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Interoperability framework for BIM-FM based on a relational database

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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Marina Bacichett Trabulci

RESUMO

Título: Metodologia Para Interoperabilidade BIM-FM Baseada em Base de Dados Relacional

As atividades relacionadas a gestão de facilidades (FM) dependem de informação continua e confiável sobre o inventário, condições e desempenho de ativos. Em vista disso, a metodologia BIM-FM apresenta consideráveis vantagens em relação a processos tradicionais, principalmente devido a melhorias associadas ao comissionamento e entrega dos dados da instalação. De fato, o BIM-FM simplifica processos do que diz respeito a transferência de dados e na redução de erros, enquanto melhora as possibilidades de gestão da informação e operação dos ativos. Existe também a tendência para sistematização de dados em forma gráfica, gerando assim uma melhor visualização do desempenho dos ativos, auxiliando as atividades de operação e manutenção da facilidade, o que serve de apoio a um sistema inteligente de tomada de decisões. No entanto, apesar da implementação de metodologias BIM-FM estarem em crescimento, não pode ser considerada uma prática difundida. Uma das razões que dificultam uma maior adoção de BIM-FM na indústria, tem relação com a falta de integração da informação e problemas de interoperabilidade entre plataformas BIM e sistemas FM. Em muitos casos isso resulta numa gestão ineficiente de dados, pois lida com informações incompletas e imprecisas dos modelos BIM (na fase de entrega), requerendo trabalho manual para coletar e inserir o restante da informação no sistema FM. Para abordar esses desafios, essa dissertação propõe uma estrutura de trabalho focada em estabelecer uma conexão bidirecional entre o modelo BIM e uma base de dados em formato SQL. A dissertação também explora possibilidades para a análise de dados de forma avançada com o uso do software Power BI, para uso dos dados disponíveis durante a operação de ativos de forma inteligente e interativa. É proposto um mapa de processos detalhado para definir as operações da estrutura de trabalho num cenário de aplicação mais amplo dentro dos processos BIM, incluso a nível interoperabilidade de software. A implementação de aplicação da estrutura de trabalho proposta no estudo de caso é para equipamentos de iluminação do edifício da biblioteca, no Campus de Azurém da Universidade do Minho, que permite demonstrar a funcionalidade e as possibilidades do desenvolvimento proposto. Sendo o objetivo de o fluxo de trabalho proposto demonstrar uma solução para a interoperabilidade entre sistemas, que conecta informações do modelo BIM a uma base de dados relacional, com o propósito de ser utilizado durante a fase de gestão do ativo. Por fim, apresenta a análise de dados com o intuito de apoiar melhorias no desempenho das instalações. Portanto, o fluxo de trabalho proposto é escalável e expansível, e oferece soluções para sistemas mais complexos e outras atividades relacionadas a gestão dos ativos.

Palavras chave: Fluxo de trabalho; Gestão de ativos (FM); Interoperabilidade; Gestão da informação; Modelação da Informação da Construção (BIM);

ABSTRACT

Facility Management (FM) activities frequently require continuous and reliable information of the asset inventory, condition, and performance. In view of that, BIM-FM methodologies present considerable advantages in regard to past conventional techniques, mainly because of improvements on commissioning and handover of facility data. Indeed, BIM-FM simplifies processes of data transfer and reduces errors, while allowing improvements on the possibilities of information management and operation of the asset. There is also a trend towards systematization of information in graphic format for a better visualisation of the assets performance, assisting O&M activities, and supporting an intelligent decision-making system. However, despite adoption of BIM-FM methodologies being in frank growth, it cannot yet be considered a widespread practice. One of the reasons that is hindering widespread application of BIM-FM is the lack of integration and interoperability issues between BIM platforms and FM systems. In many cases, this results on inefficient data management, when dealing with incomplete or inaccurate information in BIM models (at handover stage), requiring significant human labour to gather and input missing information into FM system. To address those challenges, this research proposes a BIM-FM oriented framework focused on establishing a bi-directional connection between the BIM model and a SQL format database. The dissertation further explores advanced and interactive data analysis possibilities using Power BI for leveraging the use of available data at the stage of operation of an asset. Detailed process maps are proposed to clearly define the operation of the framework in the wider scenario of a BIM-process, and also at the software interoperability level. The implementation and application of the proposed framework to a case study of the light fixtures of the library building at the Campus of Azurém of the University of Minho, allowed demonstrating the functionality and possibilities of the developments proposed. Overall, the framework goal is for an interoperability solution connecting the BIM model to a relational database with data that serves for FM purposes. Proposing the data analysis with the aim to support intelligent decision making and improvements on the assets' performance. Thus, the proposed workflow is expandable and scalable to be applicable to any type of facility and its elements.

Keywords: Building Information Modelling (BIM); Facility Management (FM); Information Management; Interoperability; Workflow.

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1. INTRODUCTION

According to ISO 41011:2018 (ISO, 2017), Facility Management (FM) is defined as an "*organizational function which integrates people, place and process within the Built Environment with the purpose of improving the quality of life of people and the productivity of the core business*". The FM activities comprises various areas and different core competencies, such as the Operation and Maintenance (O&M), risk management, and project management of an asset.

The stage of operation (O&M) represents most of the duration of the lifecycle of a given asset, corresponding to up to 60% of the total project cost (Hu et al., 2018). In order to support O&M activities, FM processes require continuous and reliable information of asset inventory, condition, and performance. For that, FM works with two main types of systems: (i) the Computer Aided Facilities Management (CAFM); and (ii) Computerized Maintenance Management Systems (CMMS). Whereas those systems have slightly different competencies, the first is used for assisting facility managers to identify patterns and trends, while the other focuses on monitoring facility maintenance work, those systems can work better when integrated. However, some of the existing problems related to FM system are: not being able to provide an automatic maintenance work order scheduling, where FM staff experiencing difficulties when accessing accurate information, and limitations for an automatic information capture and data analysis (Chen et al., 2018).

Along with that, to support integration of information through project stages, there is an increased use of Building Information Modelling (BIM) collaborative processes throughout the stages of the lifecycle of assets. Even though the benefits related to BIM processes also apply for post-construction, they are still more widely adopted for design and construction stages, as compared to O&M stages (Pishdad-Bozorgi et al., 2018a). The increasing complexity of facilities is however bringing a to a rise of attention and adoption of BIM processes and tools for FM presents, with considerable advantages that are associated with the improvement on commissioning and handover of facility data and enhancing management and operation of the asset when integrated with available FM systems (Eastman et al., 2018).

However, one of the major issues preventing broader adoption of BIM-FM is related to difficulties often encountered in the interoperability between BIM and FM systems, causing a technology/information gaps between the stages of construction and operation of the asset (Talebi, 2014). The above mentioned interoperability issues frequently result in the need ad-hoc and time/labour intensive processes for placing the necessary information on FM software, even when as-built BIM models are available (Heaton et al., 2019). These time/labour intensive processes can trigger relevant financial losses (Araszkiewicz, 2017). When taking into account that a BIM model can be considered as an assembly of a single database of integrated and interoperable information to be used by different stakeholders throughout an asset's lifecycle (Ozturk, 2020), to achieve such integration, it is crucial to have a sustained flow of information between all stages (Nicał and Wodyński, 2016).

In concern to interoperability in BIM-FM processes, major challenges can be identified on the inconsistency of data input, processing and its overall structure (Yang and Bayapu, 2019). the open formats available for a BIM-FM implementation are IFC and COBie, however they are not enough for a seamless integration and exchange of data from BIM to FM system. For which major problems are reported on the use of COBie on studies, with missing information and errors when connecting the spreadsheet with the FM system (Kensek, 2015; Pishdad-Bozorgi et al., 2018b). For the IFC format, its current structure applies for more basic specializations of FM, for which studies suggest an extension and further development of the schema when applying to more complex elements and systems (Hu et al., 2018). In this context, there is a pressing need for data structure must be standardized, with the aim to provide means for supporting the exchange of this information throughout different phases, and to facilitate the interoperability between digital information (Chen et al., 2018).

Adding to that, the interoperability between systems also lacks on bi-directional connection, which makes it difficult to manage and maintain the information that is stored on disconnected databases and different software. Usually, during operation of the asset the information is only updated on the FM system. Whereas the as-built BIM model becomes obsolete and not updated accordingly, since the systems do not communicate with each other. However, the BIM model integration with the current conditions of the asset data may enhance the use of the information throughout the facility's lifecycle (Ozturk, 2020).

One efficient approach for interoperability is the use of relational databases to provide a simplified and efficient access to BIM data. The concept of relational database management system (RDBMS) consists on a collection of information that organizes data points with defined relationships in an intuitive and straightforward way, thus simplifying the creation of relationships among data points. The concept of having a central database connected to the BIM model and to other systems for the use of O&M shows advantages also for the integrating the large amount of data that needs to be captured and managed through the operation of an asset. In this context, it is important to maintain the structure, storage and constant update of data as a base for information support throughout the lifecycle of a project (Gusakova, 2018). Overall, a model-server based data exchange is more advantageable for having a data repository that allows for more flexibility and automating analysis of data (Eastman et al., 2018), being free of version control related issues, and economically leverageable for discharging stakeholders from paying licenses to third parties which do not fully satisfy the objectives including for more flexibilization of project's requirements.

Furthermore, another point of BIM-FM implementation related to the increasing importance of the data-driven culture that has been fundamental for AECO/FM arising technologies to integrate and make sense of the data acquired throughout an assets' lifecycle. It comprises the systematization of information in graphic format for a better visualisation of the performance of assets, assisting O&M activities, and supporting well-informed and intelligent decision-making. Indeed, suitable data analyses on a facility can bring about improvements on corrective and preventive maintenance for identifying failure causes (Motamedi et al., 2014), along with a more efficient energy consumption (Liang et al., 2016), and actions that simplify the maintenance of the building and improve the occupants' comfort (Daissaoui et al., 2020).

1.1. Objectives

To address those challenges, the objective of this dissertation was the proposal of a BIM-FM oriented framework focused on establishing a bi-directional connection between the BIM model and a SQL format relational database followed by proposal of data analysis possibility using Power BI for leveraging the use of available data at the stage of operation of an asset. It was intended that the proposed framework and methodology would be scalable and applicable to new projects of any kind of facility, its equipment, and more complex systems.

The following sub-set of objectives can be identified:

i. Identify and understand the current state of application of BIM-FM and corresponding information workflows between project stages.

ii. Develop a BIM-FM oriented framework for data management through a relational database

iii. Apply the developed framework to a case study situation within BIM-FM (library of the Campus of Azurém of the University of Minho).

iv. Produce results and critical analyses based on the application of the proposed methodology

1.2. Structure of the Dissertation

After the present introductory chapter, this dissertation presents a literature review on Chapter 2, comprising subjects related to BIM data lifecycle, the facility management operation and maintenance work, type of activities and relevant definitions. The chapter further covers an overview on the current adoption of BIM-FM, addressing to the data management and interoperability subjects, as well as a review on standards and guides that directly address to the topic, including open data formats of IFC and COBie schema. Finally, a critical assessment is made on the current state of BIM-FM the implementation and barriers preventing a broad adoption of it, with a review on previous works focused on the topic of BIM-FM integration, some of those proposing a central database to manage the BIM data through different stages of the assets lifecycle.

Chapter 3 consists of the development of the BIM-FM oriented framework, explaining the established methodology and the framework application, with an overview of the tool features and data analysis proposal. The interoperability for data exchange between BIM model and the relational database is described, based on a visual programming language (Dynamo for REVIT), with focus on the bi-directional integration between the exported BIM data contained on the model and the database. Further developments are presented towards the analysis of the data included on the database using Power BI as a primary tool for generating analytics dashboard.

Chapter 4 presents the implementation of the proposed methodology on a case study project applied to a set of lighting fixtures, of the library building of the Campus of Azurém of the University of Minho. The tool for extracting data from BIM model into the relational database was tested, as well as its bi-directional connection for updating the information and bringing it back to the BIM model. A proposal of dashboard to analyse the information was implemented on the case study, with a critical assessment on the outcomes of the framework application.

2. BIM AND FACILITY MANAGEMENT

2.1. BIM Data Lifecycle

Building Information Modelling (BIM) comprises a collaborative way of working hinged by digital technologies, allowing for more efficient methods for designing, delivering and maintaining physical built assets throughout their entire lifecycle (BSI, 2019). The concept of BIM correlates with the idea of Product Lifecycle Management (PLM) that aims to improve product quality, while reducing waste and minimizing risks through integration of processes and information (Eastman et al., 2018). Those goals can be better achieved by using Integrated Project Delivery (IPD) approach, where the idea is to integrate knowledge, systems, business structures and practices of different stakeholders into a collaborative process (Talebi, 2014) by working openly and sharing information among those involved to encourage cooperation for problem solving and decision making.

In all cases, integrated projects are distinguished by effective collaboration among the owner, the prime (and possibly sub-) designers, and the prime (and possibly key sub-) contractor(s). This collaboration takes place from early design and continues through project handover. The key concept is that this project team works together using the best collaborative tools at their disposal to ensure that the project will meet owner requirements at significantly reduced time and cost. The trade-offs that are always a part of the design process can best be evaluated using BIM—cost, energy, functionality, aesthetics, and constructability. Thus, BIM and IPD go together and represent a clear break from the current linear processes that formalize and restrict information flow with obscure product representations and adversarial relationships.

For a successful IPD approach, it is fundamental that collaboration takes place during early stages of the project and continues until handover. One example of project stages involved is defined by the RIBA Plan of Work. According to the document, the lifecycle of an asset can be divided into eight different stages, from 0 being the strategic definitions to 7 the built asset in use, as shown in Figure 1.

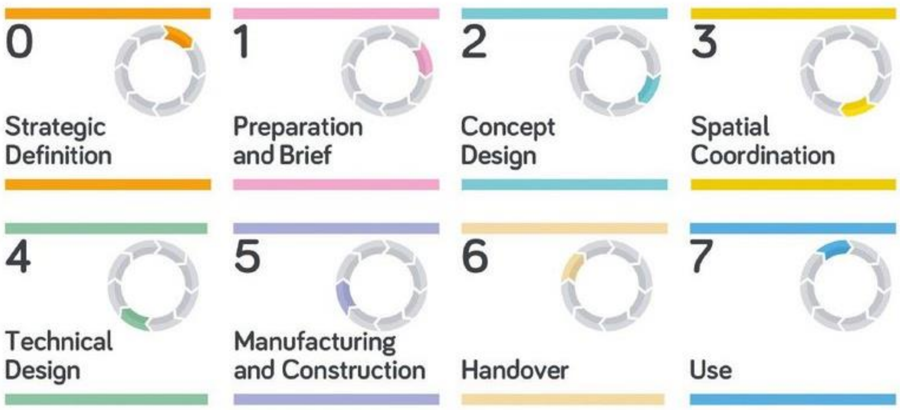


Figure 1: RIBA Plan of Work project stages. Source: (RIBA, 2019)

Throughout those stages mentioned above of the information gathered containing both geometric and non-geometric data about elements in the BIM model. The management of this information regarding an asset's lifecycle is also related to the maturity levels of BIM, where the goal is a more integrated digital environment that encourages for true collaboration (BSI, 2019).

Ideally, all the information about an asset's lifecycle would be standardized and stored through BIM processes and stored in a BIM database, encouraging centralized information management (Turk, 2016). Considering that, the BIM model amount of information increases by each stage of the project's lifecycle as shown in Figure 2, where the non-graphic data in accordance to a BIM level 2 project (BIM Portal, n.d.). Hence, for a successful BIM implementation and management of information throughout the asset lifecycle, the information requirements should be established at the beginning of the project. That stage is defined as the part of the strategic definitions (RIBA, 2020). For which, the ISO 19650 series defines the information requirements and procedures throughout an asset's lifecycle, including methods and structure for handover of the information (ISO, 2018).

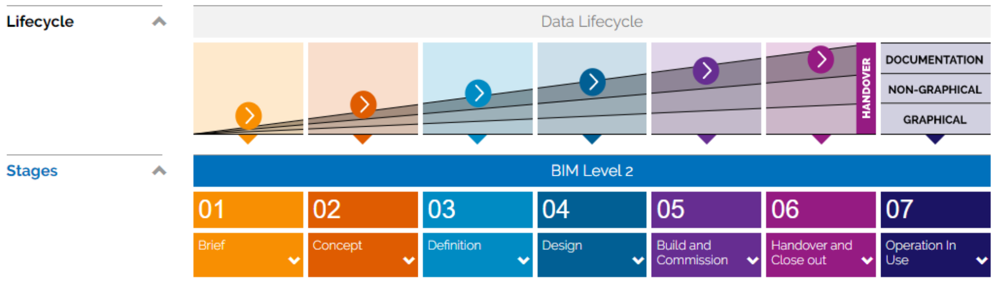


Figure 2: Data lifecycle through project stages. Source: (BIM Portal, n.d.)

Considering that a BIM model can be viewed as an assembly of a single database of integrated and interoperable information to be used by different stakeholders throughout an asset's lifecycle (Ozturk, 2020), it is crucial to have a sustained flow of information between all stages (Nicał and Wodyński, 2016) to achieve this integration. For that, BIM data structure must be standardized, with the aim to provide means for supporting the exchange of information throughout different phases, and to facilitate the interoperability between digital information (Chen et al., 2018).

In this regard, efforts are being made towards the development of more efficient BIM data sharing processes and improved interoperability to extend the reach of the benefits on the use of the BIM model information throughout an assets' lifecycle. Currently, one of the main developments is the OpenBIM concept, that aims to achieve a vendor neutral collaborative process by improving interoperability, accessibility, usability, management, and sustainability of digital data to benefit projects and assets throughout their lifecycle (BuildingSMART, n.d.). Nonetheless, the BIM adoption is faced with many difficulties regarding data sharing and inefficiencies in integration (Ozturk, 2020). Plenty of improvement is still required for BIM and the available open standards, such as IFC and COBie, to achieve the ideal exchange of information between systems to be more effective during the collaborative process (Eastman et al., 2018). The matter has been given increased attention and importance, becoming one of the main issues for advanced uses of BIM.

2.2. Facility Management Definition

According to the ISO 41011:2018, which standardize facility management vocabulary, the term Facility Management (FM) is defined as an "organizational function which integrates people, place and process within the Built Environment with the purpose of improving the quality of life of people and the productivity of the core business" (ISO, 2017). Hence, it is an interdisciplinary process, which has its activities performed during the operation phase of the built asset (BIM Dictionary, 2019), and on the economic sense, discharge building occupants from problems and tasks not directly related to their core business (Araszkiewicz, 2017).

Within the work of facility managers there are some core competencies classified in eleven different categories according to the International Facility Manager Association (IFMA), as illustrated on Figure 3. Inside those categories there are sub-categories and competencies for each one. For example, the work of Operation & Maintenance (O&M) includes: buildings; building systems; infrastructure and grounds; furniture, fixtures and equipment; physical safety and security; operations and maintenance processes; work management support systems; renewals and renovations (IFMA, 2018).

Figure 3: Core Competencies of Facility Management. Source: (IFMA, n.d.)

On the subject of O&M activities, different type of services are performed by the facility managers, and are commonly classified between 'hard services' or 'soft services' (SmartCSM, 2018):

Hard service: is considered essential to ensure safety and welfare, usually the services of this category are compulsory and required by law. It relates to the physical parts of the building that cannot be removed, such as plumbing, lighting, Heating Ventilating and Air Conditioning (HVAC) systems, and fire safety systems.

Soft service: this service is directly related with enhancing the spaces to be more pleasant and secure for its occupants. It is mostly non-compulsory and can be removed/added at any time. Some examples of this are cleaning, mail management, and building security.

Further, the maintenance tasks performed are divided between 'proactive maintenance' and 'corrective maintenance' (Hallberg, 2009), as shown in Figure 4 below:

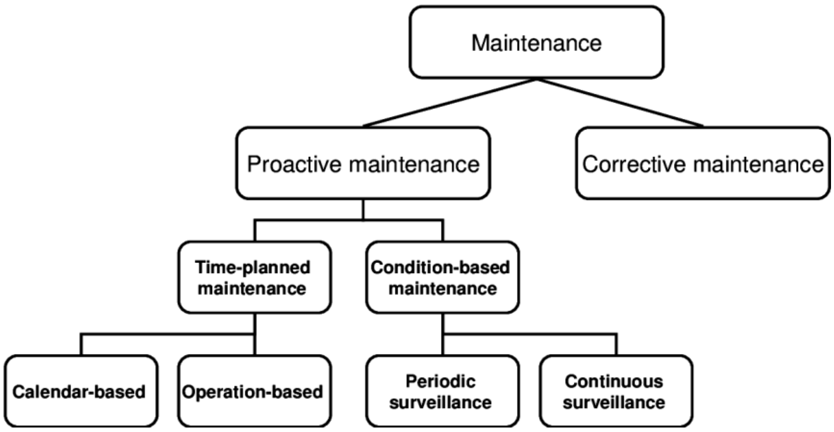


Figure 4: Maintenance strategic activities. Source: (Hallberg, 2009)

While proactive maintenance demands a more strategic planning from the FM team, either time-planned or condition-based, corrective maintenance is when something unexpectedly goes out of order and requires maintenance as soon as possible. Efficiently performing both of those maintenance strategies requires planning and pertinent information about the whole facility. This improves management during operation stage, where communication and seamless flow of information is an essential prerequisite for fulfilling FM activities (Araszkiewicz, 2017). Nowadays, the work of facility managers is even more dependable on concurrent data of the facility, in view of the fact that the facility's systems are increasingly complex. Thus, for better performance and efficiency of O&M related activities the assets' information must be available in an accessible way. Currently, FM works with two main types of systems to support those activities and store assets' data:

Computer Aided Facilities Management (CAFM): the system supports both automated facility and real estate management. By integrating with other platforms, such as Computer-Aided Design (CAD), BIM models, and relational database, it is used to plan and track events that take place throughout the facility. It provides various facility management capabilities, including space management as well as schedule repairs, preventive maintenance, and monitoring of work orders.

Computerized Maintenance Management Systems (CMMS): it is considered a component of CAFM software only focused on maintenance activities. The system operates with as a cross link with a database and is utilized to record, manage, and communicate daily operations. It stores facility information and uses modules for inventory control, preventive maintenance, work order control, and others.

Subsequently, CAFM and CMMS have slightly different competencies. The first is used for analytics and helping facility managers to identify patterns and trends, while the other focuses on monitoring facility maintenance activities. By those means they are most effective when integrated (ServiceChannel, 2017). Although, some of the existing problems with those systems are: not being able to provide an automatic maintenance work order scheduling, FM staff experiencing difficulties when accessing accurate information (Chen et al., 2018).

When considering the flow of information through the operation phase of an asset, the collected data representing the as-built conditions of the asset, is delivered to the responsible team for operation of the facility, as part of the handover stage. Currently, a lot of time is spent by facility managers to collect and enter the facility's information into FM systems, resulting in inefficient performance in FM practices (Nicał and Wodyński, 2016). This can later result in one third of maintenance costs being used inefficiently, mostly by unnecessary or improper maintenance activities as shown in Figure 5, due to the fact that asset managers usually make decisions based on sparse data available about the asset (Dejaco et al., 2017).

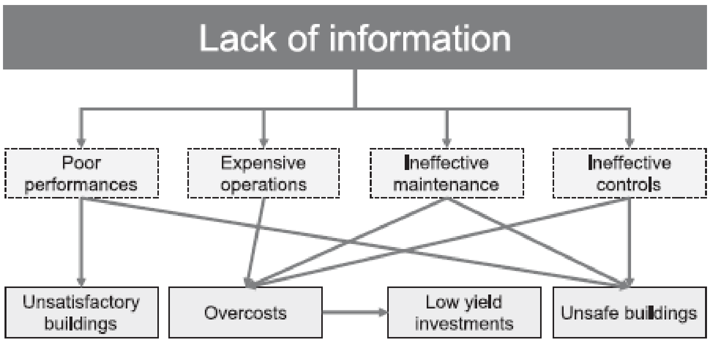


Figure 5: Main maintenance issues related to lack of information. Source: (Dejaco et al., 2017)

This performance gap affects not only the facility managers activities, but also related to a poor energy efficiency of the facility, where O&M strategies are key to building's energy performance (Cheng et al., 2020). All those factors influence not only maintenance costs, but also the user's experience and satisfaction with the built environment. In view of that, an effective use of integrated and up-to-date information of the facility, that can be also processed and analysed, is crucial for an intelligent maintenance planning. Related to that, the implementation of BIM data for the use in FM has shown many advantages by optimizing maintenance activities (Chen et al., 2018).

2.3. Application of BIM for FM (BIM-FM)

When referring to the use of BIM for Facility Management purposes, there is a lack of consensus in which of the BIM nD dimensions it should be included. This is due to a current lack of standards and parameters to define the nD BIM model with embedded information required at different stages of a facility's lifecycle. The extent use of the word 'dimensions' in BIM without proper agreement on what they represent and what constitutes them, has brought to light discussion on the matter. Some studies show that the consensus goes until the 5D BIM related to costs and quantities (Charef et al., 2018), while others uphold the argument that the last dimension of BIM is 4D, related to time, since a ‘dimension’ is associated to essential information for the identity and function of an object (Koutamanis, 2020). Thus, on the case of facility management, sustainability, and other uses of BIM data, those are not classified as new dimensions of BIM. For this reason, the prevailing form to refer to the use of BIM for Facility Management is as ‘BIM-FM’.

Nowadays, BIM is still more widely adopted for design and construction stages, and although its benefits can be applied throughout a building’s lifecycle the use of BIM tools and processes for stages post-construction is still under progress (Pishdad-Bozorgi et al., 2018a). As previously mentioned, modern facility infrastructures have grown increasingly complex, and BIM adoption can enhance operation of those facilities. Considerable advantages on the adoption of BIM-FM (Figure 6) are related to information management and the increased availability of asset’s data (Talebi, 2014). Those points are related to an efficient handover of the facility data, which results on enhancements on the management and operation of the asset when integrated with FM systems (Eastman et al., 2018).

Figure 6: Advantages of BIM-FM implementation. Source: (ndBIM, 2016)

Advantages on the adoption of BIM-FM are related to making sense of the BIM data acquired during previous stages and updated after construction to be used during operation of an asset. Those benefits are related to the FM fields of: space management; renovation planning; maintainability studies; safety management; optimization of maintenance scheduling; energy savings and control; etc. (Lin et al., 2016; Naghshbandi, 2016; Nicał and Wodyński, 2016). In addition, an automated flow of information from BIM to FM system is far more effective than manually entering essential data (Araszkiewicz, 2017). Besides, O&M phase represents the largest part of the lifecycle of a facility, resulting in the highest cost when compared to other stages (Hu et al., 2018). The optimization of this stage leveraging the use of BIM data can result in reduction of costs and economic efficiency for FM.

2.3.1. Information Lifecycle

Although many advantages are mentioned on the application of BIM-FM, there is currently limited capacity of its overall benefits, mostly due to inefficient logistics of information (Nicał and Wodyński, 2016), as well as the lack of standard methodology to determine and assess owner requirements (Naghshbandi, 2016). Hence, the as-built model for the stage of a project's handover contains a vast number of information acquired throughout design and construction stages, whereas not all of it is valuable to FM purposes.

What frequently happens by the end of each stage, is that the information is not correctly updated to reflect the actual as-built conditions or it is in a structure which cannot be properly accessed or managed by other stakeholders, especially those involved in the operation of the facility. This gap on sustained logistics causes the value of this information to drop substantially (Eastman et al., 2018). Thus, the ideal is that the BIM model is updated and integrated with the as-built asset, to reflect its current conditions and by those means enhance the use of data throughout a project's lifecycle (Charef et al., 2018).

In addition, issues on the completeness and accuracy of the delivered data point out to a need for inclusion of facility managers in the early stages of the project, to participate for definitions and provide a detailed scope with priorities amongst required data to fulfil FM needs (Araszkiewicz, 2017). The gap is on current lack of guidelines to assist owners on defining the information requirements and handover deliverables for integration of BIM with FM use (Lin et al., 2016), resulting in information quality issues with lack of accuracy, reliability and completeness of the data passed onto the facility managers. Ideally, the updated Asset Information Model (AIM) should derive from the as–built model with information required by FM to operate the building, which is defined by the ISO 19650 as the Asset Information Requirements (AIR), integrating all the information in a seamless way into an FM system.

2.3.2. Interoperability

When taking into consideration the technological perspective, a major issue preventing broad adoption of BIM-FM is related to interoperability among systems. After all BIM tools are not applicable to fit FM processes, thus causing a technology gap between those stages of the asset (Talebi, 2014). An automated data transfer from one system to another is crucial for a successful implementation of the process (Araszkiewicz, 2017). Since the systems do not smoothly communicate with each other, the common process is that the required information from the BIM model to FM system has to be transferred using ad-hoc methods for information exchange (Heaton et al., 2019), often being transferred manually, causing problems of incompleteness and inaccuracies of data, while also increasing the required time that it takes to gather and process all the required information.

The interoperability through open formats is crucial for ensuring accurate data exchange since different software and platforms are used throughout project stages by different stakeholders. There is a need for an optimized information logistics system throughout an asset's lifecycle for standardizing and structuring the BIM data, including exchange file formats and access to shared data (Ozturk, 2020). Furthermore, the FM industry faces challenges related to the amount of data that needs to be captured and managed throughout the lifecycle of an asset (Naghshbandi, 2016), considering that the operation stage involves a large number of participants with multidirectional relationships and to ensure continuity of accumulate data is difficult (Gusakova, 2018). Planning on exchange of information between tools (Pishdad-Bozorgi et al., 2018a) is needed for a successful implementation of BIM-FM. further development of neutral file formats is also crucial for a seamless interoperability and integration of technology, and also to minimize data loss and maximize data accuracy.

One of the most efficient approaches for interoperability and extraction of BIM data involves linking the BIM model to a relational database (Heaton et al., 2019). Thus supporting the development of the AIM and its update, as shown by the framework on Figure 7, using the database as a link between BIM model and FM system. (Kensek, 2015) develops an automated 'lean process' for populating the database and getting the information into FM system. With the goal of providing a simplified and efficient access to BIM data (Solihin et al., 2017) using relational database associated with the concept of data warehouse, while focusing on the perspective of the final user and the analytical capability of the BIM data.

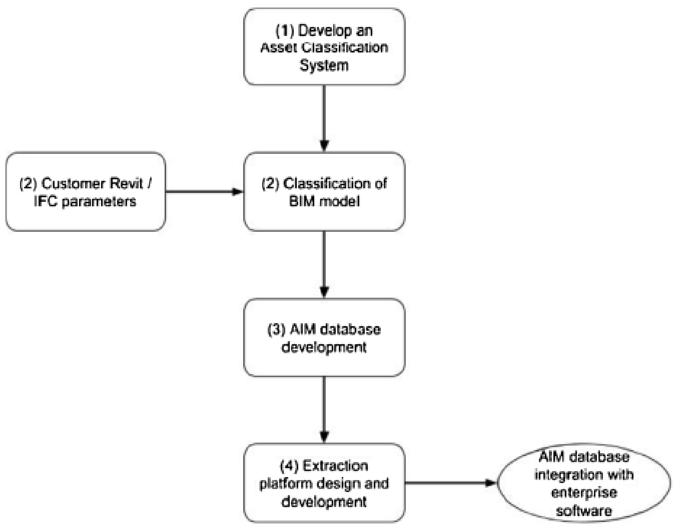


Figure 7: BIM data extraction framework. Source: (Heaton et al., 2019)

A relational database consists on a collection of information that organizes data points with defined relationships in an intuitive and straightforward way. The data structure - including columns of the table, indexes, and views - holds attributes of the data, which remain separate from the physical storage. Each record has a value for each attribute, simplifying the creation of relationships among data points (TechTarget, n.d.). The idea of having a central database connected to the BIM model and to other systems for the use of O&M is supported by other studies, there are advantages of a model-server based data exchange over the file-based exchange (Eastman et al., 2018), which depends on version control and faces concurrent interoperability issues, Opposed to having a data repository that allows for more flexibility and automating analysis of data, (Gusakova, 2018) which encourages for the structure, storage and constant update of data as a base for information support throughout the lifecycle of a project.

2.4. Standards and Guides

To assist on BIM-FM implementation and set the flow of information throughout stages, some standards and guides were developed with focus on BIM FM-oriented framework. Those documents aim to provide guidelines and instructions to enhance the project collaboration practices, improve the quality of the model data, increase data accuracy, and minimize data loss throughout project stages. Some of the most relevant standards will be mentioned in this section, focusing on parts specific to BIM-FM purposes, followed by an integrated review. In addition, the main open formats for data exchange available for BIM-FM will be mentioned and discussed.

2.4.1. ISO 19650 series

As the recognized international standard, the ISO 19650 series stands for information management processes throughout the lifecycle of a facility using BIM, containing concepts and principles to be applied using the collaborative approach. Hence, is one of the main specification documents when applying BIM principles, as it aims on BIM Level 2 of maturity, containing minimum requirements and further recommendations.

The standard series is divided into Part 1, which specifies concepts and principles for managing information, and Part 2, containing requirements for information process during for the handover of the built assets. As for the information requirements, it sets principles on the level of information to be determined by the minimum amount needed, stating that anything beyond is considered a waste. This way, the information should be determined according to its purpose, containing specification on the quality, quantity, and granularity of information.

As part of the standard definitions, the asset information requirements (AIR) concept defines the approach for information management, comprising of detailed appointments of the required information about the asset to be used during the operation stage. Which those define the inputs for the whole process as shown in Figure 8 on how they relate to each other. Moreover, the specifications and requirements should be agreed on in early stages and its details specified in the BIM Execution Plan (BEP) to be followed throughout the lifecycle of the project and after it, during operation of the asset.

Further, the Asset Information Model (AIM) that should derive from the Project Information Model (PIM) with modifications in accordance to what is previously specified in the Asset Information Requirements (AIR). The information in the AIM contains what is essential for the operation of the asset throughout its lifecycle. Consequently the previously agreed requirements for the model should be maintained and updated throughout the lifecycle of the facility in accordance to the as-built conditions, keeping consistency and quality.

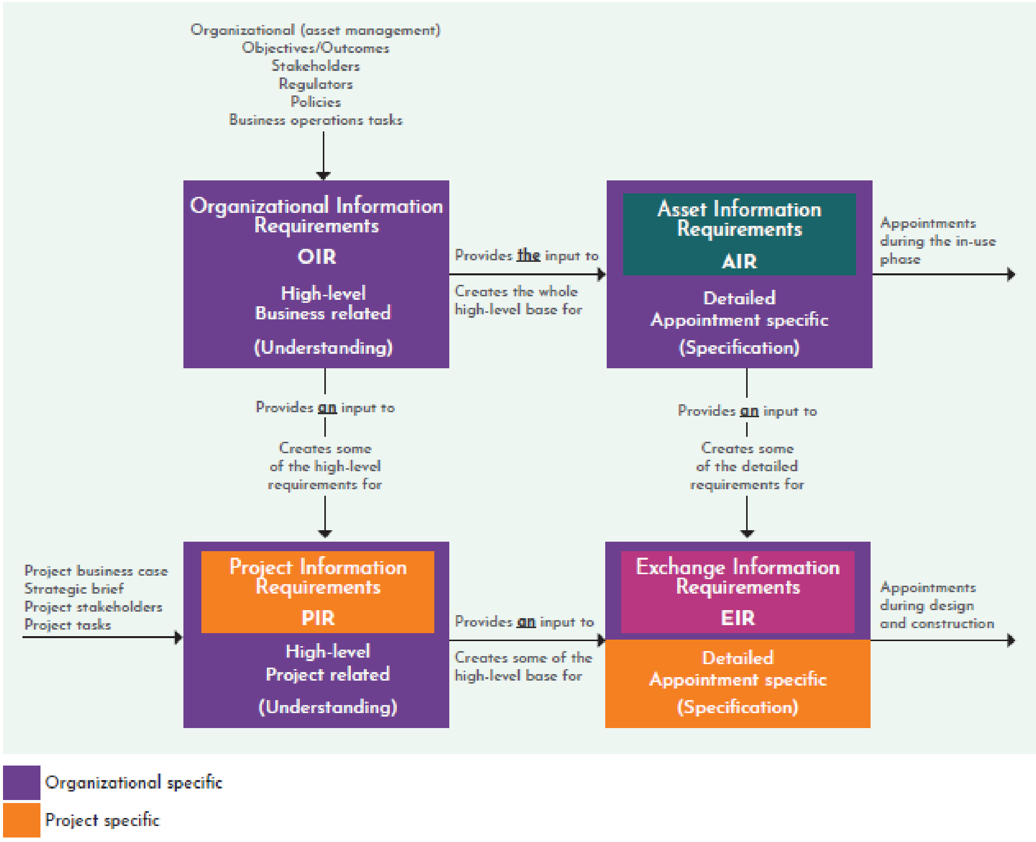


Figure 8: Hierarchy of information requirements. Source: (UK BIM Alliance, 2019)

For the handover phase, the Exchange Information Requirements (EIR) should, from a technological perspective, have pre-defined mapping structure that allows communication between different systems across the project team (UK BIM Alliance, 2020), thus improving interoperability and ensuring that the information received is compliant with what was required. On the other hand, further interoperability related issues are not covered by the standard.

2.4.2. COBIM

The Common BIM Requirements (COBIM) was developed in Finland and released in 2012. It is a series of 13 documents about different aspects of BIM uses, including the use for building maintenance, described in the Series 12 – Use of Models in Facility Management. This guide lists some benefits of the use of BIM for FM, explaining about open data transfers in BIM, FM software that are used, examples of types of data to be embedded in the BIM-FM model, and update procedures for the model emphasizing the importance of keeping the 'as-built' model updated throughout the lifecycle of a facility.

The guide sets some requirements that should be followed for a successful implementation of BIM-FM. Including on those guidelines, is that the as-built model should be constantly updated to reflect the current conditions of the asset. The guide defines this update to be made on the original modelling software, and further transferred as an open file. Further, the open format is used to import the information into FM system, as shown in Figure 9 below, which explains the workflow to be followed.

Also, for the constant update of the model, the original pre-defined modelling rules in the early stages of the project, should be preserved throughout the lifecycle.

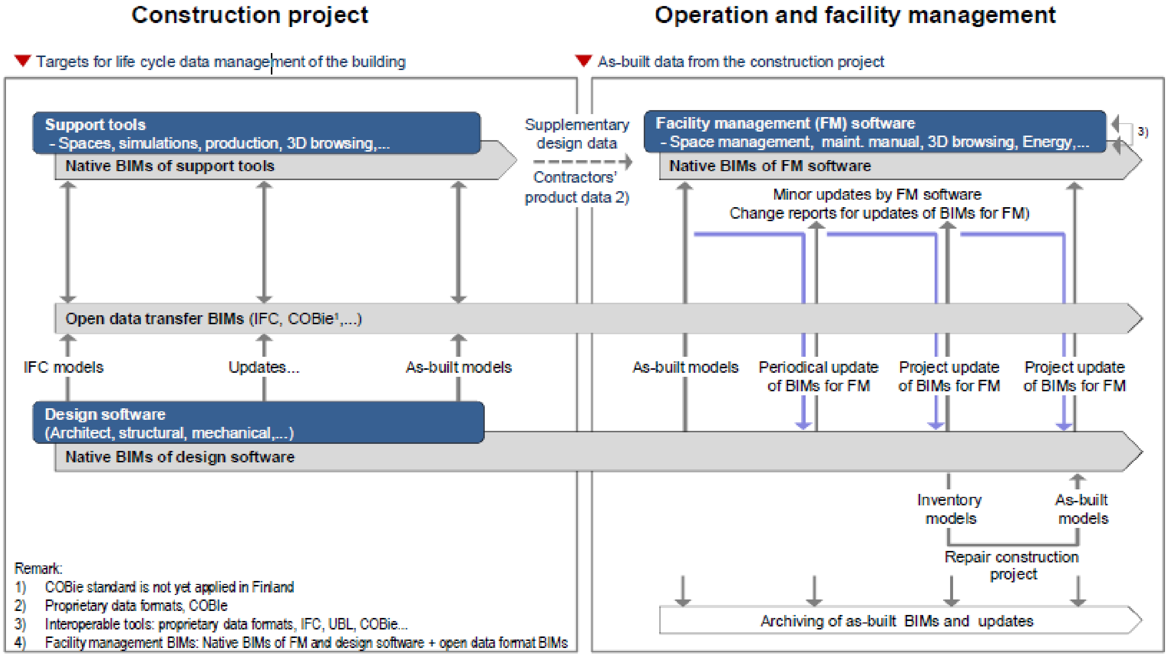


Figure 9: BIM management process throughout a facility's lifecycle. Source: (COBIM, 2012)

For the open file formats, it takes into consideration both COBie and IFC, underlining that IFC still needs further development for more specific FM requirements, and for this reason COBie can be used to complement IFC. The document sets minimum guidelines for modelling rules and product data exchange. For which the data exchange should include at least the (i) architectural space list, and (ii) MEP space-specific requirements in a spreadsheet format. Further, for the contractor's product information, it should include:

- Product data concerning the building parts, equipment, and materials
- Commissioning documentation, for example data from inspections and measurements
- Instructions for operation and maintenance

This information should be handed over in a document format, or, if agreed in project specifications, this data can be in a file format compatible with the FM software. According to the guide, the strategy and objectives for information management should all be agreed on at the beginning of the building's project. This way all the client's needs can be taken into consideration, along with the definition for modelling requirements, data exchange formats and specification of information which should be documented. During the operation phase, the COBIM guide emphasizes the importance of defining a periodic update procedure for the as-built BIM model, ensuring the continuity of the model's quality.

2.4.3. GSA BIM guide

Developed in 2012 by the General Services Administration (GSA) company in the USA, it aims to identify processes and requirements of information for FM, setting the type of information that should be embedded on the BIM model after construction phase, and approaching the importance of standard information for classifying and identifying equipment in a facility. The document its divided into five sections, stating the importance and advantages of BIM-FM, with implementation strategies, along with detailed modelling requirements.

The guide defines three layers of data requirements that are necessary: (1) containing spatial program BIM and accurate as-built geometry for equipment; (2) the accurate non-graphical product information; and (3) the as-designed BIM with energy analysis predictions. The list with minimum requirements for equipment types and attributes should be defined and included in the BIM Execution Plan (BEP), furthermore this requirements should be delivered both in BIM native format, as well as in an open format that can be either IFC or COBie, to integrate with FM system as shown in Figure 10 for appropriate management of data lifecycle.

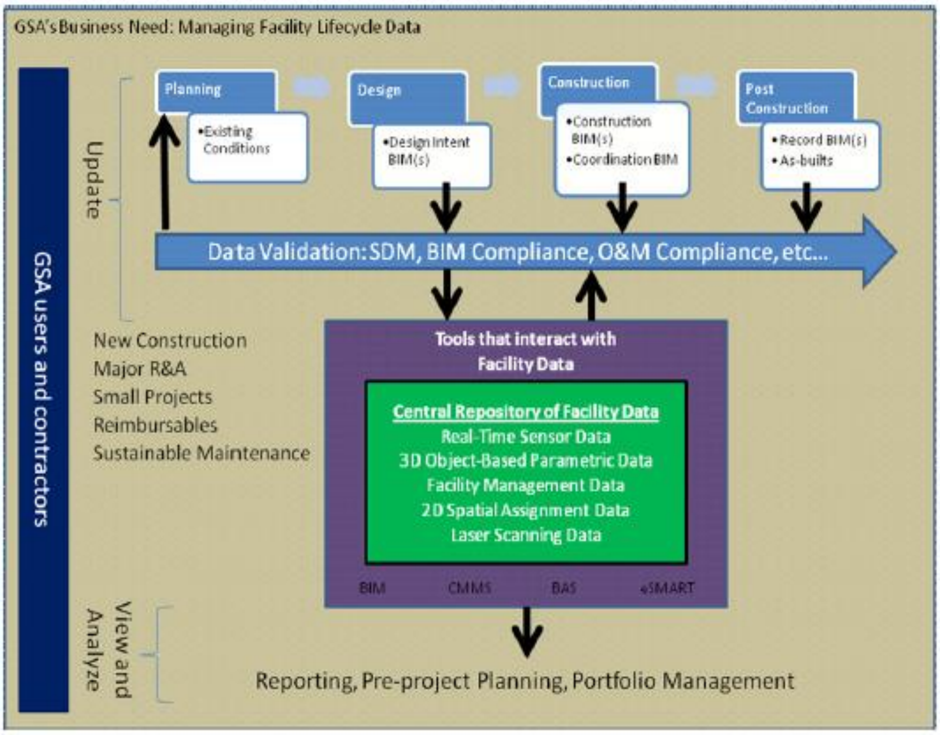


Figure 10: BIM and FM integration. Source: (GSA BIM Guide, 2012)

For the modelling rules to be applied, it focuses on high-level requirements, underlining the importance of standardizing the identification and classification of the objects. The equipment attributes required by facility management activities should be submitted using COBie to transfer the data into CMMS. The document describes minimum COBie requirements, and those must be in accordance with BEP specifications for the project. The necessary objects and a basic set of properties are also described within this section.

After the verification and handover stage of the as-built model, another important item is the maintenance and update of the information throughout the facility's lifecycle. According to the document, the non-geometric information is more easily accessed and updated if maintained in an external database, where a common unique identifier for each item in both the BIM model and the repository is required to form the link between the two. In the BIM model, designers and contractors may include additional attributes according to their needs, although as affirmed by the GSA, some issues have been identified on the maintenance of BIMs during operation of a facility. Which includes the technology gap for maintaining and update BIM model during FM operation, and further integration of the asset's information with other building information technologies, such as Geographic Information System (GIS).

2.4.4. BIM guide for asset information delivery

Developed in Singapore in 2018, it is among the most recent of the guides mentioned. It sets a framework on how to approach and gather the right information throughout a building's life cycle. Setting information requirements specifications, but not covering details on technical interoperability of data.

In accordance to other guides, the proposed framework of this document also stresses the importance of defining the information requirements in early stages of the project. Those should be specified in the BEP as shown in Figure 11. The document mentions three key elements for data management workflows, which are: (1) information requirements by the facility building owner; (2) information delivery by the project team; and (3) information exchange across project lifecycle by all project stakeholders.

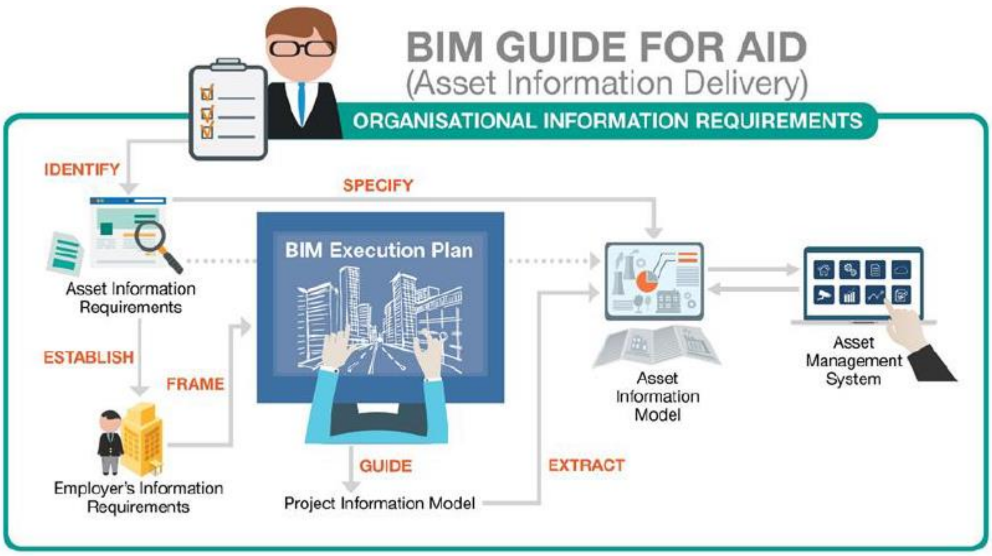


Figure 11: BIM guide simplified framework. Source: (BCA, 2018)

For the first of those key elements, it specifies the potential parties involved in those specifications, the information is defined in the accordance to the ISO 19650 series information requirements. The guide sets a number of criteria to assist the facility owner with identifying which information is important for the operation phase of the asset and recommends for early involvement of FM practitioners during the definitions of AIR.

The information to be delivered by the project team should follow the previous definitions, and establish how to plan, collect, and coordinate all the required data. The deliverables for this stage include BEP, PIM, and AIM. The guidance for handover of the information comprises of BIM deliverables - which are composed by the project's disciplines involved - and non-BIM deliverables, which can include an external database, PDF documents, and spreadsheets in formats such as COBie for data exchange between BIM and FM system.

On the matter of information exchange, the guide states the importance of the process's smoothness as being crucial for an overall success of BIM-FM. For exchange formats, it quotes IFC, COBie, and native file formats, according to specified content in each one. For the mapping of exchange of information, the guide states that it can be directly exported from the BIM platform and imported to and FM system using an open format, or through a mapping key, such as a database or spreadsheet to be imported into the FM system.

According to the document, the operation of an asset now requires much more detail and frequent update of information than conventional asset management systems did in the past. For this reason, keeping the asset information as non-BIM data has gain popularity, since it is much easier to update and set up a collaboration exchange than to modify the BIM model frequently.

2.4.5. COBie

The Construction Operations Building Information Exchange known (COBie) is a non-proprietary data format for the publication of a subset of BIM models, focused on delivering asset data distinct from geometric information (NBS, 2018) where the contractor provides as-built data to the owner for facility management of an asset (BuildingSMART, n.d.). The goal is for the format to work as an neutral format for information exchange to capture the BIM required data for operations and import it on the FM system, to improve the handover of asset data (Chen et al., 2018).

The COBie system uses a spreadsheet data format with pre-defined structure, containing information about maintainable assets in a useful form (BSI, 2019), however the mapping of this information from the BIM model to FM system is not automatic, requiring manual work. Besides, details on what information to be delivered, when and by whom are not provided, making the file format sometimes being used as complementary to others, such as IFC. Even though it is introduced as a primary form of data exchange from BIM to FM system, it is not widely used in practice (Naghshbandi, 2016).

2.4.6. IFC Schema

According to the BuildingSMART definition, the Industry Foundation Classes (IFC) "represents an open specification for Building Information Modelling BIM data that is exchanged and shared among the various participants in a building construction or facility management project. IFC's are the international OpenBIM standard" ('IFC 4.1 Intro', n.d.). For facility management purposes, what can be found on specifications of the IFC 4.1 schema is the following:

On Core data schemas: the *IfcProcessExtension* has the objective to capture information that supports the mapping of processes and the planning and scheduling of work and the procedures and resources required to carry out work.

On Shared element data schemas: *IfcSharedFacilitiesElements* defines basic concepts in the FM domain, providing a set of models that can be used by applications needing to share information concerning facilities management related issues.

Along with *IfcSharedMgmtElements* which defines basic concepts that are common to management throughout the various stages of the building lifecycle. The aim is to provide support for exchange and sharing of minimal information concerning the subjects in scope; the extent of the model will not support more detailed ideas found in more specialized management applications.

Lastly, the domain specific data schemas contain final specializations of entities, with the *IfcConstructionMgmtDomain* that defines resource concepts in the construction management domain. Together with the *IfcProcessExtension* and *IfcSharedMgmtElement* schemas it provides a set of models that can be used to exchange information between construction management applications.

Although the standard contains a set of entities helpful for FM purposes, the current state of development is not enough for seamless information exchange using the neutral open format. Whereas IFC supports a generalized BIM data structure, and for more specialized elements it is required further development or an extension of the schema.

2.4.7. Integrated discussion on guidelines

The presented guides and standards have roughly the same goal: to provide consistency on the flow of information throughout an asset's lifecycle, covering aspects on the matter of agreement and documentation of all information requirements, as well as relevancy on setting proper information exchange to avoid interoperability issues at the handover stage.

On the matter of the level of information needed for the modelled elements, while the ISO 19650 states that only the minimum should be added, without defining the types of parameters, the GSA guide defined in greater detail what are the required properties to be added on each of the elements for FM uses. Since facilities systems vary substantially, each project will have its particularities for required information.

The modelling rules also set discussion for the Level Of Development (LOD) of each element, there is not a proper agreement on the granularity of information required on the mentioned guides. However, for the use of FM the LOD 500 can be assigned. For which geometrical data required relates to general geometry or accuracy, and the non-graphical information is greater and differ from the one from design and construction stages. There has been a potential for misunderstanding LOD as a linear scale, the LOD 500 relates to field verification, and it is specified because the FM requires more information added to elements (LODPlanner, 2020). Hence, LOD 500 represents the relevant information at the stage of operation, driven by an FM workflow.

The other subject of discussion is the interoperability issue. The documents mention both IFC and COBie, the first handles graphical information better, and the spreadsheet would be complementary for FM requirements, however it is clear that they are not enough for a seamless integration and exchange of data from BIM to FM system, on the other hand this integration is mentioned as one of the priorities for a successful implementation of BIM-FM.

To conclude, it is pointed out by the mentioned standards and guides the necessity of involving FM on early stages of decision-making for the project, to set the AIR included in the final AIM. The modelling rules are more detailed in some guides, with what parameters to be included, however they are not specific on formats. Hence, the interoperability between systems is a major issue when setting the BIM-FM framework. For which the open formats available do not completely fulfil the requirements for a seamless exchange of information, requiring further development for a better integration.

2.5. Critical assessment of BIM-FM current state

In theory, the ideal is that the BIM model holds and stores all stakeholder's information throughout a facility's lifecycle, however the information that is handed over to operation of the asset usually contains information that is incomplete for FM uses or does not correspond with the as-built state of the facility. Thus, for the BIM data to be useful during operation of the facility, it is required to plan and manage the implementation process, according to (Pishdad-Bozorgi et al., 2018a) for a BIM-FM application it is recommended: (1) clear definition of what BIM-FM constitutes; (2) a practical process for collecting data throughout the project phases; (3) a well-executed interoperability plan. Where for the definition of strategies, the development of a BEP containing the FM requirements is proposed (Lin et al., 2016), which comes from the AIR definitions and includes the role of FM-manager who should participate to provide professional advice regarding maintenance management to the owner during early stages of project definition. Adding to that, the non-involvement of facility managers during early stages of the project can result in models with inaccurate and incomplete data (Naghshbandi, 2016). Hence, according to studies, a major gap in traditional approach to BIM-FM implementation (Figure 12) is due to late or no definition of information requirements and lack of collaborative approach involving FM professionals.

In addition to that, (McArthur, 2015) defines some key challenges for implementing BIM-FM oriented framework. Those are: (1) to identify the information required; (2) manage the information transfer between BIM model and FM tools; (3) manage the level of effort to create the model; (4) how to handle uncertainty when building documentation/model is incomplete. And for that, the strategic definition and the collaborative approach are critical when defining how to overcome such challenges.

Furthermore, the definition of project standards and classification system to be applied is crucial for the implementation process, followed by the definition of which elements and parameters are required by FM needs along with modelling rules in accordance to designated standards. As defined by the GSA ("GSA BIM Guide," 2012), containing a list of system and equipment required and the information to be added on the model that are useful for O&M, however the ideal still is for FM professionals to be involved in the definition of AIR. Since the facility's system vary greatly from one project to another, the collaborative approach is the adequate solution for the definition of required information.

Additionally, quality check of the model, an additional step before handover, is recommended. One approach proposed by (Lin et al., 2018) sets the role of an inspector for the as-built model, to check and analyse the completeness and accuracy of information to meet the project requirements before handover to O&M. Part of checking the final information also includes the verification of exchange requirements, for example: the files must be in the previously agreed formats interoperable with FM system. For that, some cases point to a framework process with direct export of IFC file format. (Hu et al., 2018) proposed a direct export of IFC format files to import on the BIM database, for the data to be complete, an extension of the IFC schema based on the COBie information was applied. Other researches directly used COBie to export information from BIM to FM system, however they reported problems with missing information and errors when connecting the spreadsheet with the FM system (Kensek, 2015; Pishdad-Bozorgi et al., 2018b). As suggested by (Ozturk, 2020) IFC and COBie can be used together if necessary, as a way to complement missing information.

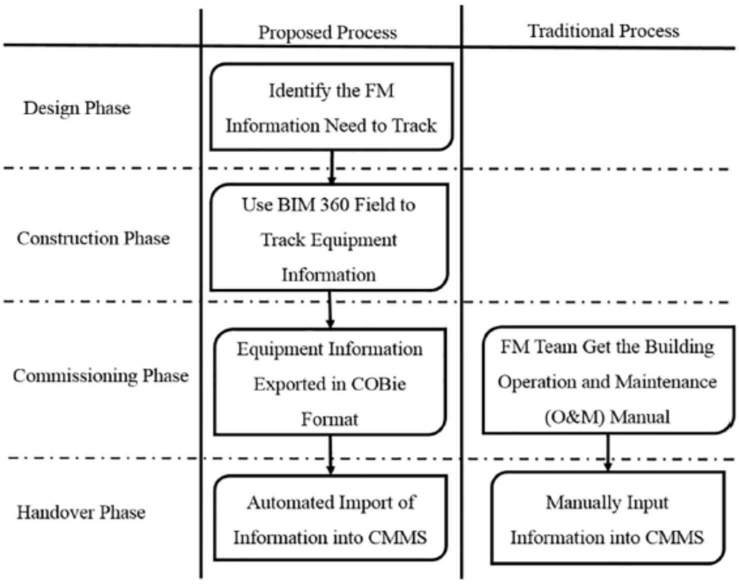


Figure 12: Comparison between processes for BIM-FM. Source: (Pishdad-Bozorgi et al., 2018b)

Lastly, another point of BIM-FM implementation related to the increasing importance of the data-driven culture that has been fundamental for AECO/FM arising technologies to integrate and make sense of the data acquired throughout an assets' lifecycle. It comprises the systematization of information in graphic format for a better visualisation of the performance of assets, assisting O&M activities, and supporting well-informed and intelligent decision-making. Indeed, suitable data analyses on a facility can bring about improvements on corrective and preventive maintenance for identifying failure causes (Motamedi et al., 2014), along with a more efficient energy consumption (Liang et al., 2016), and actions that simplify the maintenance of the building and improve the occupants' comfort (Daissaoui et al., 2020). In view of that, softwares for data analysis such as Power BI, are able to easily connect with a number of data sources, including relational databases. The tool provides access to creation of interactive dashboards to visualize the stored data in a way to support a more effective management of information.

To summarize, the main reported challenges for BIM-FM extensive adoption are due to the lack of early definition of AIR and the AIM, requiring involvement of FM professionals to define the objectives of implementation. Followed by interoperability issues and necessity of further development of open standards available, along with enhancing the communication between BIM and FM systems to establish a more sustained workflow of information, where one of the approaches suggested in the studies is linking the BIM model and the FM system to a central database that stores the information throughout the lifecycle of an asset, enhancing data integration and the capability for data analytics to assist facility managers on intelligent decision making to improve the asset's performance.

3. BIM-FM FRAMEWORK DEVELOPMENT

This chapter addresses the strategic methodology for developing a BIM-FM oriented framework focused on the project handover stage, establishing a relational database connected to the BIM model which is populated with relevant information for FM use. Followed by describing the study of possibilities for application of the proposed framework, along with the detailed computational workflow strategies and implementation.

3.1. Methodology

This section proposes a methodology that allows for the implementation of BIM-FM processes. The methodology considers the extraction of information from the BIM model into a relational database and further analysis of this data, supporting the consistency of information throughout an asset's lifecycle, according to the subsequent steps of research work:

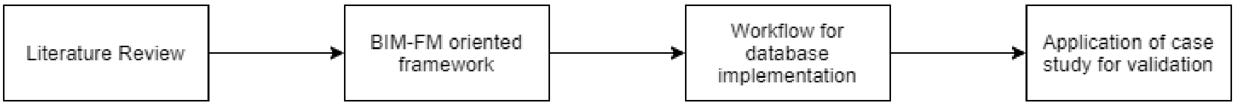


Figure 13: Research workflow

The focus of the proposed BIM-FM oriented framework is to define strategies for enriching the information of the BIM model through the processes in a way that the data is useful and accessible to support on O&M activities of a facility. Presumably, this framework is applicable only to new projects of any kind of facility which is going to be developed based on the collaborative approach using IPD, taken into consideration that design, construction, and facility management stakeholders are previously defined and involved on early stages of the project to provide inputs and set the requirements. It aims to point out a key solution for integrating BIM data for FM use with a central Relational Database Management System (RDBMS) that stores and maintains the information which has a bi-directional link with the BIM model to support the maintenance of updated information, followed by proposal of data analysis possibility using Power BI for leveraging the use of available data at the stage of operation of an asset.

For this study, the framework applies its use to lighting fixtures, elements present essentially in all kinds of facilities, by defining the required properties and performance indicators in accordance with previously presented guidelines and standards, assisting on the development of the AIM. Furthermore, the proposed tool developed in Dynamo for connection of the required BIM information into an SQLite database is described and also the analysis using Power BI. Nevertheless, the same process is also applicable to other facility equipment, such as HVAC system, plumbing, chiller, etc., satisfying the scalability of the proposed framework to other, more complex systems that can be part of a facility.

On the overview of BIM project stages, the methodology is applicable from the stages of feasibility to the handover of the model and its documentation, and further during the operation of the asset. When the database continues to be updated ensuring the maintenance of the information, following the defined quality assessments. Framework implementation steps follow the computational workflow, where modelling is done in Revit, the tool for model-SQLite database connection is made in Dynamo and further the data is analysed in Power BI. Figure 14 shows a general framework overview of the connection between the proposed software integration.

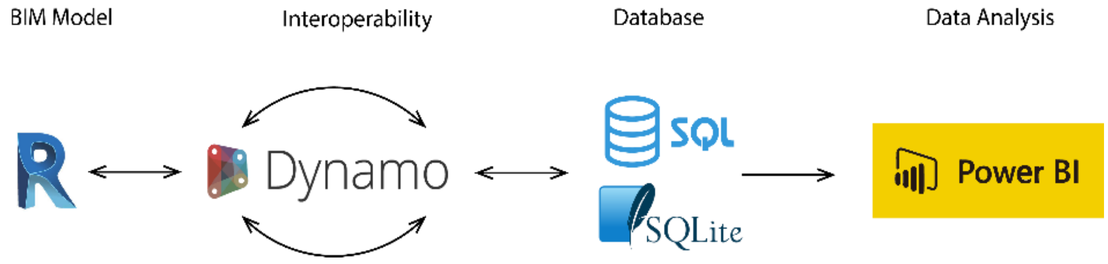


Figure 14: Overview of workflow between software

The framework processes for enhancing the information management are shown in Figure 15 in a straightforward way the involvement of stakeholders activities for the BIM-FM implementation. On the feasibility stage, marking the start of the project (from activity F1 to F6) the FM professional appointed by the project owner participates on the definition of the goals and objectives for the BIM-FM implementation and AIR of the project, along with the EIR established by the owner and the specifications made by the contractor involved, constitute the BEP document for construction appointment made by the assigned BIM manager. Those requirements must be in alignment with the standards defined for the project, as shown in section 2.4. The AIR defines the objectives and performance indicators for the operation of the facility. As part of the Key Performance Indicators (KPI) for O&M purposes must be defined by the involved stakeholders, selecting the most appropriate ones for each asset performance metrics, being crucial on the assessment of the condition of a facility.

Taking into consideration the modelling of the object properties on BIM elements, it should include on its definition the metric indicators for lighting fixture maintenance in buildings. These metrics should comprise of information regarding the equipment's energy consumption, life expectancy, warranty details, lighting controls, colour temperature, type of lamp and its total wattage, along with additional manufacturer information

During the construction phase of the asset, the contractor is responsible for updating the BIM model in accordance to the as-built conditions, fulfilling the requirements specified on the BEP (activity C1). As for the modelling of elements, those must follow the standard defined during feasibility stage to be consistent throughout the project, along with the LOD of those objects. Although the guides and standards mentioned in section 2.4 do not define a specific LOD for BIM-FM purposes. As for the quality assurance of the model (activity C2) it must be done in order to verify the accuracy, quality, and the completeness of the required data before the handover to FM. Also being necessary to verify the exchange of information between pre-defined file formats, to guarantee that there is no loss of information or issues on the files.

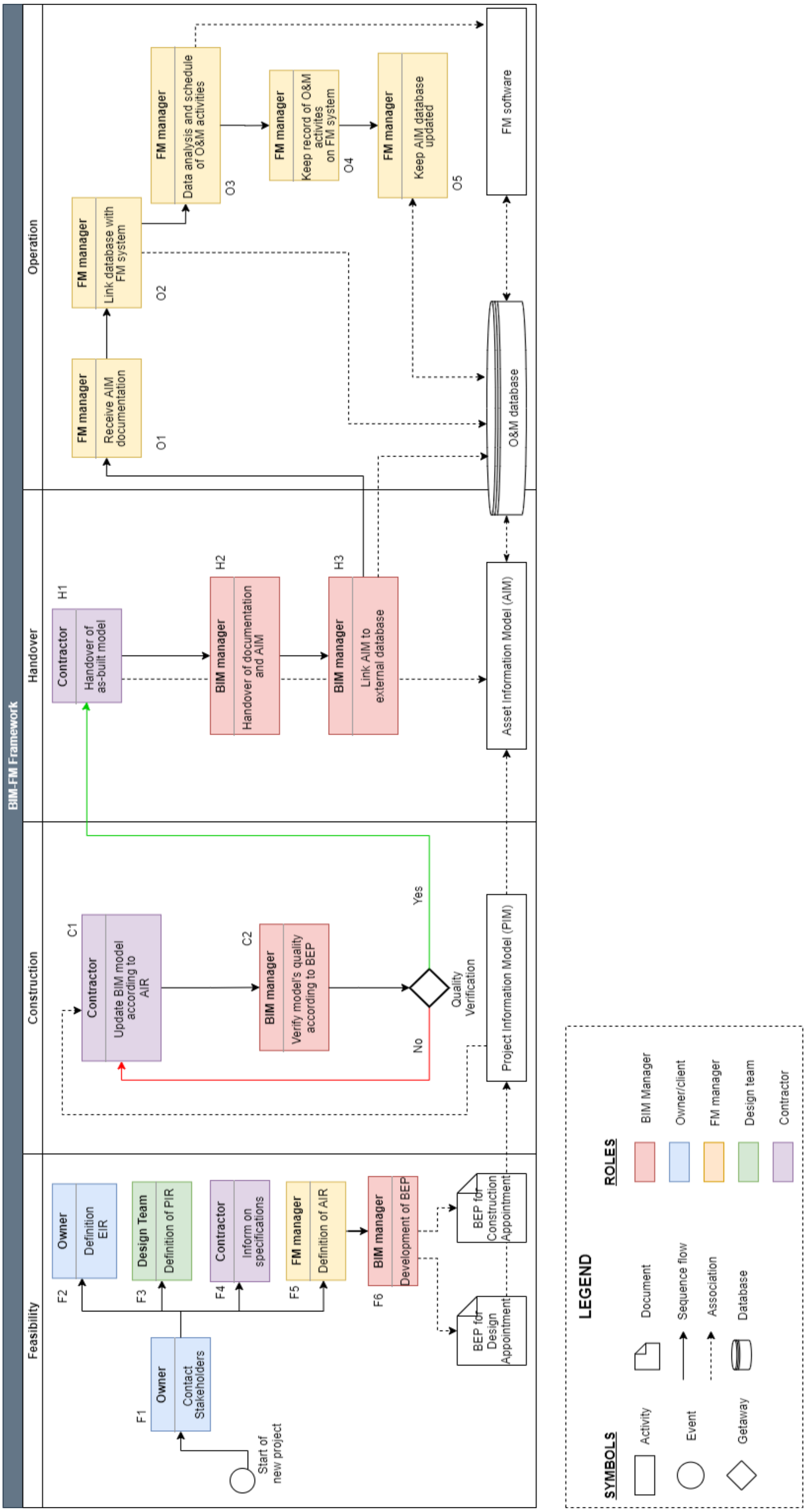


Figure 15: BIM-FM framework process for implementation

in case the model meets the standards and conditions agreed upon in BEP, the BIM manager responsible for the handover must gather the required AIM files and documents, which also includes the SQLite database populated for O&M, and transfer it to the facility manager responsible for receiving the documentation (activity O1). The assigned responsible must then connect the SQLite database with the designated FM system (activity O2) and/or with a data analysis tool For this framework the connection is made with Power BI for analytics purposes. Moreover, the schedule of O&M activities is done in the FM system (activity O3).

The record of O&M activities (activity O4) can be kept in the FM system and updated in the database on a regular basis (activity O5) to maintain the required information centralized and feed the analytics dashboard with the ongoing asset's information. The schema shown in Figure 16 demonstrates how the AIM data is structured, where the BIM model contains both graphical and non-graphical data, and the FM system with the non-graphical data related to O&M activities. As for the database, it stores only the selected non-graphical information transferred from the BIM model which is bidirectional.

Throughout the operation stage, it is crucial to keep the central database updated. To make that an easier and more efficient process the FM staff should be able to update the information directly in the database or in the adopted FM system, if it allows for a bi-directional connection to SQL, preserving the accuracy and quality of the information. Furthermore, the central database should be the main source of the asset's information, and the update of that information is made directly on the structured database. Other systems that are connected to it are fed out the information directly from the same data repository. Thus, in order to avoid issued with different sources updating the same information in different ways, maintaining the central database as a reliable source of the asset's data.

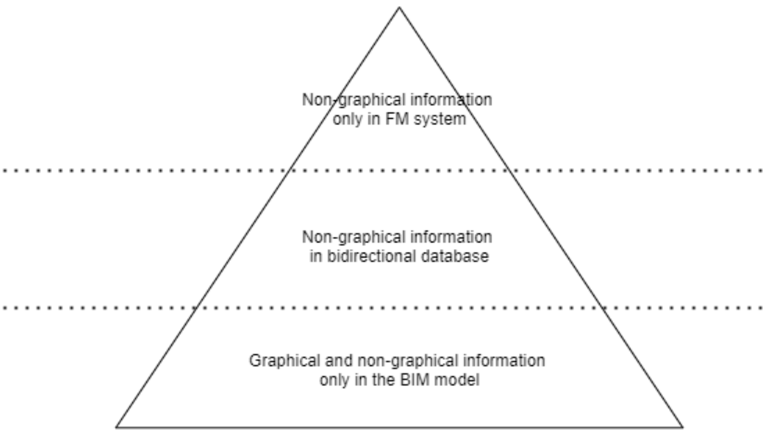


Figure 16: Schema of information structure between systems

The proposed framework greatly reduces the amount of manual work that is usually required using traditional approaches for transferring the information from the BIM model to the FM system, besides it optimizes the search, input and query of the assets' information by using the available BIM data in the relational database to support the maintenance activities. By implementing a bi-directional connection with the BIM model, integrating the information in both SQLite and Revit model. And pointing to a more efficient approach to updating the information directly in the central database. Hence, being a solution for keeping the accuracy of the information without requiring for the FM staff to learn or be familiar with BIM modelling tools.

3.2. Framework overview

This section describes and proposes the process of implementing the connection between the BIM model, the relational database, and further with the data analysis tool. The first section explains the different approaches studied for this implementation, where its benefits and limitations are described for each of the approaches. Further, the chosen approach is described, along with an illustrated workflow proposal. Which delineates the steps for the tool implementation and applications of use.

The proposed interoperability framework it is included on the stages of the project's handover, followed by its application and maintenance of the central database through the operation stage of the asset by FM professionals, where on Figure 15, comprises of the activities from H1 to 05.

3.2.1. Alternatives for tool development

To develop such a connection, a study of possibilities was first performed. to discover which options are available for integrating BIM models with an external database. The modelling tool considered for this study purposes is Revit due to its accessibility, extensive use, and connection with a visual programming tool (Dynamo). For this research it the direct use of IFC format file was not considered, for the reason that it would demand a more complex and time-consuming script development. However, and IFC file can be imported into Revit to read the model, and the information extracted from there.

The following alternatives were contemplated: (1) use Revit DB Link for direct export; (2) Save as an Open Database Connectivity (ODBC) file; (3) Use Dynamo to link Revit model with a Database Management System (DBMS); (4) Connect through Revit Application Programming Interface (API) with DBMS; (5) Export as an IFC file and link with Power BI using VCAD. Table 1 explains, in general terms, the benefits and limitations of each mentioned option.

Table 1: Study of possibilities for integration of BIM Revit model with database system

N^{O}	Benefits	Limitations
1	According to the plug-in developer, it is possible to update information from the database to the model just by refreshing though the plug in; allowing connection with many DBMS.	The available file to download did not work, could not get support from the developer for an updated link, making it impossible to test this alternative.
2	Creates a database table for each element category exported; direct export into DBMS file format.	Limits the type of information that can be exported; it is not a bidirectional relationship, just works one-way of extracting information from Revit.

3	The use of Dynamo allows for adjustments according to project's necessity. Allows for bi-directional integration between Revit and SQL database	The exported file format is for a specific database, in this case SQL. To export for a different database the script needs to be adapted; Dynamo can be limiting, as a result programming directly through Python language may be required.
4	A more flexible alternative; allows for a more seamless data integration; can be adapted to fulfil different project's necessities.	More complex and time-consuming development; requires familiarity with Revit API and Python language.
5	Web-based platform with a BIM viewer that allows for information export and report generation, connecting the linked IFC file with Power BI for data analysis.	The generated IFC file by exportingonly links directly with Power BI; to update the information an upload of a new IFC file and generating a new report is required.

As a final result of the analysis, the chosen option to develop such connection was (3) to export the information from Revit and connect it with a SQL database through a Dynamo script, thus establishing a bi-directional relationship between BIM model and the relational database, and analysing the data collected in Power BI separately. The option for using Revit software is mostly due to practical reasons and extensive use of this software for modelling purposes. In addition, Dynamo is a visual programming tool that works with Revit, by providing access to the Revit API and other Autodesk software in a more accessible manner. The connection with SQL is due to its flexibility, easily linking with other available software, such as those employed by FM, being supported by almost every DBMS available, and its capability to retrieve a large amount of data with a faster query service, a required competence when dealing with an extensive BIM project. Moreover, it is a standardized and interactive language with easy data manipulation, not requiring advanced programming knowledge to deal with the regular database. SQL is a domain specific language code, that is widely used in programming, and for managing data held in a Relational Database Management System (RDBMS), which consists on a collection of information that organizes data points with defined relationships in an intuitive and straightforward way, thus simplifying the creation of relationships among data points. For this research the one adopted is the SQLite database along with the DB Browser for SQLite to visualize the information.

3.2.2. Computational Workflow

The required activities are composed of processes of modelling, data exchange, populating the database, and data analysis which are all shown in Figure 17, that contains the computational workflow proposed. The modelling part from activity M1 to M3, is performed by the BIM specialist assigned by the contractor to update the model in accordance to the as-built conditions following the steps mentioned in section 3.1, following the AIR specifications for each element. In parallel, the activities D1 and D2 are executed , creating the Dynamo tool, for which the overview of the script used for this study case can be found in Appendix 1, and the details of each group contained on the file are described below.

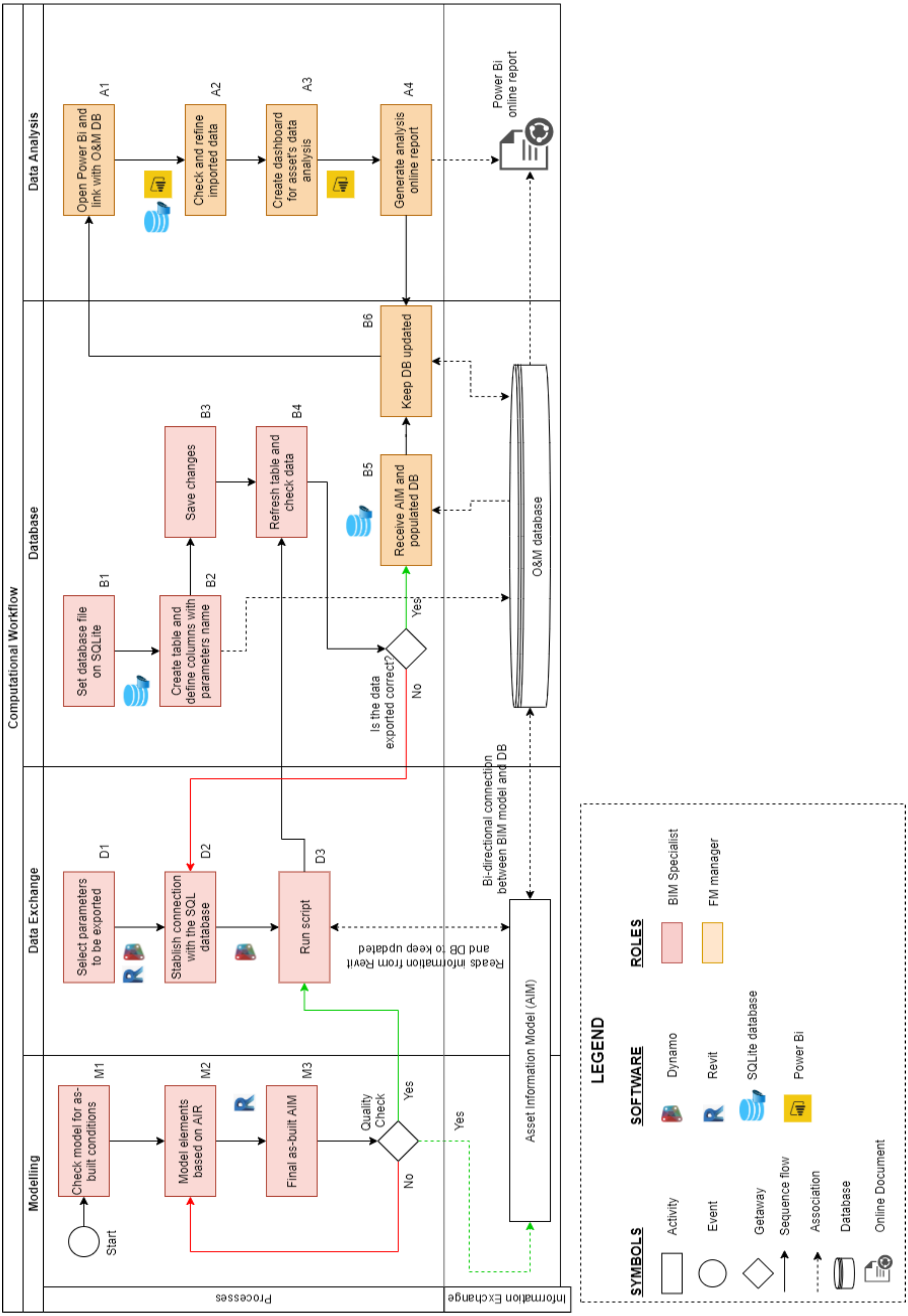


Figure 17: Computational workflow processes

To establish the relation between systems (activity D2), the script was developed in a way that first the user is able to choose which families (classes of objects) and parameters to be exported, considering that for the operation of the asset not all BIM model data needs to be entered in the database. The overview of the developed script is shown in Figure 18, which is divided into four big groups that represents the steps for implementing the framework.

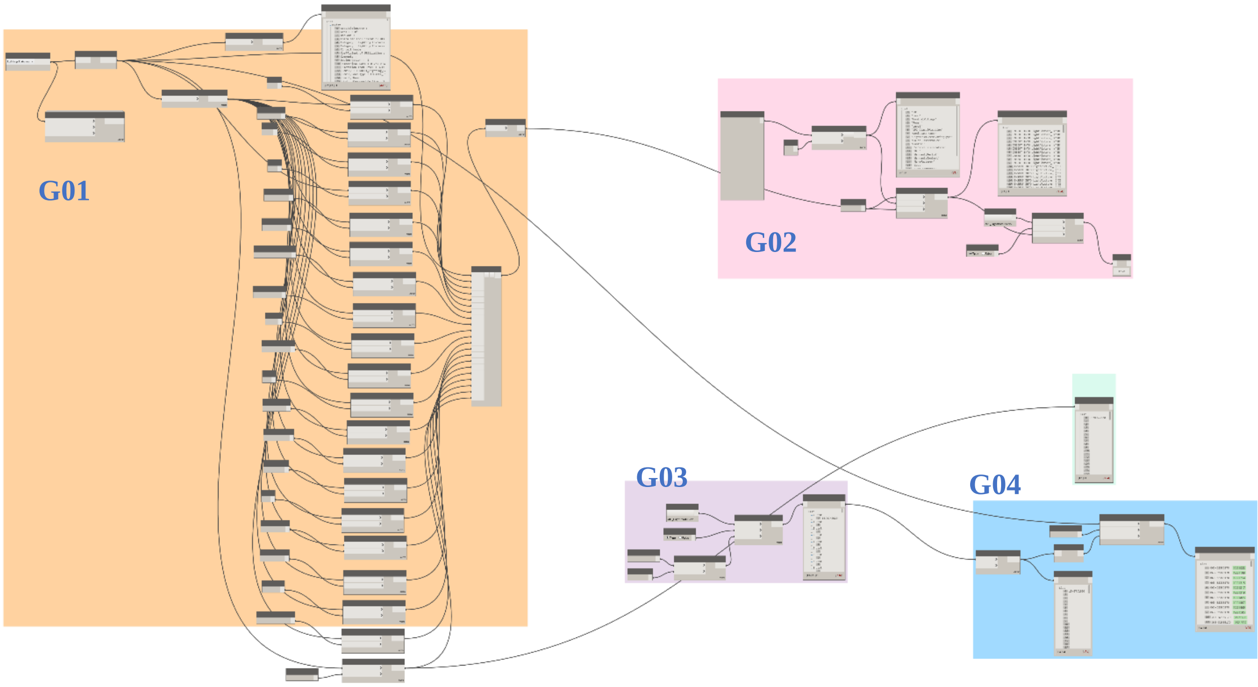


Figure 18: Overview of Dynamo script and its groups

For which G01 stands for the group with the selected classes of objects and its correspondent parameters to be exported, and the list with each element assigned to its parameter's values. The parameters list is then connected on G02 with the assigned columns containing the name of the parameters and the path for the database file and specific table. Thus, establishing the connection between Revit BIM model and SQLite database. To establish the bi-directional connection, G03 contains the nodes responsible for reading information contained on the SQLite database, followed by connecting that information to G04 where the update is inserted back into Revit through on the assigned element. This bi-directional connection is made possible through maintenance of the element unique ID on both Revit and the SQLite database, keeping the information contained in both files unified.

However, it is important to take into consideration that from the database to the BIM model it is only possible to update and have the bi-directional link on non-graphic and non-relational parameters, which are those parameters who do not interfere on the geometry of the element. For instance, if a change is made on the parameter 'level' on the SQL database and update it on Revit, the element will not change the level where it is inserted on the model. Since other constraints related to the geometry of the object apply to such case. Thus, in the case of physical changes on the facility and project renewals, the updates of graphic information must be made on the BIM model native file by the assigned responsible on the project's team involved.

Hence, it is important to take into consideration that it is only possible to update non-graphical parameters from the database to the BIM model and those that do not interfere with the elements' geometry, for example, if a change is made on the parameter 'level' (storey of a building, where the element is positioned) in the database and is then updated in Revit, the element will not change the level where it is positioned in the model, since other constraints related to the geometry of the object apply. Thus, in the case of physical changes of the facility and project renewals, the updates of graphical information must be made in the BIM model's native file by the assigned responsible in the project's team.

3.2.3. Data Analysis

The final steps of the proposed framework is to integrate the database with the software Power BI, which corresponds for the activities A1 to A4 in the workflow (Figure 17). At the beginning Power BI is connected with SQLite database and after the data from it is imported into Power BI, the software keeps a one-way integration with the database. changes to the database need to be updated into Power BI by refreshing the table on Power BI tab. The imported data requires refinement and selection of the information useful for the analysis report (A2), which can be made through the Power BI's 'query' interface. Therefore, the selected data is added to a dashboard with a previously stablished template, which works as a support system for decision making for O&M activities and evaluation of the asset's performance requirements, the overview of Power BI workflow is demonstrated in Figure 19.

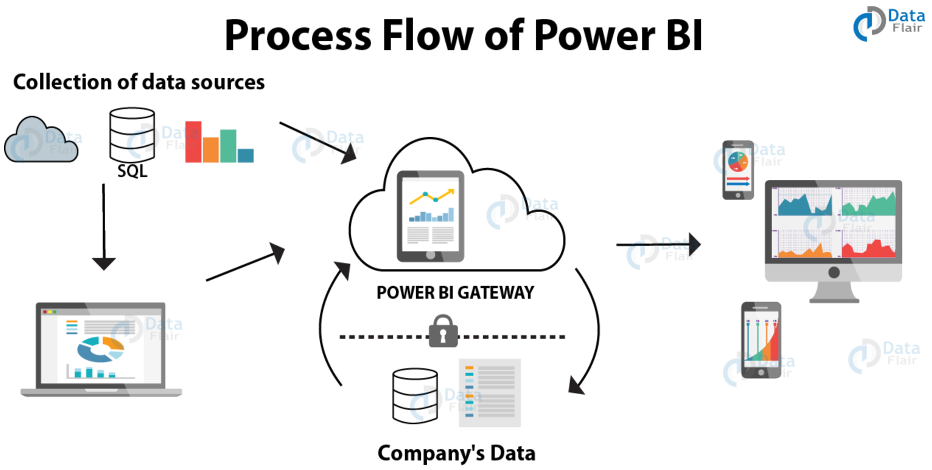


Figure 19: Power BI process workflow. Source: (Data Flair, 2020)

The generated dashboard and report can be shared as a Power BI file between members of the same company, where according to the team's hierarchy is possible for other members to apply changes on the dashboard, or can be shared publicly online through a link giving access only to visualised dashboard information, an example of Power BI online visualization of the dashboard is shown in Figure 20. Hence, Power BI is a software for creating and visualizing data analysis reports, becoming more powerful when integrated with information from the FM system such as the record of O&M activities, which can be equally stored in the SQLite database, allowing for better decision making.

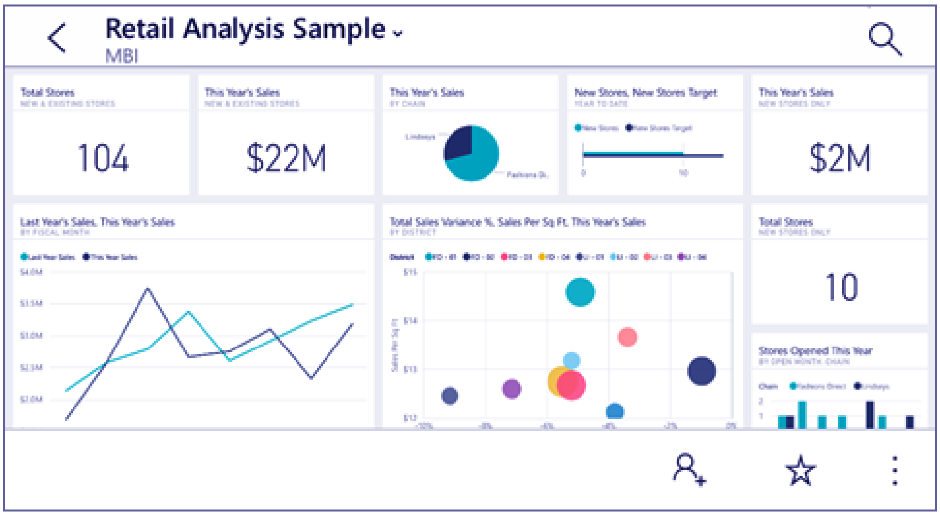


Figure 20: Power BI sample online dashboard

Overall, the proposed process maximizes data integration between BIM and FM by using SQLite as a central database, which easily integrates with both data analytics software and other FM system, establishing an automated integration and an accessible way to keep the data updated. Secondly, the connection of BIM data with an data analysis tool provides a powerful support system for leveraging the use of available information for an effective management of O&M, inciting the data-driven culture that has been arising among industries to support decision making, being fundamental in the case of AECO/FM developing technologies.

The analysis of an asset's data assists with improvements of facility management related activities to achieve a more efficient management of the asset, where an integration with a large collection of data acquired throughout the lifecycle can be processed and analysed for improvements on the performance requirements of the asset. Considering that all this information is integrated on a SQL database, that serves as a central repository for all required assets' information, updated on a regular basis, keeping the standard, structure, and quality of the data to be accessible and useful throughout the lifecycle.

4. CASE STUDY

This chapter consists on the application of the proposed framework on Chapter 3 to a case study project. The case study is based on the library building of the Campus of Azurém of the University of Minho, in Guimarães (building #13). As the purpose of application was a demonstration of feasibility of the framework in a BIM-FM setting, the sub-set of lighting fixtures information was selected to be the focus. Furthermore, the present dissertation took advantage of an existing Architectural and Structural BIM model, which was gently provided by a group of students of the BIM Module of the Integrated Master in Civil Engineering at the University of Minho (see Acknowledgments section).

After an initial overall presentation of the case study and available information, the modelling of the lighting fixtures is described (including application of pre-selected modelling rules), this chapter describes the application of the computational workflow proposed, populating the database and generating a data analysis dashboard from the extracted BIM data.

For the implementation of the workflow on this case study, the application of the framework from section 3 (Figure 15) is considered from the labelled activities C1, starting with the update of the BIM model in accordance to as-built conditions, until activity O3 for data analysis. Considering that the asset of this case study is already on operation stage, the first steps of feasibility and project definitions (activities F1 to F6) are not applicable on this study.

4.1. Description of the case study building and available information

The project adopted for this case study is the library building (#13), located in Campus of Azurém of the University of Minho, in the city of Guimarães, Portugal. The building was inaugurated in 2016, comprising of 7 floors, with one floor below the ground for storage. The library contains a vast number of rooms of study stations, concentrated on floors 3, 4, and 5, as demonstrated in the floor plan in Figure 21. Including on that, the first floor of the facility contains 24x7 study rooms.

The main entrance of the building is through a glass and steel walkway, located on the 2nd floor where multifunctional space for small events is available. The building’s façade is composed by a great number of large windows on the study rooms and areas of permanency, allowing a great amount of natural light in those spaces, in opposition to blind fronts in strategic areas. A recent photo of building is shown in Figure 22.

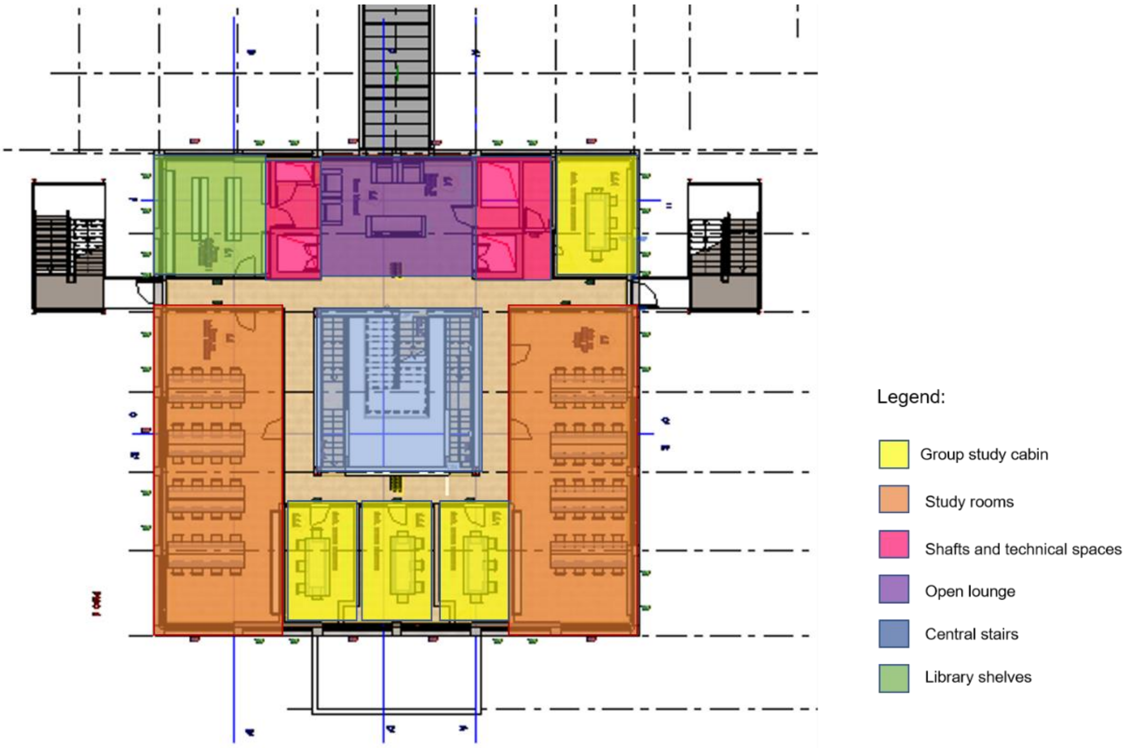


Figure 21: 3rd floor plan with rooms distribution

Figure 22: Library's building. Source: (CM-Guimaraes, 2016)

The BIM model of the building was developed in Revit software by a group of students from the same University Masters course in Civil Engineering. The BIM files applicable to this study, comprises of the architectural and structural Revit files. Where the elements of those disciplines, including general furniture, are around LOD 250 – 300, as shown in Figure 23 with a 3D section of the library's building. The lighting fixtures of the building were not included on the original Revit files. Hence, besides the Revit files of the project, it was also received the 2D CAD drawings of the electrical equipment and lighting fixtures floor plans containing the floor plans and overall description of those systems in the building. Thus, the CAD drawings contain a general description of the lighting equipment, defining the type of fixture to be placed on each room, in accordance to the distribution on the floor plan design. Hence, the information provided serve as a base for modelling the required lighting fixtures objects in accordance to the original project specifications.

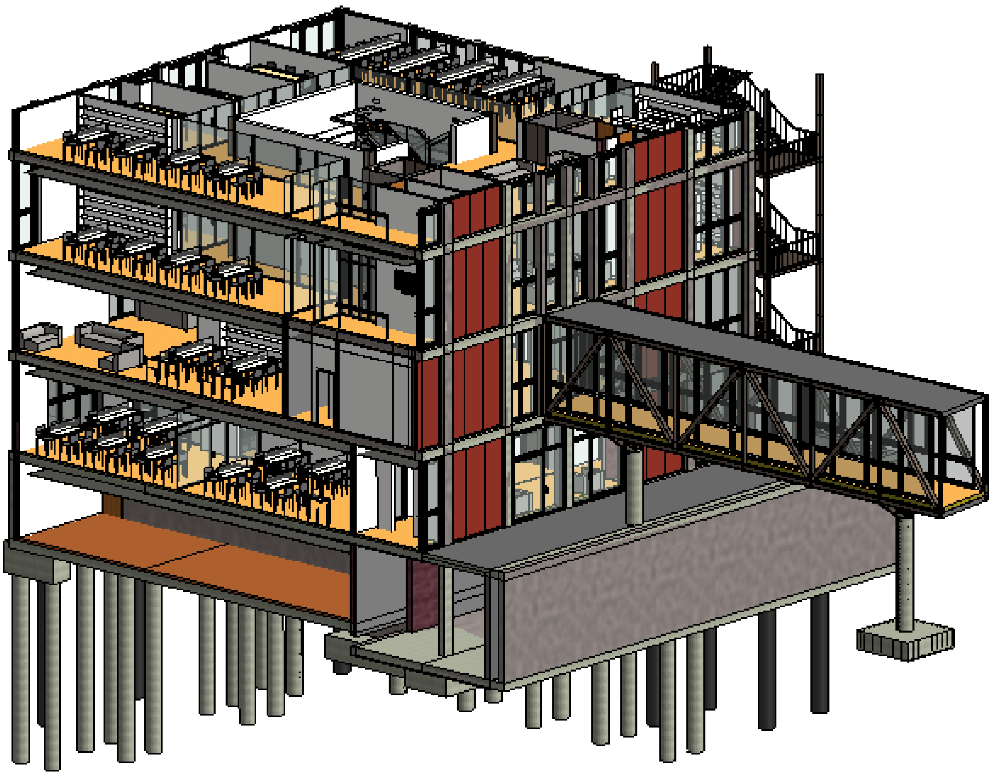


Figure 23: 3D section of the building

Which for this case study, the lighting fixtures were modelled on floors 3 and 4, both of those floors are similar in their rooms disposition, containing the space for group study rooms, two elevators next to a small equipment/storage room, and open common areas with circulation halls accessed by the central stairs, as shown previously in Figure 21. Hence, the same distribution for lighting and rooms applies also to the 4th floor. The distribution and the placement of each type of lighting fixture is demonstrated in Figure 24.

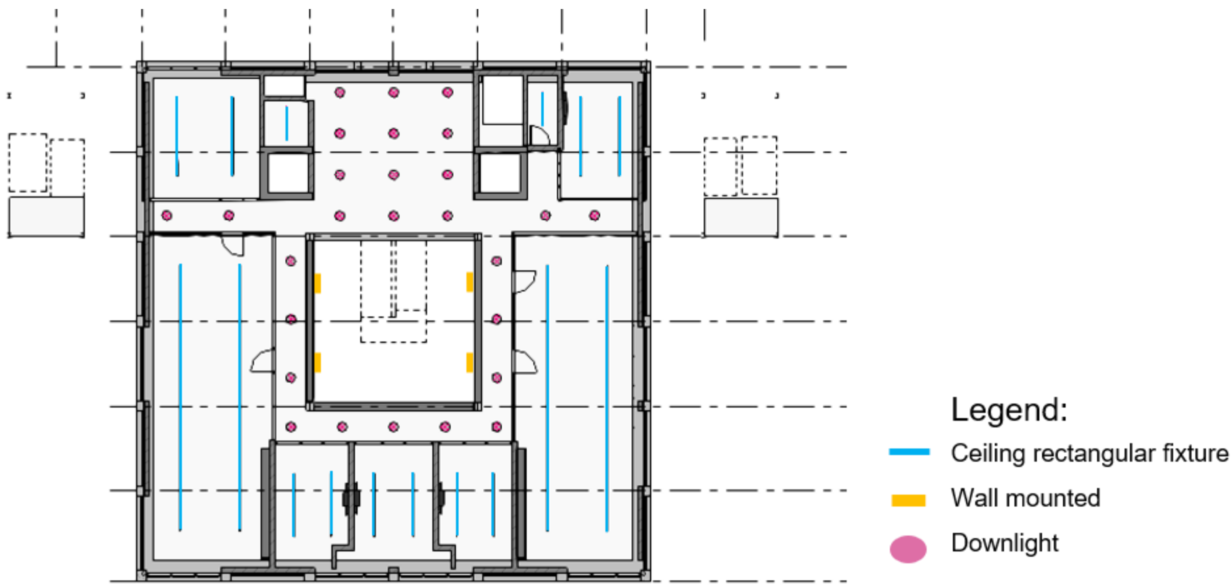


Figure 24: 3rd floor ceiling plan

There are three different types of lighting fixtures existing on the project for the assigned floor plans, as highlighted in Figure 24. However, it was not possible to have direct access to the actual information of the installed lighting fixtures, only to the proposed design. For this reason, a group of existing solutions in the market was adopted in order to satisfy the available design requirements, hence being realistic enough. In accordance to that, Table 2 describes the type and quantity of fixtures on both floors that were modelled, considering that for the rectangular type of lighting fixtures those are composed by more than one in sequence to satisfy the length required for that type of light in the study rooms. The more detailed parameters and the manufacturers' information are available on Annex 02 datasheets.

Table 2: Type of building's lighting fixture

Type of lighting fixture	**Location**	**Lamp type**	**Quantity**	**Image**
Ceiling round downlight	Corridor and common areas	LED	56	
Wall-mounted fixture	Stairs	LED	8	
Ceiling rectangular fixture	Study rooms and storage space	LED	70	

4.2. BIM modelling of the light fixtures for FM

4.2.1. Guidelines and rules followed

As a first step for modelling the elements is the definition of standard to be applied, for this study the objects are in accordance to the Open BIM Object Standard (OBOS) rules and classification (OBOS, 2018). In addition, the asset/facilities management properties to be added, are in accordance to what is required by the Property Sets (*PSet_*) from the IFC 4 schema, which is a Core Data Schema that provides basic structure, relationships and common concepts for further specializations and describes how sets of properties are associated to objects or objects types (“Industry Foundation Classes (IFC),” 2020). If necessary, in addition to the IFC properties.

The parameters required for facility management purposes are demonstrated from Table 3 to Table 7 in sequence, identifying the properties name, data type required and a generic example to demonstrate the correct format of the parameters inputs. For the case study, the tables with the parameters for the three types of lighting fixtures added can be found on Annex 02, where an example of part of the inputted parameters is shown in Figure 26.

In addition to the table parameters, the *IfcExportAs* shall be completed with the designated *IfcElementType*, which on this case of lighting fixture is *IfcLightFixture*, and the *IfcExportType* completed with the value of object *PredefinedType*, this case it is as *NotDefined*, this parameters are addes in order to ensure the correct designation of the object properties when exporting to IFC file format.

Table 3: Properties set for LightFixtureTypeCommon

Pset_LightFixtureTypeCommon		
Property	**Data Type**	**Example**
Reference	IfcIdentifier	A-52
NumberOfSources	IfcInteger	1
TotalWattage	IfcPowerMeasure	14 W
MaintenanceFactor	IfcReal	0.00
MaximumPlenumSensibleLoad	IfcPowerMeasure	1.5 W
MaximumSpaceSensibleLoad	IfcPowerMeasure	21 W
SensibleLoadToRadiant	IfcPositiveRatioMeasure	10%
Status	IfcLabel	Demolished

LightFixtureMountingType	IfcLabel	Ceiling Mounted
LightFixturePlacingType	IfcLabel	Ceiling

Table 4: Property set for ManufacturerOccurence

Pset_ManufacturerOccurrence		
Property	**Data Type**	**Example**
AcquisitionDate	IfcDate	15/07/2020
BarCode	IfcIdentifier	Add barcode
SerialNumber	IfcIdentifier	173.29376.29
BatchReference	IfcIdentifier	
AssemblyPlace	IfcLabel	Factory

Table 5: Property set for ManufacturerTypeInformation

PSet_ManufacturerTypeInformation		
Property	**Data Type**	**Example**
GlobalTradeItemNumber	IfcIdentifier	GTIN code
ArticleNumber	IfcIdentifier	345
ModelReference	IfcLabel	1708-0039-SE
ModelLabel	IfcLabel	Name of fixture
Manufacturer	IfcLabel	Manufacturer Name
ProductionYear	IfcLabel	2020
AssemblyPlace	IfcLabel	Factory

Table 6: Property set for ServiceLife

Pset_ServiceLife		
Property	**Data Type**	**Example**
MeanTimeBetweenFailure	IfcDuration	5000 h
ServiceLifeDuration	IfcDuration	5000 h

Table 7: Property set for Warranty

Pset_Warranty		
Property	**Data Type**	**Example**
WarrantyIdentifier	IfcIdentifier	
WarrantyStartDate	IfcDate	02/02/2020
WarrantyEndDate	IfcDate	02/02/2021
IsExtendedWarranty	IfcBoolean	Yes/no
WarrantyPeriod	IfcTimeMeasure	1 year
WarrantyContent	IfcText	Include content description or URL
Exclusions	IfcText	Include exclusions description

4.2.2. BIM modelling procedure

The modelling process comprises of (1) search for family type on a BIM library; (2) check for parameters and information from manufacturer; (3) place elements in accordance to the project; (4) complete object with missing parameters and information; (5) review the completeness of required information. For the application of this case study the families were downloaded from BIMobject platform library, where you have available the manufacturer information of the object and the product catalogue, as shown in Figure 25.

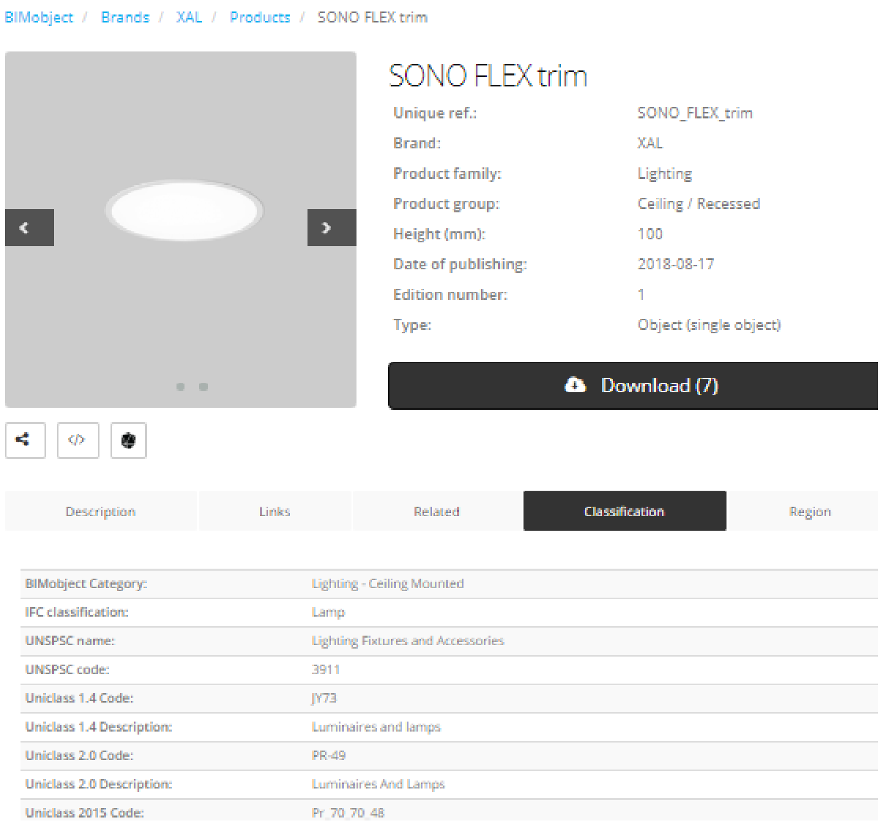


Figure 25: BIM Object library example.

Most of the required parameters were accessible on the original files, as for the missing properties the procedure is to create as shared parameters, so they can be equally added to all assigned elements following the same specifications, to complete the field, the product catalogue was consulted, and for the case when the required information of an element is not provided by the manufacturer the parameter is inserted but the specification is left as “n/a”, as demonstrated in Figure 26. Afterwards, when completing the modelling process, the procedure was to check the assigned classes of objects for the completeness of the information. Hence, in order to guarantee that all required property sets are following the same naming convention, and those are filled with the necessary information.

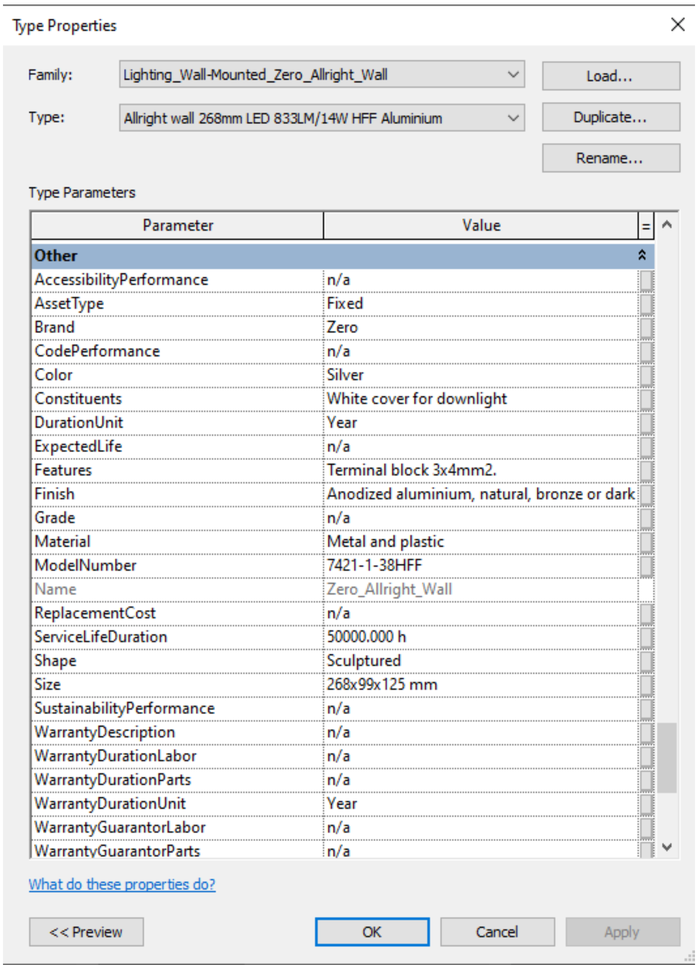
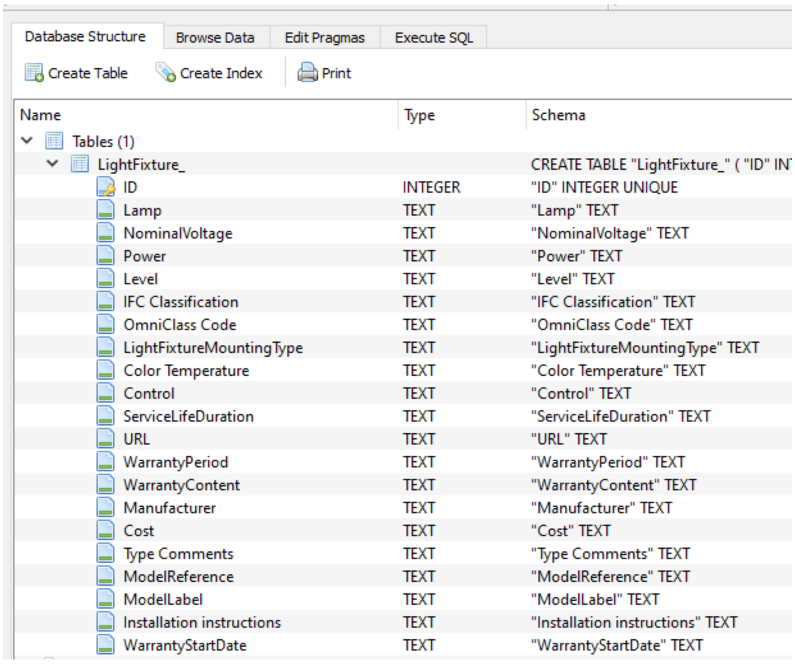


Figure 26: Example of parameters in the wall mounted lighting fixture

4.3. Application of developed tool

The application of the tool follows the steps described on section 3.1 of this document, on which some of the parameters to be exported and its values were added to the Dynamo script, that is shown in full context on Annex 01. Moreover, for setting the structure of the database file the same parameters name to be exported are added to the assigned table as unique columns, show in Figure 27. The framework applied to this case study works with a single table composing the information of the lighting fixtures elements. The element ID parameter is the assigned unique ID for each element on Revit. By keeping this association of the unique ID on both BIM model and SQL database, the interconnectivity of the data is made possible between the exported parameters.



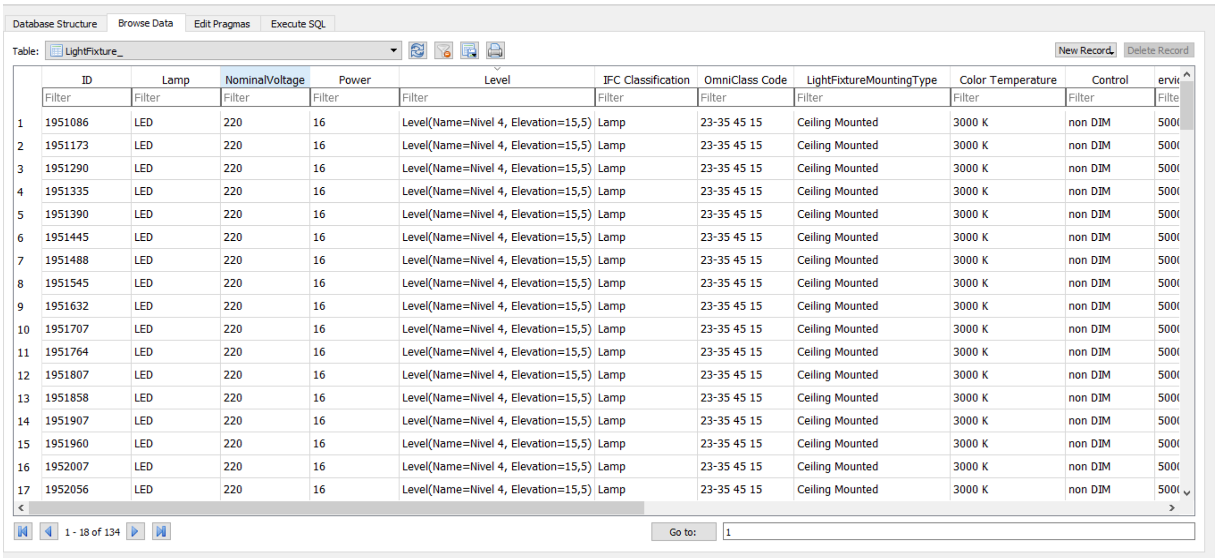
Database Structure | Browse Data | Edit Pragmas | Execute SQL

Create Table | Create Index | Print

Name	Type	Schema
Tables (1)		
LightFixture_		CREATE TABLE "LightFixture_" ("ID" IN
ID	INTEGER	"ID" INTEGER UNIQUE
Lamp	TEXT	"Lamp" TEXT
NominalVoltage	TEXT	"NominalVoltage" TEXT
Power	TEXT	"Power" TEXT
Level	TEXT	"Level" TEXT
IFC Classification	TEXT	"IFC Classification" TEXT
OmniClass Code	TEXT	"OmniClass Code" TEXT
LightFixtureMountingType	TEXT	"LightFixtureMountingType" TEXT
Color Temperature	TEXT	"Color Temperature" TEXT
Control	TEXT	"Control" TEXT
ServiceLifeDuration	TEXT	"ServiceLifeDuration" TEXT
URL	TEXT	"URL" TEXT
WarrantyPeriod	TEXT	"WarrantyPeriod" TEXT
WarrantyContent	TEXT	"WarrantyContent" TEXT
Manufacturer	TEXT	"Manufacturer" TEXT
Cost	TEXT	"Cost" TEXT
Type Comments	TEXT	"Type Comments" TEXT
ModelReference	TEXT	"ModelReference" TEXT
ModelLabel	TEXT	"ModelLabel" TEXT
Installation instructions	TEXT	"Installation instructions" TEXT
WarrantyStartDate	TEXT	"WarrantyStartDate" TEXT

Figure 27: SQLite DB columns structure

After the database is structured and the Dynamo script set to run, the table is populated accordingly as shown in Figure 28, the information was checked and it did correspond accurately to what is on the BIM model parameters.



Database Structure | Browse Data | Edit Pragmas | Execute SQL

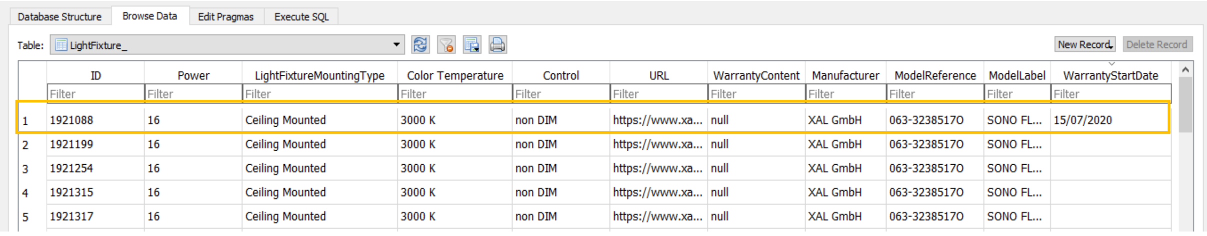
Table: LightFixture_ | New Record | Delete Record

	ID	Lamp	NominalVoltage	Power	Level	IFC Classification	OmniClass Code	LightFixtureMountingType	Color Temperature	Control	ervi
	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filte
1	1951086	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
2	1951173	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
3	1951290	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
4	1951335	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
5	1951390	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
6	1951445	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
7	1951488	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
8	1951545	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
9	1951632	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
10	1951707	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
11	1951764	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
12	1951807	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
13	1951858	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
14	1951907	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
15	1951960	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
16	1952007	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(
17	1952056	LED	220	16	Level(Name=Nivel 4, Elevation=15,5)	Lamp	23-35 45 15	Ceiling Mounted	3000 K	non DIM	500(

1 - 18 of 134 | Go to: 1

Figure 28: Populated SQLite database

After certifying the completeness and correct structure of the exported data into the database, the next step was to test the bi-directional feature of the tool to update the information directly from the central database back to Revit. On the study case, an information of date was added on the WarrantyStartDate parameter, as shown in Figure 29, for the element with a corresponding ID 1921088, to simulate a change or addition of missing information.



	ID	Power	LightFixtureMountingType	Color Temperature	Control	URL	WarrantyContent	Manufacturer	ModelReference	ModelLabel	WarrantyStartDate
1	1921088	16	Ceiling Mounted	3000 K	non DIM	https://www.xa...	null	XAL GmbH	063-32385170	SONO FL...	15/07/2020
2	1921199	16	Ceiling Mounted	3000 K	non DIM	https://www.xa...	null	XAL GmbH	063-32385170	SONO FL...	
3	1921254	16	Ceiling Mounted	3000 K	non DIM	https://www.xa...	null	XAL GmbH	063-32385170	SONO FL...	
4	1921315	16	Ceiling Mounted	3000 K	non DIM	https://www.xa...	null	XAL GmbH	063-32385170	SONO FL...	
5	1921317	16	Ceiling Mounted	3000 K	non DIM	https://www.xa...	null	XAL GmbH	063-32385170	SONO FL...	

Figure 29: Parameter update on database

The element ID contained on the table for this case study is the one that Revit assigns automatically to each unique element, and what maintains the relationship between the element information on the database and on the BIM model, making it possible the bi-directional connection between systems, where the change made on the WarrantyStartDate parameter is assigned correctly on the element that was updated, as shown in Figure 30 below.

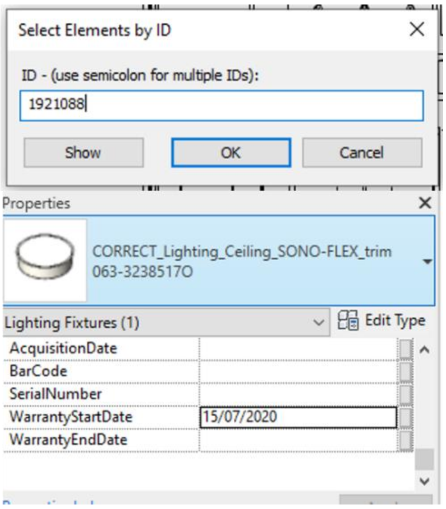


Figure 30: Information updated on Revit element

Following the framework, the next step is for analysis of the available data, where the use of Power BI for visualization of the data analysis is suggested, the tool provides an easy connection between SQLite database and the software, another relevant aspect of this connection relates to the straightforward update from the database that only requires to refresh the table on Power BI to display the changes made, keeping the previous work developed. After linking the SQLite file to Power BI, it is required the refinement of data that will be inserted on the dashboard, this data treatment consists on creating filters on Power BI query tab editor shown in Figure 31, which does not interfere or changes the original information on the database, creating just a filter on Power BI for a better visualization of the information.

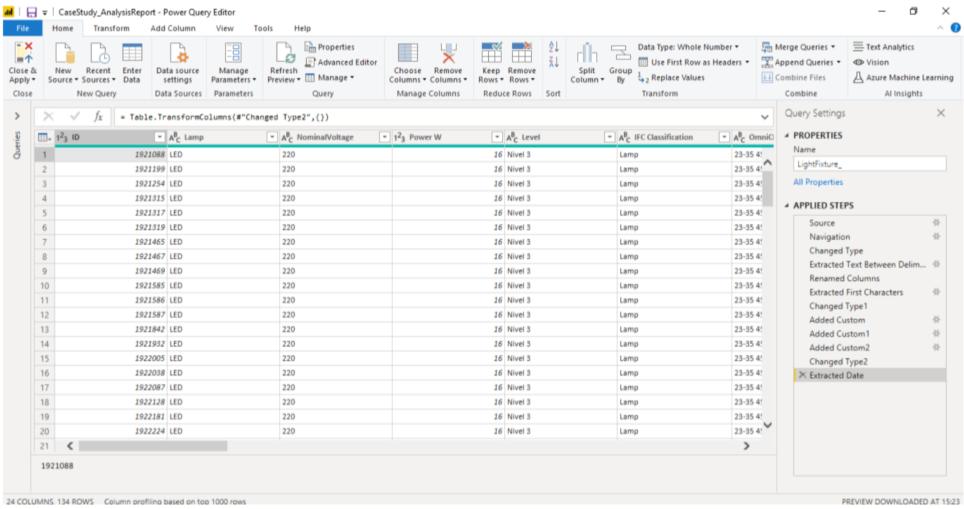


Figure 31: Power BI query editor

On this case study, one of the filters applied consisted on extracting text information that was polluting the visualization, for example on parameter 'Level' you have level name and elevation values, but for this case the elevation is not required on the dashboard, so those characters values are extracted leaving only the name of the level that applies to each element. Other refinement applied, was to insert custom columns to calculate total monthly consumption of the lamps, since the BIM data available comprises the total power of each lamp, a column was created simulating that the lamps operate during 10 hours a day and multiplying this value by 30 days of the month, resulting in a prediction of monthly energy consumption for lighting fixtures. However, this information can be originated from other sources, such as the electricity measure panel of the building connected to the lamps, by using sensors to collect accurate data of the energy consumption.

Followed by that, the information is inserted on the dashboard, which can be a standard template file or a custom one, for this case a custom one was developed in accordance to lighting fixture maintenance performance metrics and requirements for schedule of maintenance, for example having the information of next expected maintenance in accordance to the lighting fixture life expectancy, Power BI has an interactive dashboard (Figure 32) that allows for quick and easy queries of available data, on this case, date of predicted maintenance, according to the life expectancy of the lamp, types of lighting fixtures on each level, graph of monthly consumption for each type of lamp can be selected the type of lamp to see information of each floor it is inserted, the monthly consumption and a table containing the remaining information of manufacturer and descriptions. The dashboard is even more powerful over time with a constant update of information, being able to provide more precise data analytics for FM during a facility's lifecycle, according to actual use of the building.

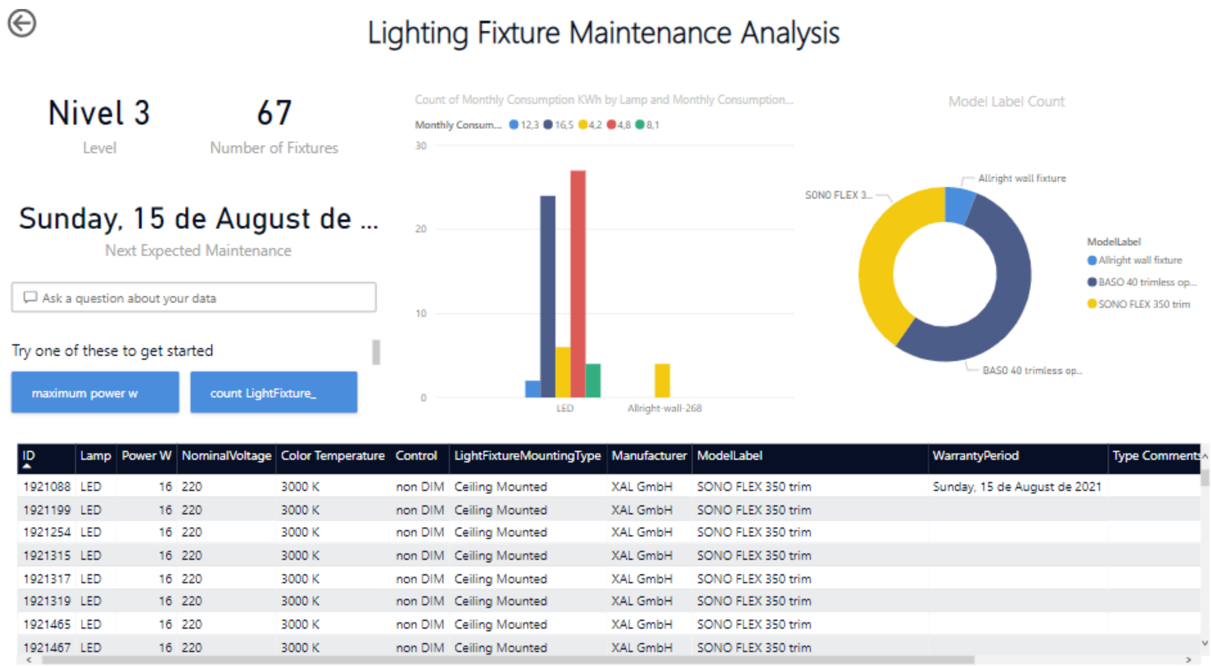


Figure 32: Power BI dashboard

To publish and give access of the report, it is possible to share it online as a public link to allow access from other not involved in the FM activities to visualize the dashboard information. Also, another way is to share it among other users inside the same organization, were the online dashboard requires a log in account. Besides, according to the hierarchy stablished is possible to provide access with clearance to modify or update the data. Here a link was generated and provides access to those with a Power BI account to visualize it, if a change is made on the original dashboard it has to be published again to update the link.

Hence, this demonstrates that the proposed tool makes it possible for an automated extraction of data from the Revit model into the SQLite database, giving facility managers access to work on a complete structured database that interacts with the original Revit model, in addition to that the data analytics is powerful for both prediction of future maintenance and analysis of the asset's performance metrics, assisting on decisions for improvements on energy consumptions of lighting fixtures on the building.

4.4. Scalability of the developed framework

Further applications of the framework in BIM-FM are related to its expandability on connecting with other FM activities and data, such as work orders, reminders, space management, assets' documentation, etc. Where the workflow proposed is scalable in an easy manner, with efforts concentrated on the programming part to scale the framework's capacity. Thus, resulting in greater independence of software licenses and higher flexibility for each project's requirements.

Including on that, the real-time data from the asset provided by IoT sensors throughout the facility, to enhance the capability of a more accurate data analysis. This is done by directly integrating the sensors data into the structured SQL database. Another point of the proposed framework is that even though the study was developed using Revit as the modelling platform, the same workflow can equally be done on an IFC-basis only. Through API programmable software, it is possible to extend the capacity of the framework to open formats, allowing for greater flexibilization.

Lastly, the main advantage of the proposed workflow is its independence and possibility of extension and customization, along with the possibility to switch interfaces easily. For example, the connection with Power BI can be easily switched to another analytics tool. This is all possible due to the empowered connection with the relational database system. The SQL database working as the central repository for BIM and FM data, allows for an easier set up of collaboration exchange through a non-BIM format, simplifying the access, update, and maintenance of the information.

5. CONCLUSION

5.1. General conclusions

This dissertation was developed with the aim propose a framework oriented to data integration between the BIM model and FM system through a relational database and a possibility for the data analysis with an integrated management of the assets information. The main conclusions of this dissertation can be summarized as:

- It was possible to implement the interconnection between a proprietary modelling platform (REVIT) and a SQL relational database developed through a visual programming language (Dynamo), which can be easily expanded towards a high number of FM required parameters related to non-graphic information of an element.

- The SQL relational database provides a structured interface populated with information required by FM and has the capability for a bi-directional interoperability established through Dynamo, for which the interconnection allows for updates on non-graphic and non-relational information of a BIM object.

- The systematization of the developed framework in the format of process maps allowed a precise indication of the relevant data exchanges and stakeholders, as well as tools involved, with potential use in further applications in real-case scenarios.

- It was possible to confirm the feasibility of establishing interactive dashboards for data analysis in PowerBI, with real-time interaction with the SQL database. This capacity of interaction with advanced analytics dashboards, can become even more powerful when integrated with other information deriving from FM system, assisting on intelligent use of data and decision making to improve a facility's performance.
- Overall, the proposed framework is scalable, allowing its extension toward application on any type of facility and elements. It is however remarked that the application of the framework requires an early definition of the FM information requirements, establishing a workflow to maintain the quality and accuracy of the BIM model linked with the database, which is updated on a regular basis during operation of the asset.

5.2. Future suggestions

The expandability and scalability of the framework should be further explored, for which future developments can focus on programming the proposed tool for bi-directional connection directly on the Revit API. Hence, freeing the use of Dynamo, and the need to refresh the model to update the information from the database. In addition to that, it could be interesting to expand the methodology towards applicability on cases of existing facilities and the integration with other FM systems available. Another point for enhancing integration, is to develop a bi-directional connection from Power BI to the database, this way the information can be updated on analytics software as well.

Future researches and improvements on the workflow could also pursue an integration of the database and the analytics tool connected with IoT sensors through the facility, allowing for constant update of accurate information of the building's performance. Further, aligned with an expansion of the framework to be IFC-based, as an attempt towards an even more integrated interoperable data exchange. Thus, the O&M dashboard would not static, being constantly being supplied with new information to support decisions of operation. Adding to that the potential of the relational database becomes more powerful with combination of datasets, including not only the BIM model's data but also the FM system information with the work orders, reminders, space management, etc., all that integrated on the analytics dashboard making sense of the acquired data.

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LIST OF ACRONYMS AND ABBREVIATIONS

AECO/FM	Architecture, Engineering, Construction, Operation, And Facility Management
AIM	Asset Information Model
AIR	Asset Information Requirements
BEP	BIM Execution Plan
BIM	Building Information Modelling
BIM-FM	Building Information Modelling and Facility Management
CAD	Computer Aided Design
CAFM	Computer Aided Facilities Management
CMMS	Computerized Maintenance Management Systems
COBie	Construction Operations Building Information Exchange
COBIM	Common BIM Requirements
DB	Database
DBMS	Database Management System
EIR	Exchange Information Requirements
FM	Facility Management
GIS	Geographic Information System
GSA	General Services Administration
HVAC	Heating Ventilating and Air Conditioning
IFC	Industry Foundation Classes
IFMA	International Facility Manager Association
IoT	Internet of Things
IPD	Integrated Project Delivery
ISO	International Organization for Standardization
KPI	Key Performance Indicators
LED	Light Emitting Diode
LOD	Level Of Development
O&M	Operations and Maintenance
OBOS	Open BIM Object Standard
ODBC	Open Database Connectivity
PIM	Project Information Model
PLM	Product Lifecycle Management

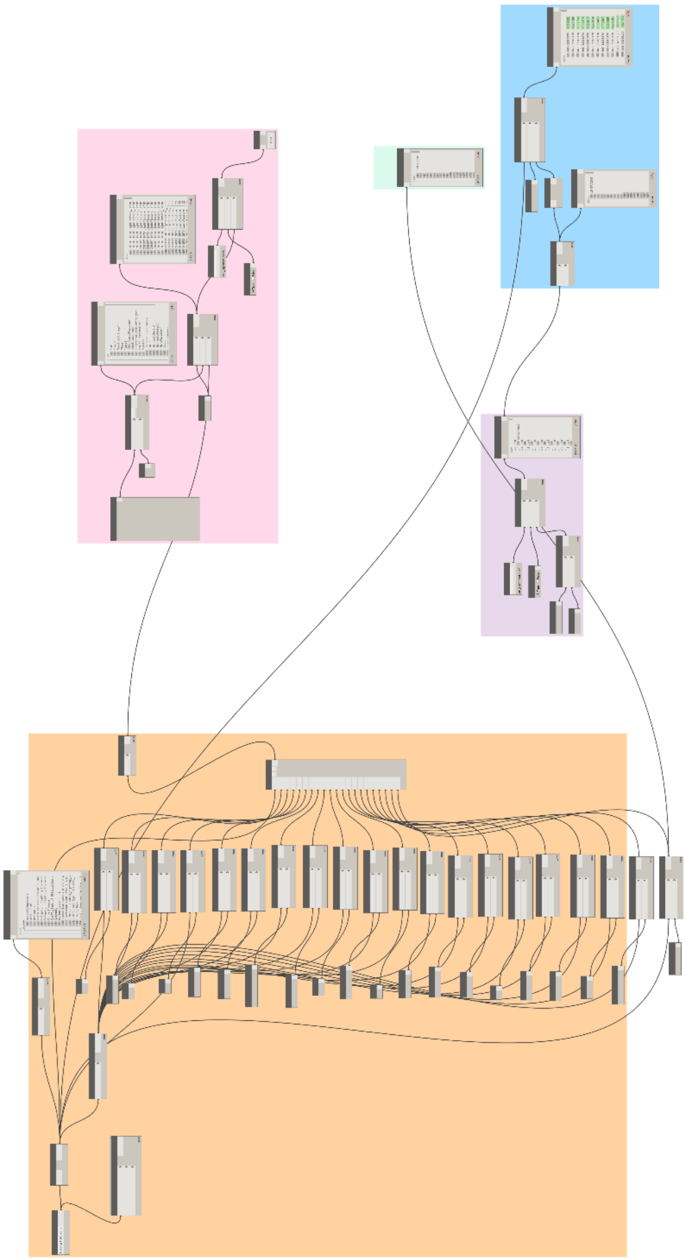
RDBMS	Relational Database Management System
SQL	Structured Query Language

APPENDICES.

APPENDIX 1: DYNAMO SCRIPT

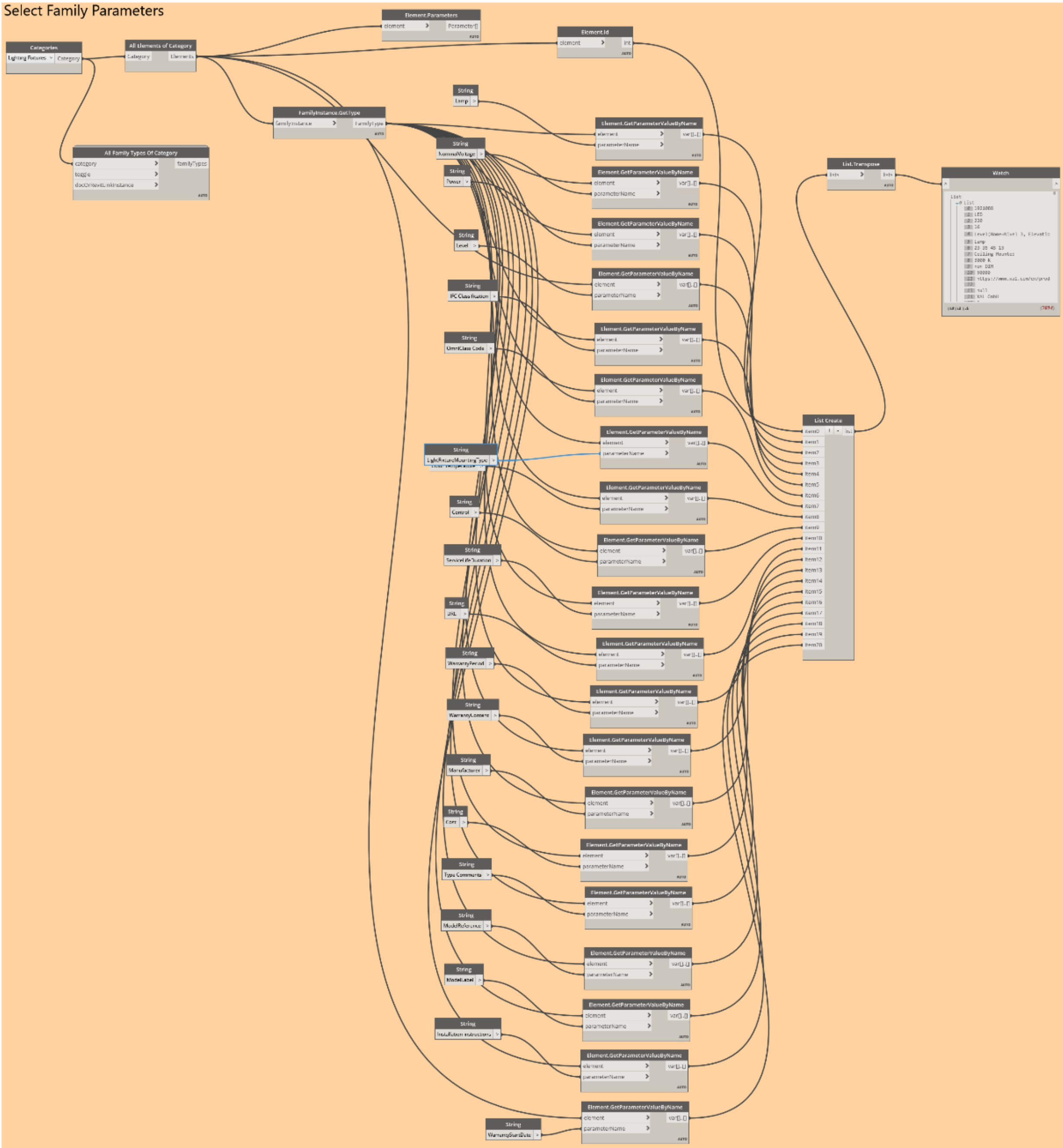
This appendix comprises of the Dynamo script used on this research study case, in accordance to the steps proposed on the framework. First with a general overview of the entire script, followed by detailed view of each group.

- Script overview



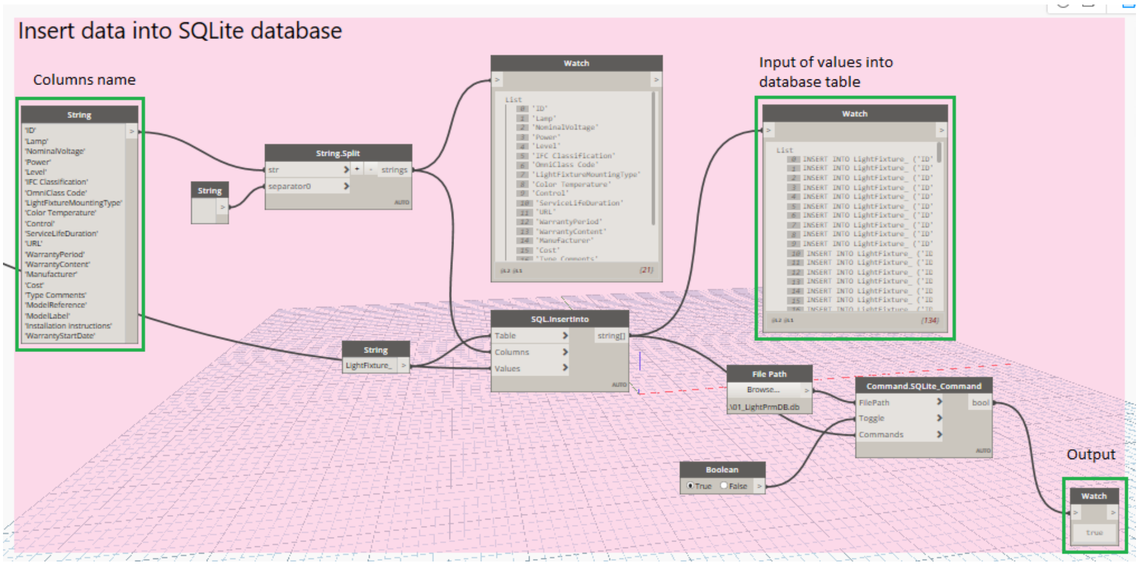
- G01: family and parameters selected

G01 comprises of the node structure to select the categories and families of the elements from the Revit model on Dynamo and the value of the parameters by their name.



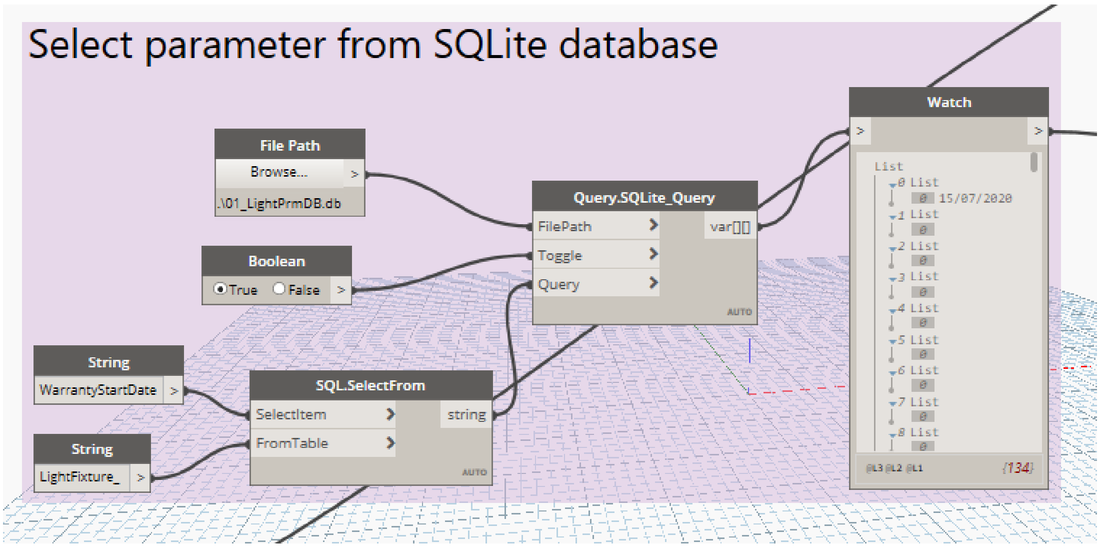
- G02: Export information to database

To connect the model and the selected parameters to the database, it is necessary to establish the link between Dynamo and the SQLite, by using the available package Slingshot! where the standard options of *insert*, *update*, and *select* are available for connection between Dynamo and SQL. When connecting through Dynamo, the *insert to* node requires the table name, and the *command* node requires the specific file path. The inputs of columns must be in accordance to the columns names created on the database, which are the name of the exported parameters.



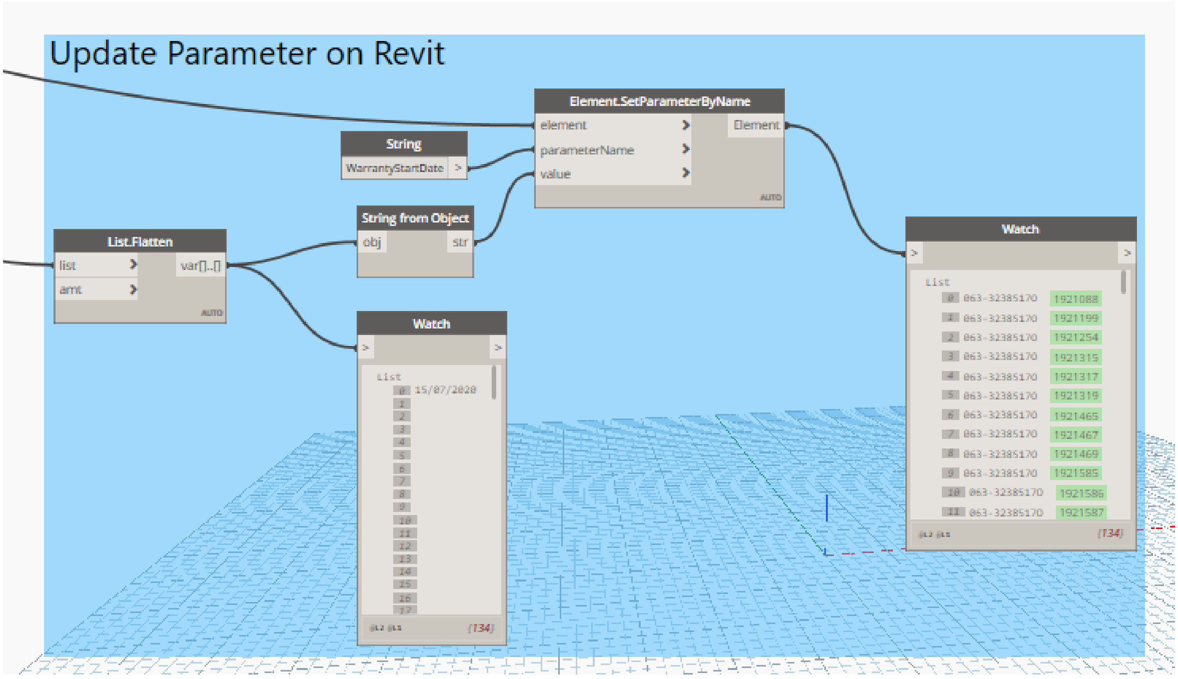
- G03: Read information from database

The bi-directional relationship is established by first Dynamo read the information from the database, using the nodes *Select From* and *Query*, it is possible to select all parameters from the chosen table or only the required ones. The important is that if an update is made on the selected parameters the script is able to read the changed information on the database.



- G04: Update database information to Revit element

The update on Revit element is made through the connection between the *Query* node with *SetParameterByName*. This relationship between both software is made possible by keeping the standard unique identifier of the element on both Revit and database files, thus keeping the BIM model updated in accordance to the asset's conditions.



APPENDIX 2: LIGHTING FIXTURES PARAMETERS

- Lighting fixtures classes of objects and its parameters

Object family: Allright wall 268mm LED 833LM/14W HFF Aluminium

Parameter Name	Value	Exported to database
ID	1955405	x
Level	Level(Name=Nivel 4, Elevation=15,5)	x
Reference	n/a	
NumberOfSources	0	
TotalWattage	14.00 W	x
NominalVoltage	230.00 V	x
MaintenanceFactor	0.00	
MaximumPlenumSensibleLoad	n/a	
MaximumSpaceSensibleLoad	n/a	
SensibleLoadToRadiant	n/a	
Status	n/a	
LightFixtureMountingType	Wall Mounted	x
LightFixturePlacingType	Wall	
Control	SwitchDim	x
Lamp	Allright-wall-268	x
ColorTemperature	3200 K	x
AcquisitionDate	n/a	
BarCode	n/a	
SerialNumber	n/a	
BatchReference	n/a	
AssemblyPlace	n/a	
GlobalTradeItemNumber	n/a	
ArticleNumber	7421-1-38HFF	
ModelReference	0046-1708-0039-SE	
ModelLabel	Allright wall fixture	x
URL	https://www.zerolighting.com/allright-inomva/	x
Manufacturer	Zero	x
ProductionYear	n/a	
InstallationInstructions	n/a	x
MeanTimeBetweenFailure	n/a	
ServiceLifeDuration	50000 h	x
WarrantyIdentifier	n/a	
WarrantyStartDate	n/a	x
WarrantyEndDate	n/a	
IsExtendedWarranty	n/a	
WarrantyPeriod	n/a	x
WarrantyContent	n/a	x
Exclusions	n/a	
IfcExportAs	Lamp	x
OmniClass Code	23-35 45 15	x

Object family: 063-3238517O		
Parameter Name	**Value**	**Exported to database**
ID	1951707	x
Level	Level(Name=Nivel 4, Elevation=15,5)	x
Reference	n/a	
NumberOfSources	0	
TotalWattage	16.00 W	x
NominalVoltage	220 V	x
MaintenanceFactor	0.00	
MaximumPlenumSensibleLoad	n/a	
MaximumSpaceSensibleLoad	n/a	
SensibleLoadToRadiant	n/a	
Status	n/a	
LightFixtureMountingType	Ceiling Mounted	x
LightFixturePlacingType	Ceiling	
Control	non DIM	x
Lamp	LED	x
ColorTemperature	3000 k	x
AcquisitionDate	n/a	
BarCode	n/a	
SerialNumber	n/a	
BatchReference	n/a	
AssemblyPlace	n/a	
GlobalTradeItemNumber	n/a	
ArticleNumber	n/a	
ModelReference	063-3238517O	
ModelLabel	SONO FLEX 350 trim	x
URL	https://www.xal.com/en/products/detail/XAL-VOL18-2;product_line__name=SONO%2520FLEX%2520trim	x
Manufacturer	XAL GmbH	x
ProductionYear	n/a	
InstallationInstructions	https://pim-api.xal.com/xalwebapi/v2/mountinginstructions/ed83efdb-776b-4ac8-a963-c608cd68b336	x
MeanTimeBetweenFailure	n/a	
ServiceLifeDuration	50000 h	x
WarrantyIdentifier	n/a	
WarrantyStartDate	n/a	x
WarrantyEndDate	n/a	
IsExtendedWarranty	n/a	
WarrantyPeriod	n/a	x
WarrantyContent	n/a	x
Exclusions	n/a	
IfcExportAs	Lamp	x
OmniClass Code	23-35 45 15	x

Object family: BASO 40 trimless opal high performance, 3000 K, length 1220 mm, 045-07245#0H		
Parameter Name	**Value**	**Exported to database**
ID	1937477	x
Level	Level(Name=Nivel 3, Elevation=11,7)	x
Reference	n/a	
NumberOfSources	0	
TotalWattage	27.00 W	x
NominalVoltage	220.00 V	x
MaintenanceFactor	0.00	
MaximumPlenumSensibleLoad	n/a	
MaximumSpaceSensibleLoad	n/a	
SensibleLoadToRadiant	n/a	
Status	n/a	
LightFixtureMountingType	Ceiling Mounted	x
LightFixturePlacingType	Ceiling	
Control	non DIM	x
Lamp	LED	x
ColorTemperature	3000 K	x
AcquisitionDate	n/a	
BarCode	n/a	
SerialNumber	n/a	
BatchReference	n/a	
AssemblyPlace	n/a	
GlobalTradeItemNumber	n/a	
ArticleNumber	n/a	
ModelReference	045-0724510H	
ModelLabel	BASO 40 trimless opal high performance	x
URL	https://pim-api.xal.com/xalwebapi/v2/mountinginstructions/454fdbd3-8db5-4ca3-8691-59ba33964665	x
Manufacturer	XAL	x
ProductionYear	n/a	
InstallationInstructions	https://pim-api.xal.com/xalwebapi/v2/mountinginstructions/454fdbd3-8db5-4ca3-8691-59ba33964665	x
AssemblyPlace	n/a	
MeanTimeBetweenFailure	n/a	
ServiceLifeDuration	50000 h	x
WarrantyIdentifier	n/a	
WarrantyStartDate	n/a	x
WarrantyEndDate	n/a	
IsExtendedWarranty	n/a	
WarrantyPeriod	n/a	x
WarrantyContent	n/a	x
Exclusions	n/a	
IfcExportAs	Lamp	x
OmniClass Code	23-35 45 15	x