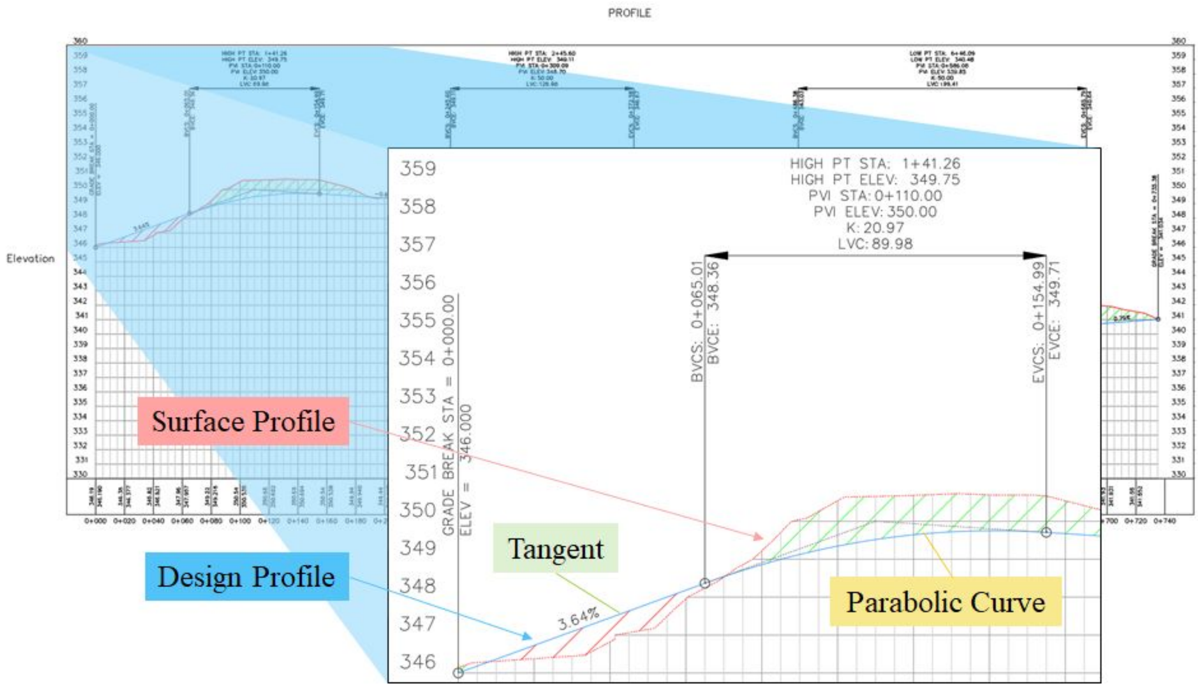



Figure 13: Example of the representation of the vertical profiles.

The combination of the horizontal and vertical alignment results in a 3-dimensional path of the asset. This element often serves as the representation of the centerline of the asset and the corresponding cross sectional representation is connected to it. It is also not uncommon that these elements serve as base for the positioning of other elements such as barriers for example.

The cross section definition is one of the most interesting steps of the design, as the dedicated tools now allow for the creation of dynamic parametric cross-sections, meaning that their individual components are interlinked and can be defined to be dependent on each other and follow the rules defined by the designer. This feature boosted the capacity to analyse different options in terms of geometric configuration, due to its interactive customizable possibility to dynamically be processed. Usually, the tools provide users with predefined template cross-sections, at a national level different specifications result in different cross-section requirements and geometries and therefore these cross-sections often constitute base libraries. More important than that is the possibility to create custom cross-sections and the corresponding individual elements. Although linear infrastructure projects present normally a predefined number of typical cross-sections, it is not rare specific ones are required and therefore particular elements need to be designed. Such cross sectional elements can be designed also in geometric modellers (e.g. FreeCAD, OpenSCAD), but most of the dedicated tools for linear infrastructure design present also that feature, usually through plug-ins or add-ons (e.g. Bentley's OpenRoads Designer contains a template creation tool) or independent tools as is the case of Autodesk Subassembly Composer.

An example of a custom built cross-section is presented on Figure 14. The option to add restrictions and establish connections and dependencies between the different elements is given through the creation of parameters, e.g. Figure 15 presents the details of the edge of pavement point 3, where the positioning is defined though slope and width. Although a default value can be defined by the user, later on, in case of a needed modification to the project, there is no need to adjust the value for each element individually. The dynamic aspect of parametric cross-section design proves to be a time saving feature during project preparation, although requiring initial training.

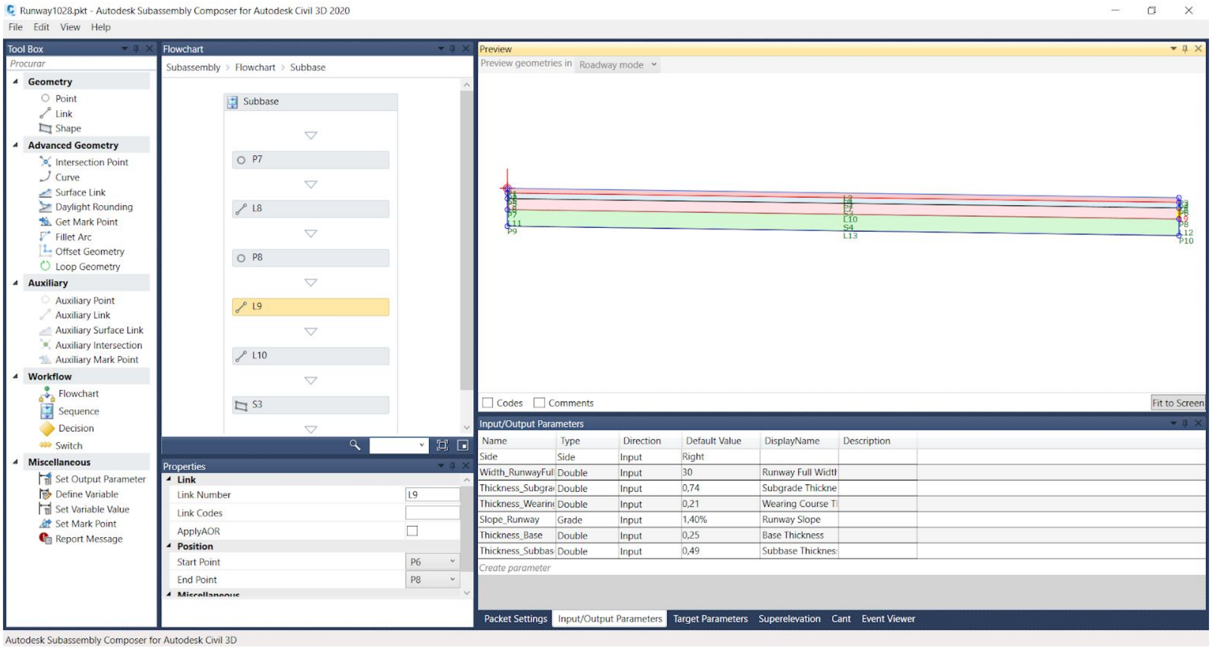



Figure 14: Custom cross-section, Subassembly Composer.

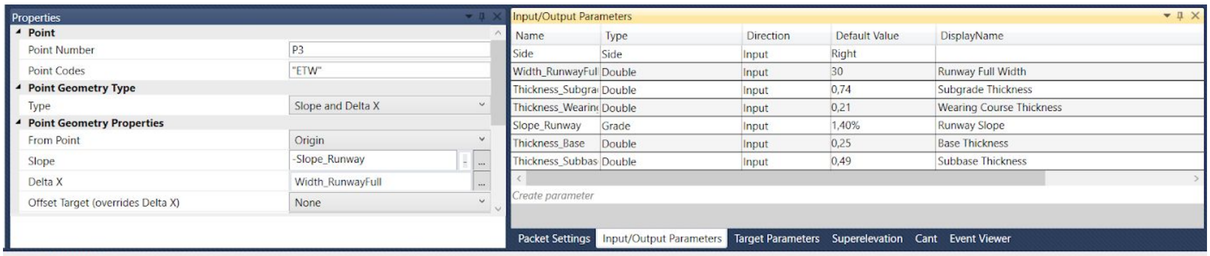



Figure 15: Parametrization of a cross-section point.

Once the cross sectional sections of the infrastructure are defined, the corridor/s can be processed, embodying what can be considered the digital twin of the asset to be built, or of the pre-existing infrastructure.

Most commercial tools dedicated to the design phase of linear infrastructure projects offer the possibility of inserting semantic information to the model, as can be seen in Figure 16, where radargram test results are associated with the corresponding location on the asset in the model. However, when exporting the project in an open file format this information is lost, which constitutes a major problem. Design teams need to invest time in the development of projects which can later be shared with other project participants confident that all the information inserted is shared without omissions.

One of the major issues addressed in the present dissertation is establishing the connection between the semantic data to the BIM model through the use of open standards, and the proposed framework proves to overpass the insufficient exportation capability of BIM models to open format files.

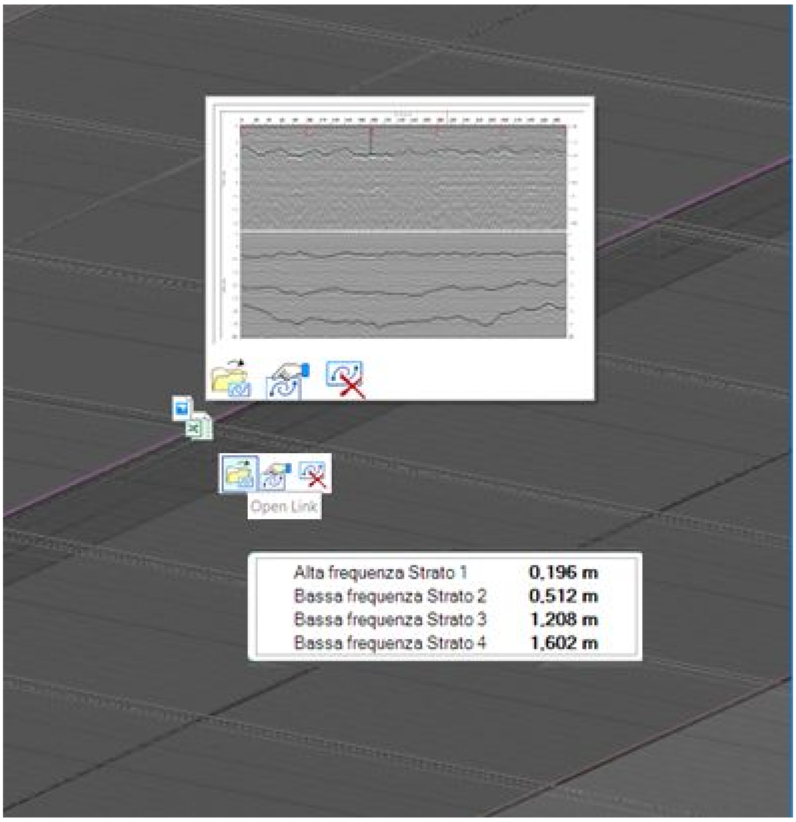



Figure 16: Connection of semantic information to a BIM model.

Amongst the most used supporting software tools for the design phase of linear infrastructure projects are Autodesk's Civil 3D and Bentley's OpenRoads Designer. A review of the design of the Lamezia Terme Runway supported by Civil 3D is described in the present section.

The base information for the model consisted of a series of non georeferenced CAD drawings, which added some difficulties on the correct location of the runway. Once the coordinate system was set, reference points were created to establish the exact position of the asset. One of the first things of concern was the georeferencing of the model, being that the Lamezia Terme International Airport is located in Lamezia Terme, Province of Catanzaro, Italy, the coordinate system selected was WGS 84 / UTM zone 33N (Figure 17), Geodetic CRS: WGS 84, Datum: World Geodetic System 1984, Ellipsoid: WGS 84, Prime meridian: Greenwich, Data source: OGP. Since the base CAD drawings contained topographic points and curves, those were imported to refine the definition of the airport's terrain model (Figure 18).

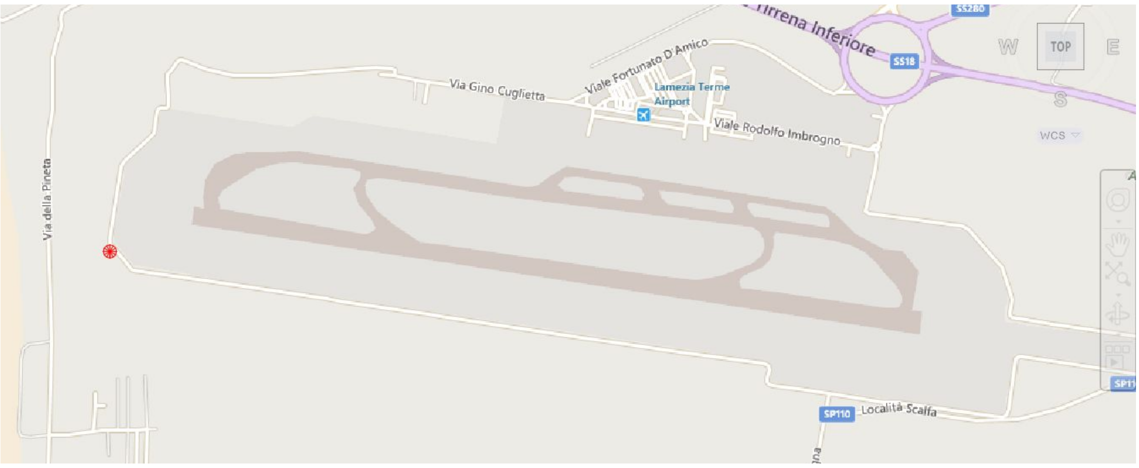



Figure 17: Geolocation of the Lamezia Terme International Airport.


Figure 18: TIN model of the Lamezia airport airside terrain model.

Once the terrain was modelled, the definition of the alignments was made (Figure 19) and of the profiles (terrain and runway), for the creation of the 3D alignment, that defines the centerline of the runway.


Figure 19: Alignment definition.

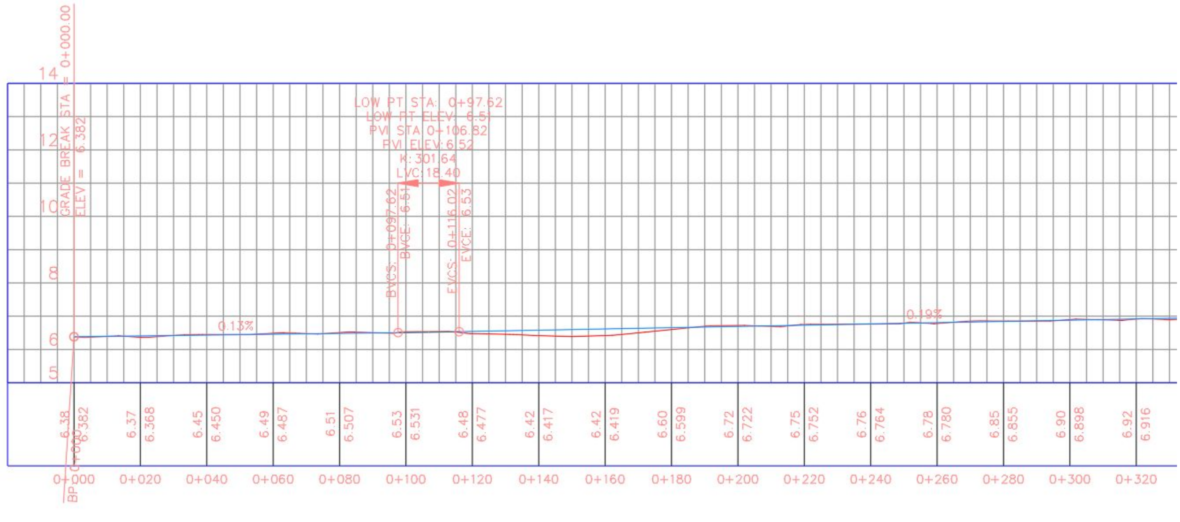



Figure 20 – Profiles definition (detail).

After those steps, the custom cross-section created in Autodesk Subassembly Composer 2020 was placed and the corridor processed.

### 4.1.1. IFC for infrastructure development

From the beginning BuildingSMART has introduced and supported the creation and adoption of open, international standards as the Industry Foundation Classes (IFC) to improve interoperability (Figure 21).

| Version | Name | ISO publication | Published | Current Status |
|---|---|---|---|---|
| 4.2.0.0 | IFC4.2 | - | 2019-04 | Draft |
| 4.1.0.0 | IFC4.1 | - | 2018-06 | Official |
| 4.0.2.1 | IFC4 ADD2 TC1 | ISO 16739-1:2018 | 2017-10 | Official |
| 4.0.2.0 | IFC4 ADD2 | - | 2016-07 | Official |
| 4.0.1.0 | IFC4 ADD1 | - | 2015-06 | Retired |
| 4.0.0.0 | IFC4 | ISO 16739:2013 | 2013-02 | Retired |
| 2.3.0.1 | IFC2x3 TC1 | ISO/PAS 16739:2005 | 2007-07 | Official |
| 2.3.0.0 | IFC2x3 | - | 2005-12 | Retired |
| 2.2.1.0 | IFC2x2 ADD1 | - | 2004-07 | Retired |
| 2.2.0.0 | IFC2x2 | - | 2003-05 | Retired |
| 2.1.1.0 | IFC2x ADD1 | - | 2001-10 | Retired |
| 2.1.0.0 | IFC2x | - | 2000-10 | Retired |
| 2.0.0.0 | IFC2.0 | - | 1999-10 | Retired |
| 1.1.1.0 | IFC1.5 ADD1 | - | 1998-08 | Retired |
| 1.1.0.0 | IFC1.5 | - | 1998-01 | Retired |
| 1.0.0.0 | IFC1.0 | - | 1996-12 | Retired |

Figure 21: History of the IFC versions, adapted from [102]

Since 2014 the organization dedicated specific attention to the infrastructure field. Currently the IFC “infrastructure room” totals a number of five Working Groups specific to infrastructure: IFC Road, IFC Rail, IFC Bridge, IFC P&H (Ports and Harbours) and IFC Tunnel. All these initiatives find their foundation on the already published and in use specifications such as IFC4/ISO16739, IFC Overall Architecture and IFC Alignment (Figure 22).

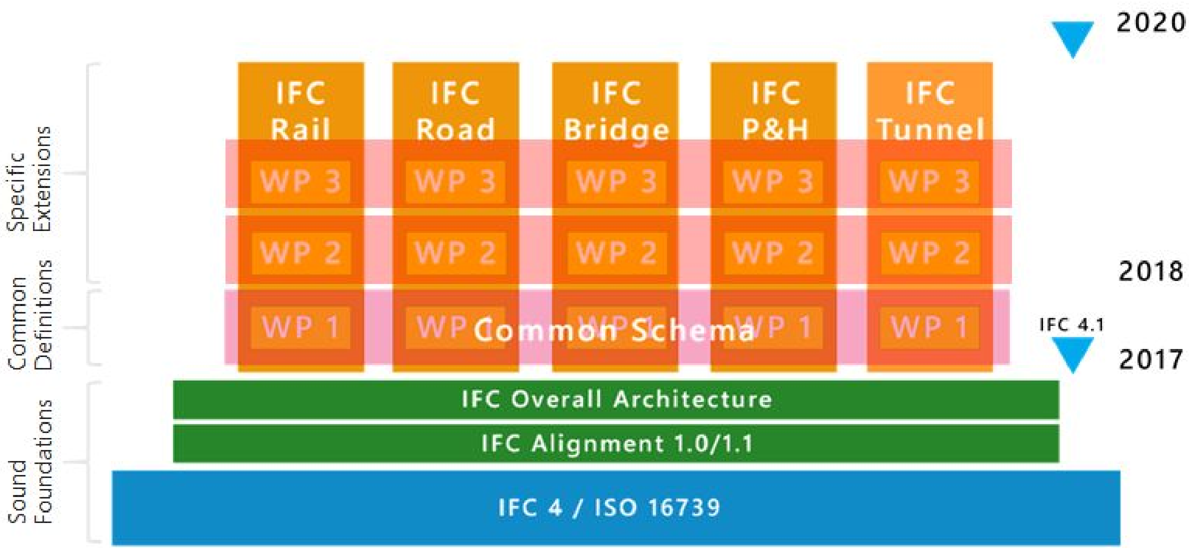


Figure 22:  IFC extension schedule, adapted from [102].

A more detailed history of released versions of IFC relevant to the infrastructure field can be viewed on Figures 23 and 24.

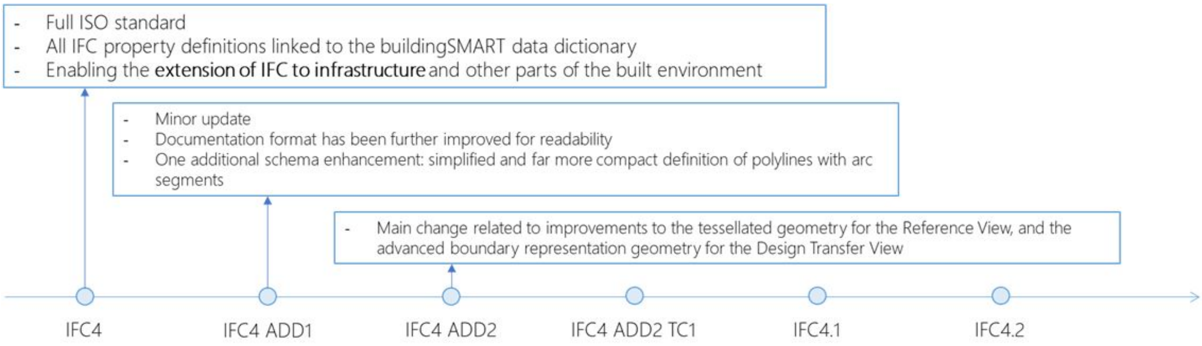



Figure 23: Updates made in IFC4, IFC4 ADD1 and IFC4 ADD2.

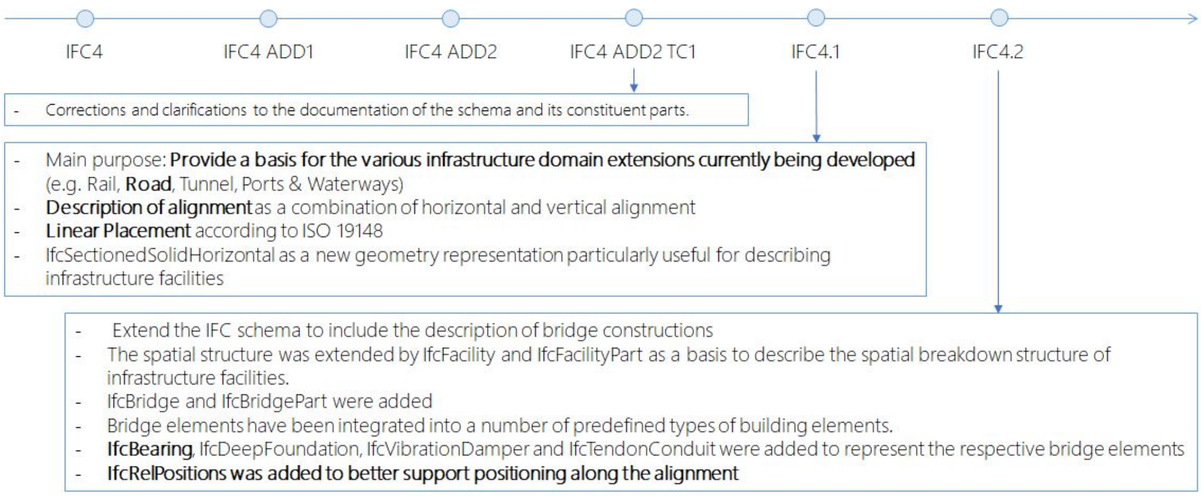



Figure 24: Updates made in IFC4 ADD2 TC1, IFC4.1 and IFC 4.2.

Industry Foundation Classes are one of the five standards developed by BuildingSMART International and were created with the intention of improving the sharing of information regarding the built environment industry throughout all phases of the project and asset lifecycle. The other four standards are Information Delivery Manual (IDM), Model View Definitions (MVD), BIM Collaboration Format (BCF) and buildingSMART Data Dictionary (bSDD), and are referent to documenting business processes and data requirements, data model exchange specifications, communication protocols and to a standard library of general definitions of BIM objects and their attributes [103].

IFC is often simplistically referred as a file format, but it should be instead referred to as a common data schema (standard) for Open BIM data exchange, as it codifies the description of the concepts, processes, actors, components, characteristics, geometry, semantics, analysis etc. that later can be retrieved and decoded from machine-readable to user data. The IFC data is mostly encoded in the STEP Physical File (SPF) format, based on the ISO standard for clear text representation of EXPRESS data models, ISO 10303-21 [104].

One of the files formats resulting from the encoding of data has the extension .ifc and presents a structure divided into two sections: header and data. The header section contains general information: file name, description, the application that exported the file, file schema and Model View Definition (MVD). The data section is where all instances of the entities are defined.

### 4.1.2. Pavement modelling options assessment

As previously mentioned, BuildingSMART is devoting its attention to infrastructure projects, and with particular interest to the present dissertation, one of the initiatives focuses on roads, and how IFC can after the release of IFC 5 fully encompass all descriptions required when such projects are being developed.

The geometric representation of the asset structural body is currently limited (in the latest release IFC standard - 4.2) to the adoption of the entity IfcBuildingElementProxy to define the pavement courses, which doesn't provide a defined meaning to the "building" elements as needed, and represents basically an anonymous IFC element. The IFC Road project focused on creating new entities and properties that allow designers and remaining participants to properly define all components and special events connected to the asset (e.g. courses, kerbs, superelevation).

As an example, for the purposes of the present work, the exportation of runway corridor model of the Lamezia Airport required the use of the feature "extract corridor solids" in Civil 3D, in order to enable the exportation of the complete runway structure to an IFC file. The exportation of the project to the Industry Foundation Classes file format, allows the selection of the objects to be exported (e.g. alignment, Zone, Spaces or Solids), and the exported view definition by default is CoordinationView_V2.0. The supported IFC Schemas for the 2020 version of the software are IFC 2.3, IFC 4 and IFC 4.1. Some entities of the IFC can be detailed on the exportation options menu, namely, IfcAddress, IfcActor and IfcOwnerHistory.

The resulting IFC file, was then analysed and viewed with the support of BIMCollab ZOOM (Figure 25), a free model viewer based on BuildingSMART's open standards IFC. This viewer only allows visualization of IFC up to 4.0 that is why the airport runway model was also exported to the IFC 4.0 compliant file. The visualizer allowed a detailed view of the runway's corridor. The structural layers of the pavement (courses) are clearly represented, however, their designation is either <unknown> or <BuildingElementProxy>, which is semantically not sufficient.

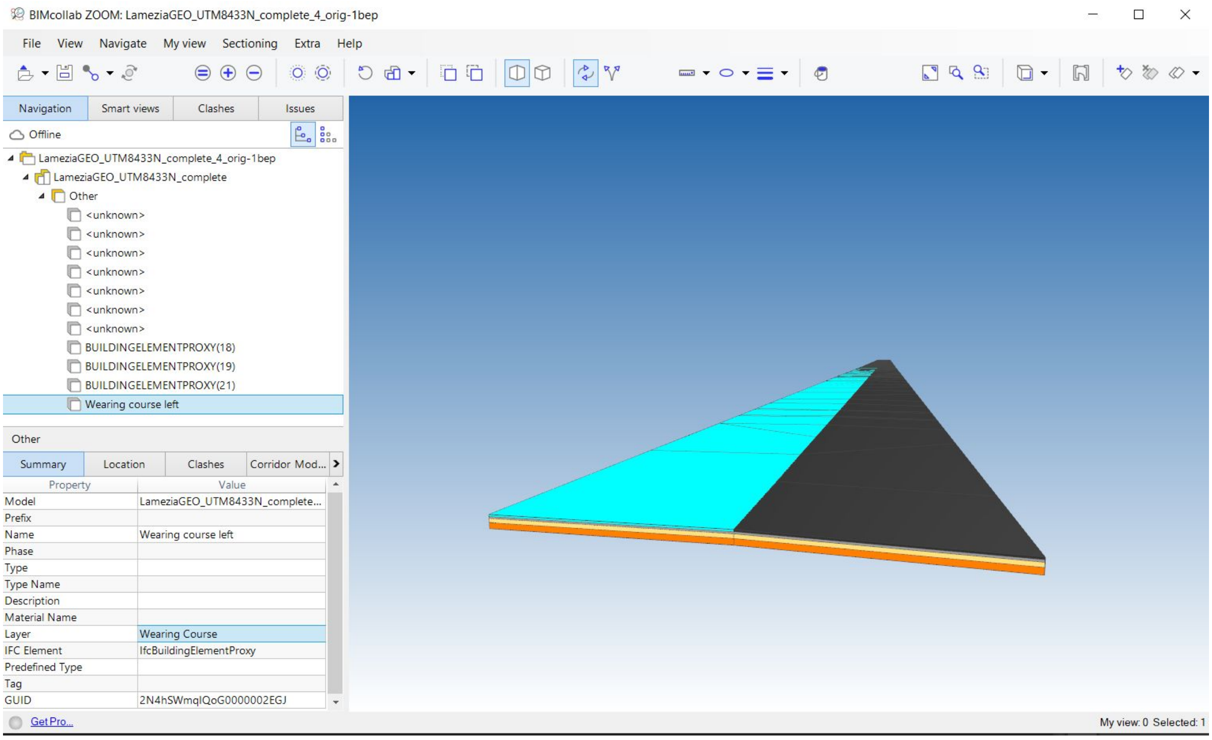



Figure 25: Visualization of the airport runway model (IFC 4.0)

The IfcBuildingElementProxy serves as a proxy definition that provides the same functionality as the subtypes of IfcBuildingElement, without predefining the meaning of the specific type of building element it represents. IfcBuildingElementProxy is in this case used to exchange  specific types of element (pavement layer) for which the current specification does not yet provide a semantic definition.

The IfcBuildingElementProxy entity contains 9 attributes: (GlobalID, OwnerHistory, Name, Description, ObjectType, ObjectPlacement, Representation, Tag and PredefinedType). The IfcBuildingElementProxy's Name attribute in the IFC file was modified to the “Wearing Course left” as follows.

#192= IFCBUILDINGELEMENTPROXY('2N4hSWmqIQoG0000002EGJ',#53,'Wearing course left',$,$,#209,#215,$,$);

The manual update of missing semantic information contributes to understanding the individual airport pavement courses, which also can be done programmatically using one of the software libraries with an API (Application Programming Interface) that supports relevant IFC schema.

When working with open standards, one should always privilege the minimization of the creation of new entities and make the most of the already released ones, in a harmonization process. Since the current released version of the schema only provides an anonymous element to define each individual course layer, it is predicted that this will be a specific entity in future releases of the standard.

Therefore, for effects of representation via IFC, an entity designated IfcCourse (from the IFC4.3 First Draft) was selected to define each individual layer of the pavement, also specified through a specific entity IfcPavement (from the IFC4.3 First Draft). With the introduction of these new entities, it is possible to define the assets structure, following the diagram presented in the next figure.

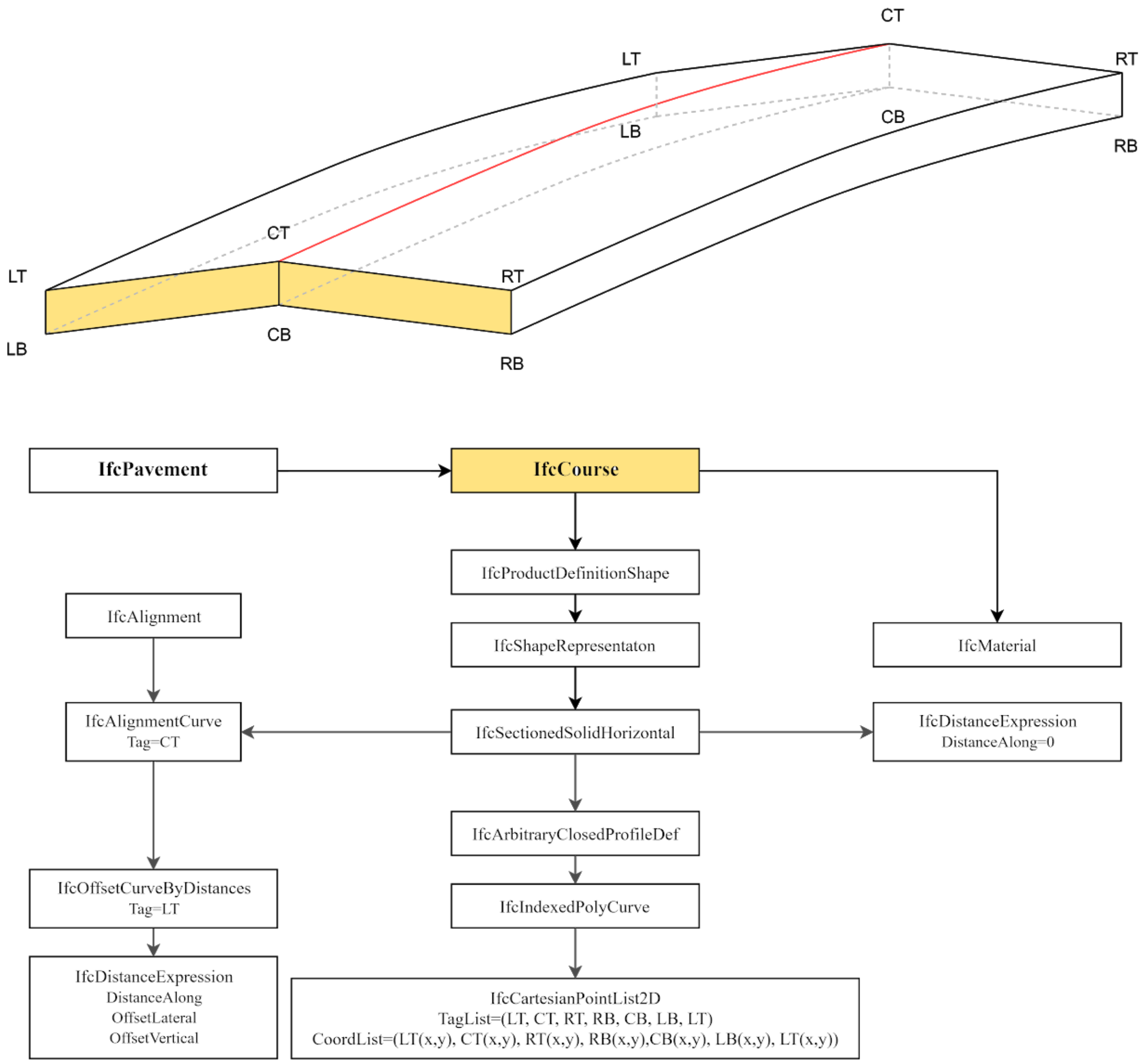



Figure 26: Pavement layer representation in IFC.

This representation uses two entities not yet released and all the remaining elements are already official entities of the standard latest official version. In this representation, every pavement layer corresponds to an entity IfcCourse. Each course can be connected to the respective material information (IfcMaterial).

The geometry of each layer is described by defining its shape and representation, through the entities IfcArbitraryClosedProfileDefinition and IfcIndexedPolyCurve, supported by the definition of the list of points that define the shape of the layer (IfcCartesianPointList2D).

The definition of the central alignment of the linear infrastructure is represented by the entity IfcAlignmentCurve and elements that correspond geometrically to offsets from the alignment are represented by the entity IfcOffsetCurveByDistances (where a distance along, and the horizontal and vertical values of the offset have to be specified). The possibility to position the cross-sectional element is given by the entity IfcDistanceExpression.

# 5. Infrastructure data sets

The data required for smooth operation of linear infrastructures could be split into various categories including a) Traffic volume, speed, journey time; b) Pavement data such as surface condition, markings, message signs, surface markings,intersections, bridges on the network, c) asset edge data such as shoulders, curbs, gutters, driveways, inlets, and d) data connected to ditches, stormwater management, vegetation, topographical information.

As previously described, linear infrastructure projects are complex and contain large amounts of associated data. A road project for example includes information on pavement structure, pavement layers, shoulders composition, maintenance and rehabilitation related, climate and performance data, geometric design, location data, drainage, geotechnics, earthworks, pavement design, signalling and safety, lighting and telecommunications, risks and impacts assessment. The same applies for airport airside paved surfaces.

All the described areas and the corresponding deliverables that they provide, useful for the operation phase of the asset for example can be described as sources of data which can be of static and dynamic nature.

As the main objective of the proposed platform for connecting pavement big data to the projects IFC file it is relevant to differentiate static data sets and their correspondence to IFC Entities, e.g. topology and geometry of positioning elements (IfcProduct → IfcPositioningElements), alignment related data (IfcAlignment), pavement data (IfcPavement), course (IfcCourse), but also the technical equipment (e.g. lightning features, manhole covers and gratings, location of sensors).

Dynamic data sets are usually the result of different infrastructure operation and maintenance procedures, surveys and field tests, including, for example, timestamped data series from pavement measurements. The information required for the proper maintenance of the infrastructure can and is usually organized in tables.

# 6. InfraGOTdata framework: procedural modelling for infrastructure data sets

The software framework “InfraGOTdata” (as in Infrastructure got data) was developed as the main part of the research. The framework (Figure 27) integrates an IFC model with corresponding big data sets (i.e. pavement measurements) obtained from infrastructure site facilities and other sources of data (e.g. images and PDF documents). The integration is implemented with the InfraGOT relational database.

First, an IFC model file content is stored in the database (in the table Document). Next, the database is populated, with the IFC model data, meaning that the instance objects composing the highest level spatial project structure (as IfcProject, IfcSite, IfcFacility and IfcRoad) are extracted from the IFC model and stored in the database.

Instances of geometric shape representation elements (i.e. IfcArbitraryClosedProfileDef, IfcIndexedPolyCurve) for the infrastructure elements (i.e. IfcPavement, IfcCourse, IfcAlignment) are also extracted from the IFC model and stored in the corresponding database tables. After all relevant data is extracted from the IFC model and stored in the database, the data set document (i.e. Excel sheets) is read and the data imported in the database tables related to performance history.

The performance history controller connects the data to the corresponding IfcAlignment instance of the IfcPavement.

Finally, a new property set (IfcPropertySet) is added to the original IFC model file with values for the URL of the database and the SQL queries that return the data set/s to the consumer of the exchanged IFC model.

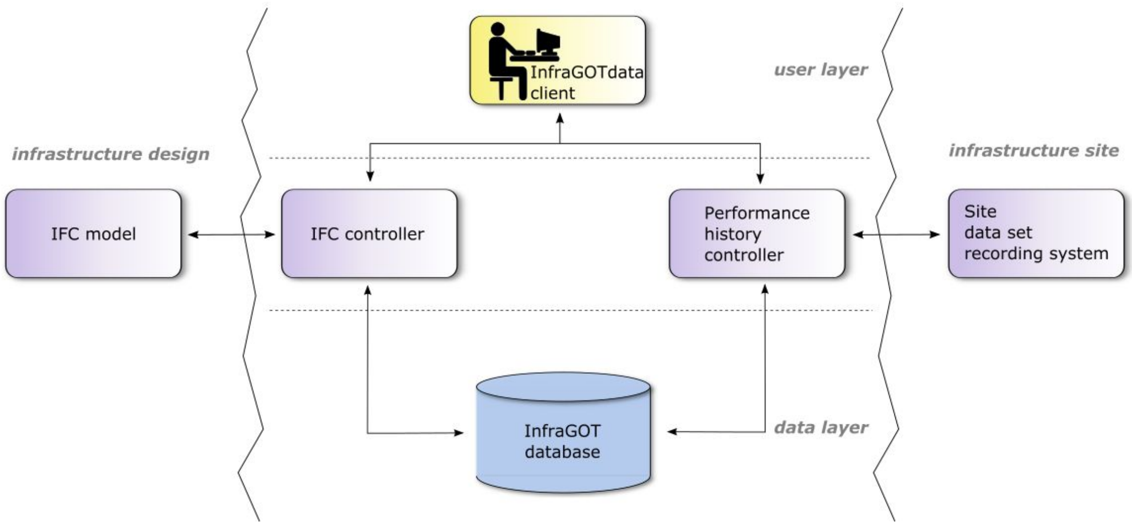



Figure 27: Technical framework InfraGOTdata for the management of infrastructure site big data sets connected to IFC model.

## 6.1. IfcOpenShell

IfcOpenShell is an open source (Lesser General Public License) software library that enables users to work with the IFC format, essentially providing the necessary suit of data and code to convert what is implicitly in the file to explicitly work with the information it contains, using open CASCADE community edition. The latest source codes can be downloaded from GitHub, a cloud-based website that stores and manages code for different projects. Relevant for the present dissertation are the latest IFC support code releases for IFC2x3 TC1 and IFC4 Add2 TC1.

Since for the optimal description of linear infrastructures, using the IFC schema, the released version IFC4 Add2 TC1 proved insufficient (namely in terms of the elements definition, please review subchapter 4.1.2), a version of IfcOpenShell based on IFC 4.3 was created.

The creation of the IfcOpenShell for IFC 4.3 involved branching (i.e. duplicating the code for experiment and development without affecting the master branch) from the IfcOpenShell:master and updating it through for later merging in the master branch through a pull request.

In IfcOpenShell the schema is compiled (i.e. converted for later execution) into the early-bound definitions, creating wrapper classes for the entities hierarchically defined with the respective names, types and functions, and the methods to operate on the definitions at the execution time (late-bound access).

Figure 27.1 shows the Python code that supports the framework form Figure 27. It has following features:

- Enables to select and input IFC model, spreadsheet documents with data sets (i.e. measurements), image files, PDF documents, etc.;
- Inserts data from the input data set to the InfraGOTdb database as performance history data;
- Reads the IFC model (IFC version <= 4x3) and, optionally, stores the model file to the database table, as Character Large Object (CLOB);
- Upgrades the IFC file to IFC 4x3 if needed (i.e. if the IFC version of the input IFC file is previous to IFC 4x3);
- Creates performance history data elements in the IFC model and updates them with information about the corresponding database connection, Uniform Resource Identifier (URI), and the queries needed to obtain all relevant data sets for the corresponding IFC model;
- Exports the (updated) IFC file;
- Holds the database that stores and manages big data sets (e.g. performance data) related to the IFC model, the database design enables storage of historical data.

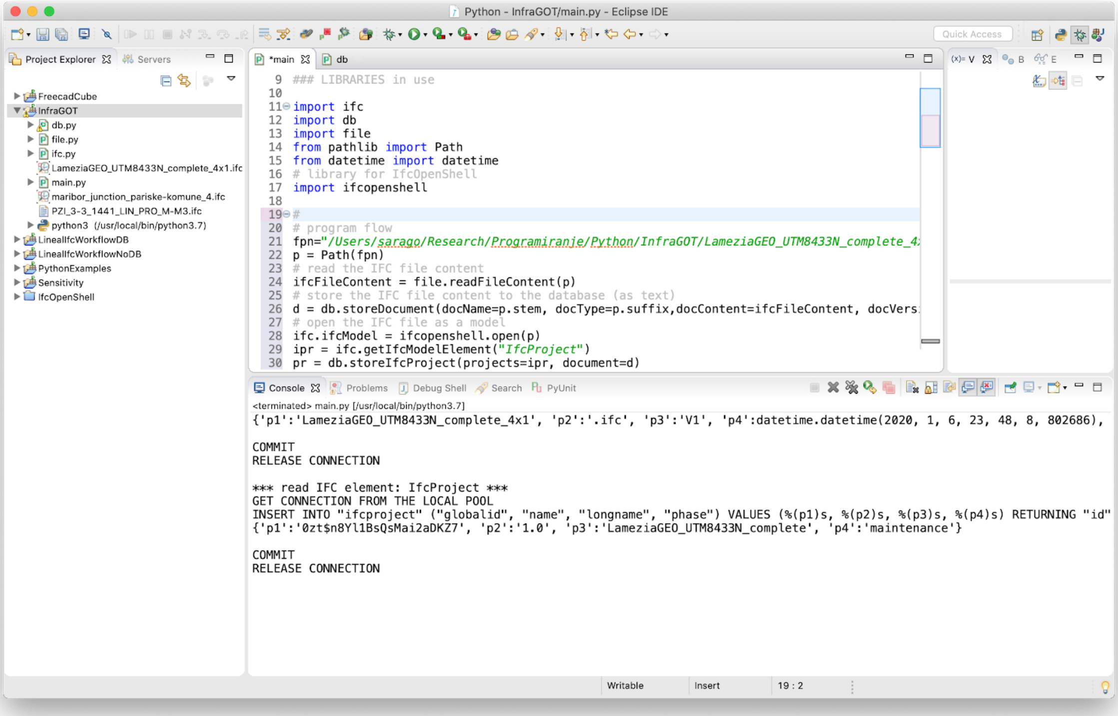
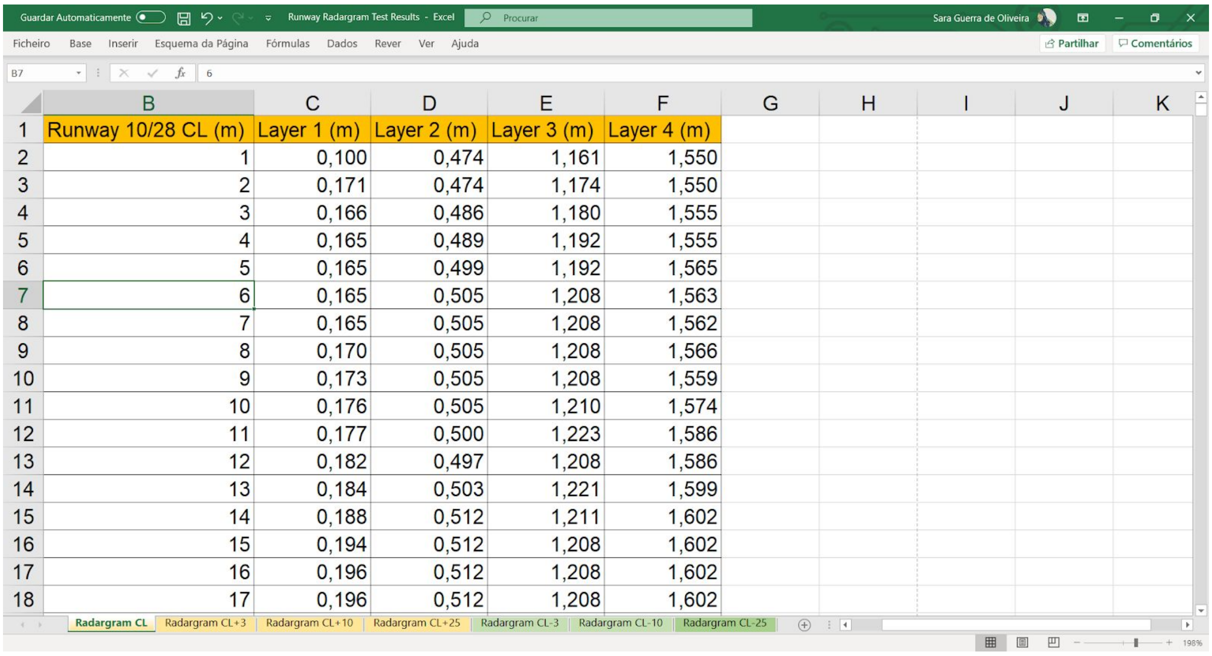



Figure 27.1: Technical framework for the management of infrastructure site big data sets connected to IFC model.

## 6.2. Linear infrastructure projects data

As mentioned the Lamezia Terme main runway is the case study used for support and validation of the proposed platform for the connection of pavement big data to the projects IFC file.

For the validation approach data results from a radargram test to the runway's pavement was used. The equipment Ground Penetrating Radar (GPR) allows to perform a nondestructive field test that provides an evaluation of the current condition of the pavement structure. The results of a radargram test can be organized in tables that can later on populate the database. The tables with the results were organized in a spreadsheet (Figure 28).



| Runway 10/28 CL (m) | Layer 1 (m) | Layer 2 (m) | Layer 3 (m) | Layer 4 (m) |
|---|---|---|---|---|
| 1 | 0,100 | 0,474 | 1,161 | 1,550 |
| 2 | 0,171 | 0,474 | 1,174 | 1,550 |
| 3 | 0,166 | 0,486 | 1,180 | 1,555 |
| 4 | 0,165 | 0,489 | 1,192 | 1,555 |
| 5 | 0,165 | 0,499 | 1,192 | 1,565 |
| 6 | 0,165 | 0,505 | 1,208 | 1,563 |
| 7 | 0,165 | 0,505 | 1,208 | 1,562 |
| 8 | 0,170 | 0,505 | 1,208 | 1,566 |
| 9 | 0,173 | 0,505 | 1,208 | 1,559 |
| 10 | 0,176 | 0,505 | 1,210 | 1,574 |
| 11 | 0,177 | 0,500 | 1,223 | 1,586 |
| 12 | 0,182 | 0,497 | 1,208 | 1,586 |
| 13 | 0,184 | 0,503 | 1,221 | 1,599 |
| 14 | 0,188 | 0,512 | 1,211 | 1,602 |
| 15 | 0,194 | 0,512 | 1,208 | 1,602 |
| 16 | 0,196 | 0,512 | 1,208 | 1,602 |
| 17 | 0,196 | 0,512 | 1,208 | 1,602 |



Figure 28: Spreadsheet of the radargram test results .

In this particular field test the radargram provided the assessment of the thickness of the runway pavement layers, along the centerline of the runway, and in parallel to the centerline with offsets of 3, 10 and 25 meters to both the left and the right side, as can be seen in the following Figure.

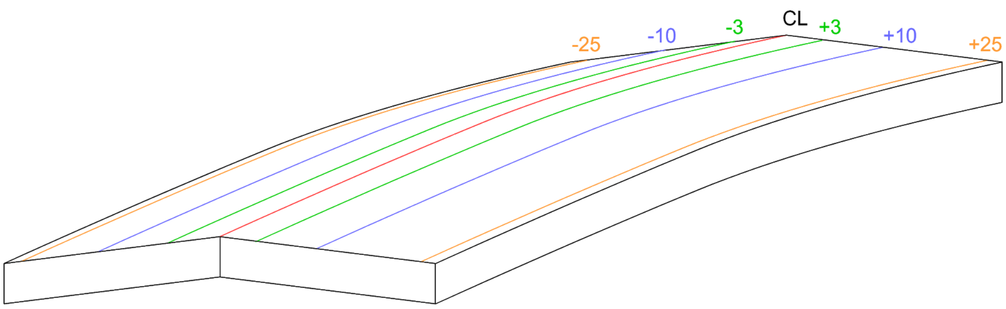



Figure 29: Radargram test survey layout.

### 6.2.1. Design and development of the Entity Relationship Model

The entity relationship model that constitutes the database was designed with the support of Pony, an advanced object-relational mapper. The choice for this particular tool finds justification in the perfect fit with the structure of any IFC file.

The design tool allowed for a clear understanding of the connections and hierarchy structure of the IFC file. For a better insight of the full database, some parts are detailed below, as well as a description of the entities meaning and corresponding attributes contained.

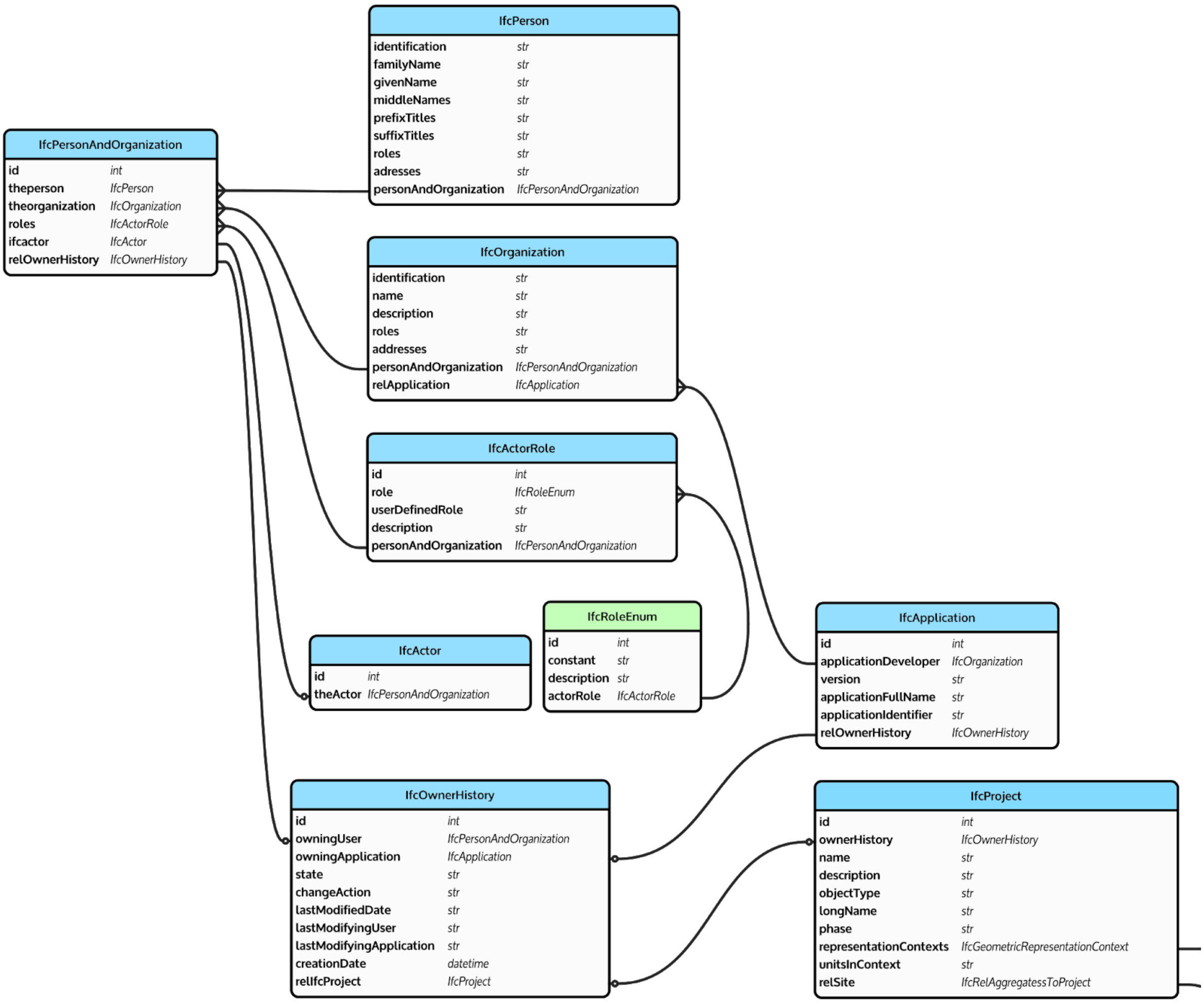



Figure 30: IfcProject and connected entities (database detail).

IfcProject: IfcProject indicates the undertaking of some design, engineering, construction, or maintenance activities leading towards a product. The project establishes the context for information to be exchanged or shared, and it may represent a construction project but does not have to. The IfcProject's main purpose in an exchange structure is to provide the root instance and the context for all other information items included.
New entity in IFC1.0.
This entity contains 9 attributes, namely: GlobalId, OwnerHistory, Name, Description, ObjectType, LongName, Phase,RepresentationContexts and UnitsInContext.

IfcOwnerHistory: IfcOwnerHistory defines all history and identification related information. In order to provide fast access it is directly attached to all independent objects, relationships and properties.
IfcOwnerHistory is used to identify the creating and owning application and user for the associated object, as well as capture the last modifying application and user.

New entity in IFC1.0.
This entity contains 8 attributes, namely: OwningUser, OwningApplication, State, ChangeAction, LastModifiedDate, LastModifyingUser, LastModifyingApplication and CreationDate.

IfcApplication: New entity in IFC1.5.
IfcApplication holds the information about an IFC compliant application developed by an application developer. The IfcApplication utilizes a short identifying name as provided by the application developer.
This entity contains 4 attributes, namely: ApplicationDeveloper, Version, ApplicationFullName and Application Identifier.

IfcOrganization: A named and structured grouping with a corporate identity.
New entity inIFC 1.5.1.
This entity contains 5 attributes, namely: Identification, Name, Description, Roles and Addresses.

IfcPerson: This entity represents an individual human being.
New entity in IFC1.5.1.
This entity contains 8 attributes, namely: Identification, FamilyName, GivenName, MiddleName, PrefixTitles, SuffixTitles, Roles and Addresses.

IfcPersonAndOrganization: This entity represents a person acting on behalf of an organization.
New entity in IFC1.5.1.
This entity contains 3 attributes, namely: ThePerson, TheOrganization and Roles.

IfcActor: The IfcActor defines all actors or human agents involved in a project during its full life cycle. It facilitates the use of person and organization definitions in the resource part of the IFC object model.
New entity in IFC2.0.
This entity contains 6 attributes, namely: GlobalId, OwnerHistory, Name, Description, ObjectType and TheActor.

IfcActorRole: This entity indicates a role which is performed by an actor, either a person, an organization or a person related to an organization.
New entity in IFC1.5.1.
This entity contains 6 attributes, namely: Role, UserDefinedRole and Description.

IfcRoleEnum: This enumeration defines roles which may be played by an actor.
New entity in IFC1.5.

Enumeration definition: Supplier, Manufacturer, Contractor, Subcontractor, Architect, Structuralengineer, Costengineer, Client, Buildingowner, Buildingoperator, Mechanicalengineer, Electricalengineer, Projectmanager, Facilitiesmanager, Civilengineer, Commissioningengineer, Engineer, Owner, Consultant, Constructionmanager, Fieldconstructionmanager, Reseller, Userdefined.

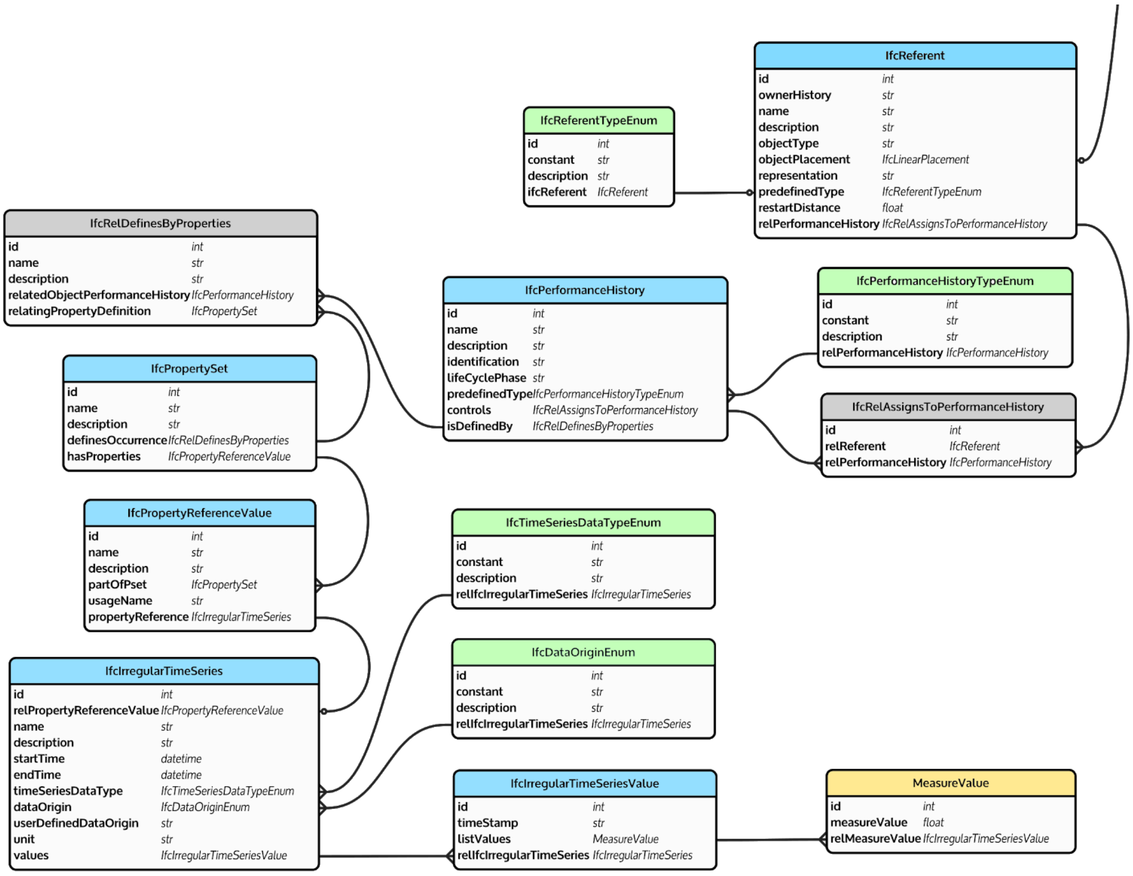



Figure 31: IfcReferent (database detail).

IfcReferent: IfcReferent defines a position at a particular offset along an alignment curve. Referents may be used for several scenarios, in this case, the purpose is to indicate domain-specific design parameters (via property sets) at locations along an alignment curve. This entity contains 10 attributes, namely: GlobalId, OwnerHistory, Name, Description, ObjectType, ObjectPlacement, Representation, PredefinedType and RestartDistance.

IfcReferentTypeEnum: This enumeration defines the different types of referents, in this case the type is Station.

IfcPerformanceHistoryTypeEnum: This enumeration is used to identify the primary purpose of performance history. The IfcPerformanceHistoryTypeEnum can be user-defined.

IfcPerformanceHistory: IfcPerformanceHistory is used to document the actual performance of an occurrence instance over time. It includes machine-measured data from building automation systems and human-specified data such as task and resource usage. The data may represent actual conditions, predictions, or simulations.
This entity contains 8 attributes, namely: GlobalId, OwnerHistory, Name, Description, ObjectType, Identification, LifeCyclePhase and PredefinedType.

IfcPropertySet: The IfcPropertySet is a container that holds properties within a property tree. These properties are interpreted according to their name attribute. Each individual property has a significant name string. Some property sets are included in the specification of this standard and have a predefined set of properties indicated by assigning a significant name. These property sets are listed under "property sets" within this specification. Property sets applicable to certain objects are listed in the object specification. The naming convention "Pset_Xxx" applies to all those property sets that are defined as part of this specification and it shall be used as the value of the Name attribute.
In addition any user defined property set can be captured. Property sets that are not declared as part of the IFC specification shall have a Name value not including the "Pset_" prefix. IfcPropertySet can be assigned to object occurrences and object types. An IfcPropertySet assigned to an object type is shared among all occurrences of the same object type. An IfcPropertySetTemplate may define the underlying structure, i.e. the required name, the applicable object or object types to which the property set can be attached, and the individual properties that can be included. Property sets are related to other objects by using the relationship object that refers to the corresponding object:

- Occurrence Object: IfcRelDefinesByProperties using the inverse attribute DefinesOccurrence.
- Type Object: using a direct link by inverse attribute DefinesType.
- Underlying template: IfcRelDefinesByTemplate using the inverse attribute IsDefinedBy.
- External reference: subtypes of IfcRelAssociates are used to provide a link to a classification system, or external library providing further reference to the property set. Accessible by inverse attribute HasAssociations.

This entity contains 5 attributes, namely: GlobalId, OwnerHistory, Name, Description and HasProperties.

IfcPropertyReferenceValue: The IfcPropertyReferenceValue allows a property value to be of type of a resource level entity. The applicable entities that can be used as value references are given by the IfcObjectReferenceSelect.
This entity contains 4 attributes, namely: Name, Description, UsageName and PropertyReference.

IfcIrregularTimeSeries: In an irregular time series, unpredictable bursts of data arrive at unspecified points in time, or most time stamps cannot be characterized by a repeating pattern.

This entity contains 9 attributes, namely: Name, Description, StartTime, EndTime, TimeSeriesDataType, DataOrigin, UserDefinedDataOrigin, Unit and Values.

IfcIrregularTimeSeriesValue: The IfcIrregularTimeSeriesValue describes a value (or set of values) at a particular time point.
This entity contains 2 attributes, namely: TimeStamp and ListValues.

IfcTimeSeriesDataTypeEnum: IfcTimeSeriesDataTypeEnum describes a type of time series data and is used to determine a value during the time series which is not explicitly specified. The type of time series data can be described as continuous, discrete, discretebinary, piecewiasebinary, piecewiaseconstant, piecewiasecontinuous or non-defined.

IfcDataOriginEnum: IfcDataOriginEnum identifies the origin of time data, as measured, predicted, simulated, user-defined or not defined.

IfcRelDefinesByProperties: The objectified relationship IfcRelDefinesByProperties defines the relationships between property set definitions and objects. Properties are aggregated in property sets. Property sets can be either directly assigned to occurrence objects using this relationship, or assigned to an object type and assigned via that type to occurrence objects. The assignment of an IfcPropertySet to an IfcTypeObject is not handled via this objectified relationship, but through the direct relationship HasPropertySets at IfcTypeObject.
The IfcRelDefinesByProperties is an N-to-N relationship, as it allows for the assignment of one or more property sets to one or more objects. Those objects then share the same property definition.
This entity contains 5 attributes, namely: GlobalId, OwnerHistory, Name, Description, RelatedObjects and RelatingPropertyDefinition.

# 7. Discussion of results and Conclusions

The present thesis details a first innovative attempt of establishing a connection between pavement big data and the IFC file. Linear infrastructure projects, such as roads and highways, railways, tunnels and bridges can benefit from the application of the proposed platform, with some minor adaptations.

## 7.1. Recommendations and Future Developments

It was confirmed that the establishment of mechanisms to connect Big Data to open standard linear infrastructure files (IFC) is not absent of challenges. The first one is the fact that the IFC 5 schema (although under development) is still not available as an official version and therefore the support needed for these projects is still not present. The IFC 5 is expected to be released in the first trimester of 2020, and future validation of the upcoming new entities will obviously face the major test when professionals will pick it up for their projects.

The proposed platform connected pavement data to an IFC file, using an asset-centric workflow that proves advantageous in the operation, management and maintenance phases of the asset.
Although comparable to approaches such as Common Data Environment or BIM platforms, the InfraGOTdata framework distinguishes itself by the innovative approach to Open standardization throughout.

Future developments of the presented work can extend it by integrating prediction models (e.g. performance wise, climate changes impact analysis) and establishing the connection to technologies related to the smart city concept, where Internet of Things (IoT) solutions improves even further the efficiency and sustainability of the assets’ management. The possibility to create areas where the data can be classified as: work in progress, shared, archived or ready to be published, following the usual structure of a CDE can also be considered a future development of the work.

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# 9. Appendix

## 9.1. Case study - Lamezia Terme Runway 10/28

Lamezia Terme International Airport is the main airport in the Calabria Region, Italy, with the identifier codes, International Air Transport Association: SUF and International Civil Aviation Organization: LICA. The airport opened in 1976, and has since then been subject to improvements, namely in 1982 and in 2007, the latter where a structural requalification of the air-side pavements took place. The airport airside is composed of one runway, one taxiway, four taxi lanes and aprons, distributed as can be seen in the following figure.

Figure A1 - Lamezia Terme International Airport.

The Airside pavement description and main characteristics are described as follows: The runway is designated Rwy 10/28, according to its magnetic azimuth orientation. The runway has a flexible pavement type, with a loading-carrying capacity, pavement classification number PCN 58/F/B/W/T, where F: flexible pavement; B: subgrade strength (CBR between 8-13%); W: tire pressure supported unlimited and T: PCN estimated by technical evaluation (De Luca and Dell'Acqua, 2018).

It presents a length of 3000 m, width of 45 m; shoulder width: 14 m, and variable longitudinal slope (ranging from 0.13% to 0.38%). The transversal slope presents values of 1.25% or 1.40% according to the section.

The taxiway, designated “Sierra”, presents a flexible pavement type. The taxiway has a length of 1750 m, width of 30 m, shoulder width: 10 m, longitudinal slope: variable ranging from 0.09% to 0.49%, transversal slope: variable: 1.30%, 1.50%.

The airside contains four taxiway exits also with flexible pavement type structure and variable geometric characteristics, highly dependent on the constraints imposed by the connection of the runway to the taxiway (namely in terms of longitudinal and transversal slope). Generally, the sections of the exits present a width of 25 m and 10 m shoulder width.

The Lamezia Terme airside case study focuses on the construction of the runway 10/28 digital twin, i.e. a model that mirrors the asset (data-rich 3D model), and represents, reacts and can cause changes in the actual runway, when connected to the Airport Pavement Management System (APMS). First and foremost, it is important to highlight that the runway model was produced with a tool dedicated to road design, from the Bentley Systems company, and for that motive, all the digital runway components had to be customized and detailed for the airport case, namely the transversal sections of the runway. The overall view of the airside model can be seen in Figure A1, the model also includes the alignments for future incorporation of the taxiway and taxiway exits model.

Figure A2: Overall view of the airside model.

The corridor of the runway 10/28 was created based on a custom parametric cross-section that incorporates the designation of the pavement layers and specific identification point designations, as can be seen in Figure A3. The main constraints imposed for the construction of the cross-section were of the horizontal, vertical and slope nature and the connection to the terrain was established defining an end-condition component for both the cut and fill cases. It is important to mention that in the general model, at this stage, the connection to the terrain from the left side of the runway (West-East direction) was purposely excluded from the model, for future study of the intersections between runway and taxiway exits.

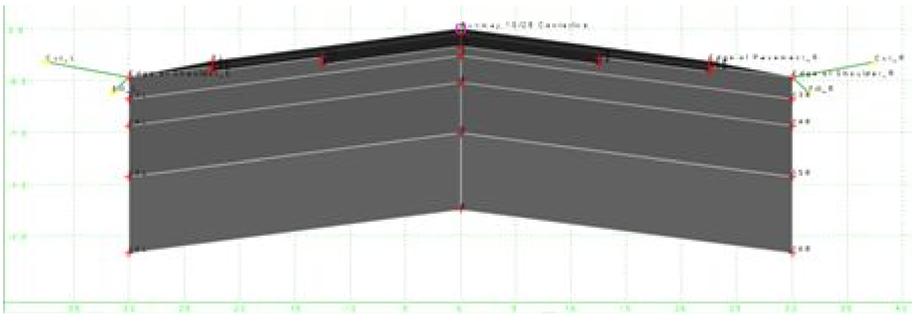

Figure A3: Runway 10/28 parametric cross-section.

One of the main advantages of developing the BIM-model is the capacity of integrating non-graphical information. Even though the UNI 11337- 4 (U. Committee, 2017), does not illustrate in detail the runway case application, the description of a Level of Development G, provides guidelines as to the information that a model built for operation and maintenance purposes should include. Although inspired by the USA scale (LOD 100, 200, …, 500), and integrating aspects of the UK LOD convention, the Italian scale is affected by national requirements not present in both systems. The national Italian LOD scale is represented by capital letters in alphabetical order from A to G. In the LOD G the model elements should express the updated virtualization of the status of the asset, including information about every management, maintenance and / or repair and replacement intervention carried out over time, as well as the current level of degradation.

Quantitative and qualitative characteristics, namely performance indicators, dimensions, form, location, cost, etc. should be updated with respect to the life cycle phase.

Figure A4 illustrates the integration of information to the runway model, connected at the branch and sample unit levels, in this case data related to a radargram test performed.

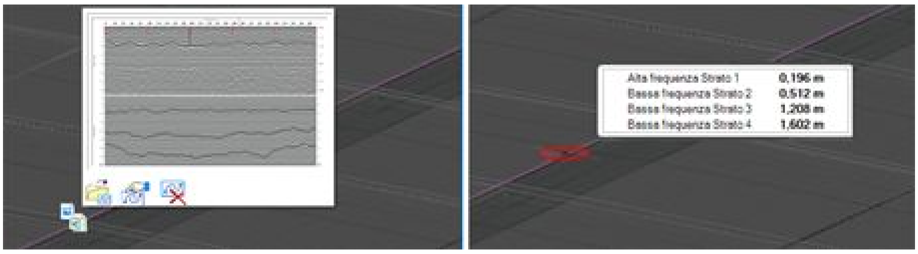


Figure A4: Radargram field test data.

All data related to the pavement reported distresses should also be included, e.g. eventual alligator or fatigue cracking, bleeding, corrugation, depression, raveling, weathering. Indicators related to the pavement deterioration and characterization as the Pavement Condition Index (PCI) and the integrity of the top surface of the runway, are other important features that should be part of the records. The surface condition is evaluated by regular inspections, dependent on the environmental conditions, the wear and tear and on the accumulation of rubber deposits. The integrity of the runway can be evaluated through the study of its surface friction levels.