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APPLICATION OF THE DIGITAL TWIN FRAMEWORK FOR BIM-BASED FACILITY RENOVATION MANAGEMENT

APLIKACIJA OKVIRJA DIGITALNEGA DVOJČKA ZA UPRAVLJANJE PRENOVE OBJEKTA S TEHNOLOGIJO BIM

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Building Information Modelling

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Izvleček:

V tej diplomski nalogi je raziskano povezovanje informacijskega modeliranja stavb (BIM) z upravljanjem in vzdrževanjem objektov (FMM) z uporabo funkcionalnega delovnega postopka digitalnega dvojčka. Razlaga razvoj BIM, FMM in interneta stvari ter njihove izzive in prispevke k temu, kaj je digitalni dvojček. Poleg tega je razvit okvir, ki se osredotoča na izkoriščanje glavnih prednosti digitalnega dvojčka s standardiziranim poimenovanjem po vzoru ISO in COBie, opredelitvijo skupnega podatkovnega okolja (CDE), ki izkorišča statične informacije modela BIM in dinamične informacije oddaljenih podatkovnih storitev za vzpostavitev funkcionalnega portfelja upravljanja objektov, ter opredelitvijo informacijskih zahtev, ki omogočajo napredovanje informacijskega modela stavbe v informacijski model sredstev (AIM). Poleg tega študija primera prikazuje uporabo okvira v vzorčnem projektu. Ta raziskava prispeva k organiziranemu delovnemu toku BIM, ki omogoča učinkovito upravljanje objektov, trajnost in odločanje na podlagi podatkov.

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Abstract:

This thesis explores the integration of building information modeling (BIM) with facility management and maintenance (FMM) using a functional Digital Twin workflow. It explains the development of BIM, FMM, and IoT along with their respective challenges and contributions to what a digital twin is. Moreover, a framework is developed that focuses on harnessing the main strengths of a digital twin through standardized naming inspired by ISO and COBie, defining a Common Data Environment (CDE) that leverages both the static information of a BIM model and the dynamic information of remote data services to build a functional facility management portfolio, and defining information requirements that enable the progression of a building information model into an Asset Information Model (AIM). Furthermore, a case study demonstrates the framework's application in a sample project. This research contributes to an organized BIM workflow that enables efficient facility management, sustainability, and data-driven decision-making.

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LIST OF ACRYONYMS AND ABBREVIATIONS

Industry Software	
GLIDE	Graphical Language for Interactive Design
BDS	Building Description System
BPM	Building Product Model
SBM	Single Building Model
CAD	Computer Assisted Design
EDMS	Electronic Document Management System
GBM	Graphical Building Model
Standardization Entities	
COBie	Construction-Operations Building Information Exchange
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
NBS	National Building Specification
Model Related Items	
BEM	Building Energy Model
BEP	BIM Execution Plan
BIM	Building Information Model
GUID	Global Unique Identifier
IFC	Industry Foundation Class
RDS	Remote Data Services
Network Related Items	
HTTPS	Hypertext Transfer Protocol Secure
IT	Information Technology
LAN	Local Area Network
RBAC	Role Based Access Control
TCP	Transmission Control Protocol
HTTP	Hypertext Transfer Protocol Secure
IP	Internet Protocol
MFA	Multi Factor Authentication
Document Related Items	
ADIM	Asset Dynamic Information Model
AIM	Asset Information Model
AIR	Asset Information Requirements
ASIM	Asset Static Information Model
OIR	Organizational Information Requirements
PIM	Project Information Model
PIR	Project Information Requirements
EIR	Exchange Information Requirements
LOIN	Level of Information Need
CDE	Common Data Environment
Industry Terms	
AEC	Architecture, Engineering, and Construction
AECO	Architecture, Engineering, Construction, and Operation
BAS	Building Automation System

BMS	Building Management System
CMMS	Computerized Maintenance Management System
DTw	Digital Twin
FM	Facility Management
FMM	Facility Maintenance and Management

Table 1: List of Acronyms and Abbreviations

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1 INTRODUCTION

Throughout the life of a building, a building information model (BIM) holds data that may be accessed and exported for different purposes, particularly for operations and facilities management (FM). Designers and contractors can create a data model that is rich in information and beneficial to the client by following well-designed BIM criteria that guarantee completeness and compatibility with FM software (Kensek, 2015). Facility and asset management can best be described as finding the optimal way to correctly manage the maintenance phase to reduce energy waste and lower costs (Villa et al., 2021). ISO 19650-3 defines asset management as “the coordinated activity of an organization to recognize value from assets”, and defines facility management as “ an organizational function which integrates people, places, and process within the built environment with the purpose of improving the quality of life or people and the productivity of the core business” (ISO, 2020).

The design to construction process usually takes around two to five years, but the building will likely survive considerably longer than that—probably much longer, which is why the FMM industry has always been an issue of great concern for stakeholders as it could account up to 85% of the total cost of a building's life cycle (K. Chen et al., 2019). Also, the importance of facility and asset management has recently reached new heights as a result of a convergence of technology development and rising environmental responsibility, where buildings make up one-third of global greenhouse gas emissions and about 40% of total global energy use (Eneyew et al., 2022). This means that the careful management of assets and the seamless management of facility services has become crucial in creating a dynamic and interconnected environment and has prompted major efforts focused on improving the efficiency of facility management practices and achieve sustainable environmental goals. Facility and asset management is therefore required to influence industry trends and promote a more peaceful coexistence with our environment, serving as both conduits for operational efficiency and vanguards of sustainability.

The paradigm change that has occurred has ushered in a comprehensive approach that goes beyond the traditional methods of management and maintenance where a lot of strategic information planning is involved. BIM is at the forefront of new digital innovation in the AEC industry and is playing a crucial role as a contributor to new FMM workflows, mainly by providing 3D geometry and attribute data that can long-term streamline operations and maintenance (Succar & Kassem, 2015).

1.1 Digital Transformation

Pairing the above with the digital transformation that the built environment is going through with the increase of use and standardization of BIM, it enables the FM industry to adopt new digital tools that enhance the maintenance and management process (ISO, 2020; Moretti et al., 2020). This digital transformation, also known as the fourth industrial revolution (Industry 4.0) has been focused on integrating real-time sensor data, cyber-physical connectivity, and autonomous control to propel the efficiency of the industry (Eneyew et al., 2022). This creates the ecosystem that has been coined “Digital Twins”, and it can be best understood as mentioned in (Standards Australia, 2023): “It is not a piece of technology, an IT system, or a single deployable thing. DTw reflects a way of working with existing data and new data in novel ways that allow an organization to improve or enhance its core purpose in ways not hitherto possible.”

1.2 Research Structure

1.2.1 Problem Statement

Currently, it is clear after reviewing existing relevant studies that there are not enough comprehensive frameworks that successfully handle the BIM for FM workflow, which handicaps Asset Information Models (AIM) in terms of fulfilling and maintaining facility management requirements.

1.2.2 Thesis Structure

In this paper, a BIM based framework will be developed to create the required ecosystem of a digital twin for a building facility that enhances facility management and maintenance processes. The following section is a literature review that covers BIM, facility management, IoT, digital twins, and how all these topics intertwine. The third section discusses the methodology of the BIM for FM framework, which includes identifying the required functionalities of a BIM to digital twin framework and developing the information requirements. This is followed by a case study that demonstrates the developed BIM framework and its integration into a digital twin environment.

2 LITERATURE REVIEW

2.1 Building Information Modelling

2.1.1 Evolution of BIM

Building information modelling (BIM) is a field that has heavily matured since its inception in 1975, where BIM was first introduced by Eastman as BDS - Building Description System. It focused on facilitating coordination in the design development phase by creating a model of various physical systems that contain element specification and enabled the designers to create many elements from individual library databases and coordinate them in a single model (Eastman et al., 1975). However, the element library was very limited and did not support disciplines outside or architectural and structure, which hindered its adoption for mainstream use (Dobelis, 2013).

Shortly after, GLIDE – Graphical Language for Interactive Design – was introduced in 1977, where it built on what BDS had already accomplished by adding the consistent capability to produce more accurate 2D drawings from the models. Again, the constricted involvement of the different disciplines at the design stage limited its adoption in the industry (Eastman & Henrion, 1977).

GLIDE continued to be used until 1989, where a newfound program called BPM – Building Product Model – was introduced with the goals of delivering product design applications, cost estimation, and more importantly the integration of different disciplines of the construction industry (Björk, 1989). BPM stood out with a comprehensive project library that covered the product information required for a project throughout the planning and construction process, in addition to being a powerful communicator with Computed Aided Design (CAD) for design and construction purposes. However, the main drawback to BPM was that its focus was on product information without it being integrated for design and construction management purposes (Luiten et al., 1998).

The next iteration in the development of BIM came in 1995 with the development of GBM – Graphical Building Model. The main concept was to introduce a 3D building model with intelligent information attached to it. It built on the concept of BPM to integrate the geometrical model, identity information, and physical properties with its components' individual functions throughout the lifecycle in the construction process. This led to different CAD software vendors (e.g. Bentley, Autodesk…) developing multiple SBM – Single Building Model software (Reza Mohandes et al., 2014).

Fast forward to the early 2000s, BIM was introduced as being able to represent different building elements in a well-structured model (Ameziane, 2000), and by the mid-2000s, the AEC industry started effectively using BIM in design and construction projects (Azhar, 2011). Moreover, BIM managed to integrate the pre and post construction phases together, and in 2005 was defined as a "development and use of computer software to simulate the construction and operation of a facility" (Associated General Contractors of America, 2005). By 2006, BIM was established as a modern methodology that can handle and enhance the AEC workflow and project management (Penttilä, 2006). The models that are created using BIM are described as "rich models" due to all the elements inside it being embedded with relationships and properties Furthermore, the attributes of a BIM model are described as "robust geometry, lifecycle support, integrated information, semantic richness, comprehensive and extensible object properties that expand the meaning of the object". Benefits of using a BIM model include an improved and faster design, improved construction and production quality, automated assembly, improved customer service, and lifecycle data. (The Cooperative Research Centre for Construction Innovation, 2007).

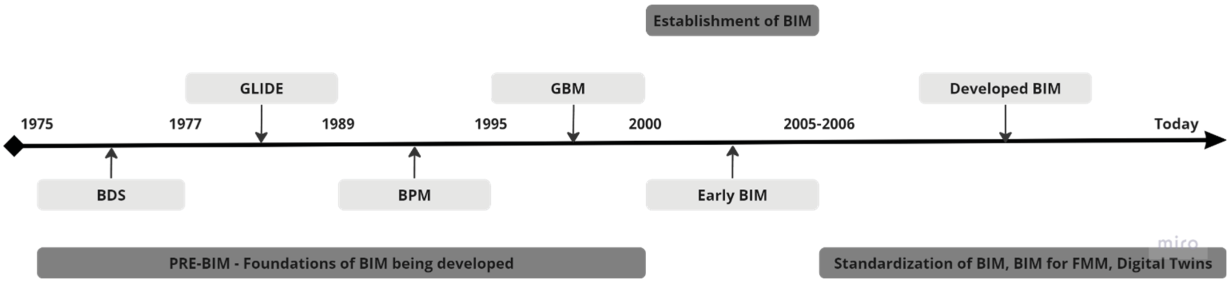


Figure 1: Evolution of BIM

2.1.2 BIM Today

Since its establishment in the early 2000s, BIM has become extensively used and standardized (ISO, 2020). At first, many described BIM as temporary buzz word that will pass; however, the attention that BIM has deservedly attained has propelled it to be one of the essential drivers for the industry's digitalization. The workflows built on the use of BIM have immensely grown, resulting in further advantages in enhancing processes in collaboration, design, construction, and information management throughout the lifecycle of the facility (Moretti et al., 2023).

Source	**Definition of BIM**
(ISO, 2020)	"Use of a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions."

(Teicholz, 2013)	describes the 3D geometry, elements, and attribute information of a physical facility. At its core BIM consists of building geometry and a structured database that serves as a base for detailed nongraphic information regarding the building elements.
(Eastman et al., 2011)	a socio-technical system that integrates all the different process changes throughout the design, construction, and facility management.
(Azhar, 2011)	a virtual process that covers all the different disciplines and systems of a project through one virtual model, which enables all stakeholders to collaborate in a more optimized way compared to traditional processes.
(NBS, 2019)	a reliable resource for decision making throughout a project's lifecycle since it provides a digital representation of a facility's physical and functional qualities as well as a digital representation of what will be built in a construction project.
(Pärn et al., 2017)	a collaborative information-sharing process that integrates project stakeholders over the design, construction, and operation phase of projects.

Table 2: BIM Definitions

Furthermore, BIM has proved its importance through the many advantages it provides, such as design visualization, cost and time estimate, clash detection, and enhanced stakeholders' interoperability (Volk et al., 2014). In addition, BIM can simulate site construction operations, which enables a higher level of operation management and an optimized project schedule (Radzi et al., 2023). This has led to the widespread adoption of BIM workflows, where a poll revealed that 75% of professional designers in developed countries trust that BIM is an essential technology for the coming future. Moreover, BIM targets are being set in BIM-driven countries such as the UK's "Digital Built Britian" agenda, where a level 2 BIM adoption has been instructed on government projects since 2016, with level 3 BIM to follow in purpose of integrating digital design with facility and asset management (Jang & Collinge, 2020). This digitalization trend meant industries need to undergo a paradigm change in the ways they define and handle the semantics of geometry-linked product models. As a result, there was an increase focus on integrating and exploiting the semantics of a building throughout its entire lifecycle, including its operational phase (Pauwels et al., 2017).

2.2 Facility Management and Maintenance

Facility management has been around for as long as buildings existed; however, the term was only coined in the 1960s by Ross Perot of EDS in the USA (Wiggins, 2014). Since then, many definitions have come to light with all of them focused on the optimization and integration of the 3 Ps (people, places, processes).

Source	**Definition of Facility Management**
(ISO, 2020)	asset management is a process carried out by an organization to optimize assets' value, and facility management is a process carried out by an organization that aims to improve the quality of people's lives and enhance the productivity of the business by integrating process, places, and people within the built environment.
(McGregor, 1999)	facility management integrates the management expertise of processes, property, and people in what is described as a hybrid management domain.
(Alexander, 2013)	the method by which an organization carries out maintains support services to meet strategic needs in a quality environment.
(Nutt, 2004)	a supporting tool that enables an organization's operational and sustainable schemas over time via proper infrastructure resources management and services administration.
(Atkin & Adrian Brooks, 2000)	a holistic approach that encapsules everything from maintenance and cleaning to financial and real estate management.
(Villa et al., 2021)	Facility maintenance can be divided into scheduled, predictive, preventive, proactive, and run-to-failure.

Table 3: Facility Management Definitions

The core enabler of facility management is reliable and accessible information (Atkin & Adrian Brooks, 2000). Most of this information is one that is created throughout the planning, design, and construction processes, the smoother the process of handing over this information to the facility management systems the more effective it becomes. (Edirisinghe et al., 2017).

In the 1980s, a framework called "Building Management System" (BMS) was built to visualize and manage collected data (Villa et al., 2021). Before BMS, different systems where managed independently, which resulted in an overwhelming management protocol, higher operational costs, and required more expertise, therefore, BMS was developed with the goal of integrating building management systems under a unified framework, such as lighting, heating, electrical and mechanical services, security, and safety(Malatras et al., 2008).

Moreover, CMMS - Computerized Maintenance Management Systems, EDMS – Electronic Document Management Systems, and BAS – Building Automation Systems are all FMM data systems that are traditionally used (since the 1960s) to maintain and organize information (Patacas et al., 2015). As technology became more advanced, CMMS systems became more competent in the transfer of information: first in 1990s through local networks (LAN) and then in the 2000s through the internet and web-based connectivity, which also allowed the integration of BMS and CMMS systems together (Dudley, 2020).

2.3 Challenges Faced by The Facility Management and Maintenance Industry

Many challenges unfold as the traditional landscape of facility and asset management changes. One significant challenge is the storage and handling of information in paper documents, which not only occupies excessive physical space due to the sheer quantity and complexity of data created over a building's lifecycle, but also poses difficulties in their retrieval and management (Teicholz & IFMA Foundation., 2013),(Reza Mohandes et al., 2014). Pärn also claims that the FMM industry finds it difficult to manage information with a lot of it being lost due to the fragmentation and peculiarity of information, where facility managers lose over 80% of their time looking for information that is more than often ignored by designers (Pärn et al., 2017).

Moreover, the operation and maintenance of built assets is heavily dependent on accurate and reliable data, which makes information created during planning, design, and construction vital for commissioning of built assets (Patacas et al., 2020). Also, Computerized maintenance management systems (CMMS) and other facility management software only process digital formats of information, necessitating an additional investment of time and effort to digitize and verify asset documents after the completion of the construction phase (Patacas et al., 2020; Teicholz & IFMA Foundation., 2013).

In addition, the interdependent relationship between people's comfort and competent asset management has become increasingly relevant, where environmental conditions have proven to have a direct impact on people's performance and level of happiness. Facility performance expectations continue to rise, where smart facilities are being desired to leverage the booming IoT technology with the goals of environmental monitoring to maximize indoor comfort and analyzing building energy performance (Radzi et al., 2023)

Another challenge faced in the industry is the integration of static FMM data with dynamic data coming from due to the difference in the information management requirements, storage, measurements, and interoperability issues (Eneyew et al., 2022; Moretti et al., 2020).

Furthermore, facilities are expected to focus on the changing needs of facility operators and occupants, which will be 75% millennials by 2025, who are characterized as being a tech savvy generation and expect an enhanced level of building functionality such as more flexibility in the utilization of assets and spaces, improved user productivity, and a more efficient process to detect and resolve problems (Siemens, 2018).

2.4 BIM and FMM Integration

Studies that propose utilizing BIM models to facilitate the sharing of information with facility management computer applications can be found as early as the 2000s (Patacas et al., 2020). BIM models are generally recognized as data mines that can be heavily leveraged to enhance the facility management process, where facility managers seek to use BIM as a structured information database to support the management of building maintenance workflows in both existing and new facilities (Volk et al., 2014).

The process to reconcile BIM and FMM is not a straightforward process, as the two are created using different software and standards. Therefore, their integration hinges on developing adequate tools, workflows, and standards to enable the organization, management, and delivery of information needed for FMM (Eastman et al., 2011). The key to develop these data-driven AM workflows hinges primarily on identifying the proper requirements, which include properly defining the organization’s business needs by higher management, compiling and comprehending the different kinds of information created at the facility and built environment levels, defining the data modelling strategy that enhances the quality of the data and supports its timely update and relational hierarchical dependencies (Moretti et al., 2023). Moreover, these requirements translate into what is considered an AIR – Asset Information Requirements, which is now crucial to match an organization’s objectives with the required operational informational categories. Also, an AIR should properly categorize assets by adopting a clear relational asset classification that hierarchically defines the physical and abstract entities according to their different uses (Afsari & C. M. Eastman, 2016). Furthermore, the AIR guides designers in developing their models by shifting their focus on what information is important for facility management. For example, the explicit geometry representation of an asset is not needed; however, the location and topology would be crucial for asset management operations (Moretti et al., 2023).

2.4.1 Benefits of BIM and FMM Integration

The integration of BIM and FMM is something heavily perused because of how much it improves facility management process. The benefits can be summarized below:

Reference	BIM FMM Integration Benefits
(Azhar, 2011; Teicholz, 2013)	data system integration over an entire lifecycle of a facility, with asset information being incrementally built up as the project develops.
(Azhar, 2011; Eastman et al., 2011; Kensek, 2015; Pärn et al., 2017; Teicholz, 2013)	Improved accuracy of FM data, smoother workflows and reduction in cost and time of FM related information, with key information being captured from BIM model rather than having to be reentered into a downstream FM system.
(Azhar, 2011; Pärn et al., 2017; Teicholz, 2013)	increases the efficiency of work order executions by enhancing communication between stakeholders and facilitating key data retrieval.
(Eastman et al., 2011; Kensek, 2015; Teicholz, 2013)	leveraging BIM for preventive maintenance, equipment failure reduction, longer equipment life, which all contributes to a better and more effective way of maintenance.
(Chong et al., 2014; Eastman et al., 2011; Kensek, 2015)	performing building performance simulations, system component visualization, and accurate space management.
(Chong et al., 2014)	ease of modification of asset information.

Table 4: Benefits of BIM-FMM Integration

2.4.2 Obstacles Facing BIM and FMM Integration

Although the BIM FMM integration is a heavily sought out feature, there are many obstacles that are hindering it. The obstacles can be summarized below:

Reference	BIM FMM Integration Obstacles
(Liu & Issa, 2014)	BIM project participants neglect developing a healthy asset information model and ignore future proofing it for maintenance accessibility because of their predominant focus on clash detection.
(Eadie et al., 2013; Jafari et al., 2020)	studies and research are heavily skewed towards addressing BIM adoption in the design and construction phase, where a survey showed that only 10% of companies/projects give attention to adopting BIM for the FM phase.

(Arayici et al., 2012; Pishdad-Bozorgi et al., 2018)	users are worried about the trouble of maintaining model integrity for it to remain functional, where it is generally perceived too labor intensive and time consuming to update thousands of assets with different parameters.
(Jang & Collinge, 2020; Patacas et al., 2020; Pishdad-Bozorgi et al., 2018)	lack of IT competency of BIM-FM integration in key stakeholders of the project, including the client and FM teams that are often unsure of BIM deliverables demand and results in unclear requirements definitions.
(Patacas et al., 2020; Pishdad-Bozorgi et al., 2018)	lack of standard taxonomy, workflows, and processes for developing an FM-enabled BIM model, leading to models that hinder FM operator's work either due to lack of information or too much of it.
(Wang et al., 2013)	lack of designer hands on operational experience, which leads to relevant information being dropped from the model even with FM teams providing the designers with operational perspectives.
(British Institute of Facilities Management, 2013; Jang & Collinge, 2020; Patacas et al., 2020)	major interoperability challenges between BIM and FM software in transferring FM semantic data. Even when COBie data is correctly transferred to FM teams, there are still obstacles in integrating them with AIM software.
(Jang & Collinge, 2020)	lack of involvement of FM teams from the start of the project.
(Patacas et al., 2020)	poor applications of compliance checking in the BIM for FM domain.
(Patacas et al., 2020)	lack of a CDE that can validate and consolidate the BIM model (geometry and information), the maintenance documents, and the maintenance operation creation and documentation.

Table 5: BIM-FMM Integration Obstacles

2.5 Internet of Things

IoT – Internet of Things is defined as an environment that integrates smart items equipped with sensors with networking and processing technologies containing networking and processing technologies, sensors equipped on smart objects to deliver smart services to the end-users (Villa et al., 2021).

IoT Benefits	**IoT Drawbacks**
Strong potential in enhancing FM operations where IoT offers the chance to monitor and	Potential bad sensor quality and measurement capabilities, range and bandwidth

control-built assets in real time (Tang et al., 2019; Villa et al., 2021).	communication issues, calibration issues, data quality, sensor maintenance (Merino et al., 2022).
Possibility of providing alerts and warnings in real time as a reactive measure to unexpected disruptions of failures (Moretti et al., 2023).	
Better effectiveness in the operation and control of a facility with improved safety, internal comfort, indoor air quality, and occupancy monitoring (Moretti et al., 2023; Poli et al., 2020a).	Real time sensor readings require to be enriched with reference lifecycle asset data to provide context (Moretti et al., 2023).
Gathering data from buildings can be instrumental in predicting fault patterns in similar assets, predict energy consumption, and optimize space utilization (Moretti et al., 2023).	

Table 6: IoT Benefits and Drawbacks

2.6 Industry Standardization and Compliance Checking

2.6.1 Industry Standardization

The facility management industry has repeatedly expressed how vital it is for an organization to adopt a strategic management of its asset's semantic properties. This is reflected as industry standards that clearly describe the standardization of data exchange formats, enhancing interoperability of semantic data (Pärn et al., 2017). Moreover, open standards are instrumental in defining data requirements for the operational phase, which enables the collection, verification, and management of the data throughout the lifecycle of the project (Patacas et al., 2014).

For example ISO, one of the most prominent industry standards, describes the ideal process of building information management for the operational phase of assets in what is called the "Information Requirement" phase. It starts from the top level where the client's requirements should be developed from the OIR - Organizational Information Requirements. Then from the OIR, the AIR – Asset Information Requirements is created to define the asset data that is required to be captured. Next, the EIR – Exchange Information Requirements is developed from the AIR to define the definitive information required to be submitted from the end contractor to the client. After the information requirement phase is completed, a BEP – BIM Execution Plan is created to kick start the development of the PIM – Project Information Model, where graphical and non-graphical information are designed and produced. Finally, the data is integrated into an AIM – Asset Information Model at the handover phase (ISO, 2020).

Another open standard is IFC – Industry Foundation Class, which is developed by buildingSMART as an open data model that defines architectural, building, and operation industry data. The goal of IFC is to tackle the interoperability of data exchange between different disciplines involved in delivering a built asset (Patacas et al., 2020). More specifically, facility lifecycle management is a core concept in the IFC specification as it is composed of a rich description of assets and systems through geometry and relational properties that deliver a holistic description for a built facility (The Cooperative Research Centre for Construction Innovation, 2007).

In addition to the above, COBie – Construction Operations Building Information Exchange is an open standard data format for delivering handover data created throughout the project design and construction (Pishdad-Bozorgi et al., 2018). It was developed to enhance interoperability between systems and is supported by the buildingSMART alliance. Moreover, COBie was chosen as the format to specify and hand over data in the UK BIM framework for the operational phase of assets (Patacas et al., 2020). Also, the final deliverable is an excel spreadsheet, making it friendly enough for people of all backgrounds to interact with (Teicholz, 2013). Despite the utility COBie provides with the structuring of information into a universal language, the amount of different types of data is introduced is overburdening if the proper FM information is not specified at the start of the project. Another criticism of COBie is that it does not ensure comprehensive semantic data for FM and cannot guide the design team on obtaining required operational semantic data (Pishdad-Bozorgi et al., 2018).

Fig. 1 summarizes the timeline of international and UK standards that tackle the FM industry, in parallel to the major developments in BIM and FM UK documentation.

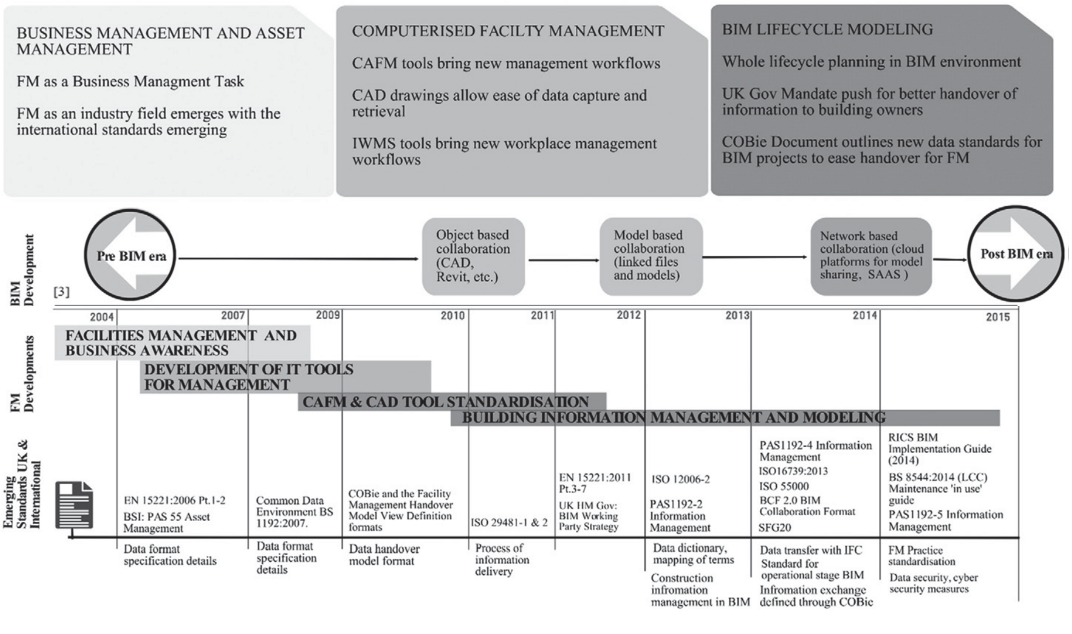


Figure 2: Development of BIM and FM Standards. (Pärn et al., 2017, p. 48)

2.6.2 Compliance Checking

Compliance checking is necessary to ensure the quality of information that is being delivered, especially in BIM for FM applications where the semantic information that is available in the BIM model has to be up to date and correct to enable efficient facility management (Motamedi et al., 2018; Zadeh et al., 2017).

It is generally composed of four main points. First the checking rules need to be interpreted into machine language format, the more prominent the availability of semantically rich BIM models, the stronger the capabilities to express the checking rules in machine language. Then, the information model needs to be prepared by specifying all necessary compliance checking information requirements in the structure of a model view. Third, the rules are executed against the structured information models. Lastly, the results of the rule executions are reported with procedures set up for automatic correction (Eastman et al., 2009; Patacas et al., 2020; Pauwels et al., 2011; Solihin & Eastman, 2015).

One of the biggest advantages of adopting open standards is that it enables compliance checking procedures over the entire life of the project, which is a major concern for designers, contractors, and facility managers. AIMs can be developed with rule checking procedures providing crucial quality assurances, validating the AIRs vs the AIM throughout the lifecycle of the project (Patacas et al., 2020). Designers and contractors following FMM BIM standards and requirements will make it easier to integrate the information into FMM systems and paves the way to establish what could be described as a digital twin (Kensek, 2015).

2.7 Digital Twins

2.7.1 Digital Twins Definition

DTw – Digital Twin first appeared in NASA's Apollo program, where it was defined as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Hicks, 2021). The definition of DTw has evolved over time, with the AECO industry having different takes on what a DTw is.

Reference	DTw Definition
(Bolton A, 2018; Khajavi et al., 2019)	generally regarded in the entire AECO industry as a digital replica of an asset that facilitates the operation and control of the asset's physical counterpart through data being processed in real time.

(Qi & Tao, 2018)	a virtual representation of a built product (asset, process, or system) to diagnose malfunctions and predict future problems over the product's lifecycle.
(Glaessgen & Stargel, n.d.)	the three core components of a DTw are the digital model, the built physical asset, and the linkage between them.
(Siemens, 2018)	A DTw ecosystem consists of a product twin that describes the geometric and non-geometric information of an asset, a construction twin that provides the as built static representation of all built assets, and a performance twin that convolutes dynamic data with static data throughout the lifecycle of the built asset.
(Zhang et al., 2021)	integrating machine learning and big data with the AECO industry to create new forms of analysis and modelling.

Table 7: Digital Twin Definitions

DTw is the biproduct of not being able to properly communicate and interpret the huge amount of information that is created throughout the project phases (Bilal et al., 2016; Gündüz et al., 2013). There are many benefits to employ DTw in the AECO industry. Nasaruddin and Khajavi claim that a DTw helps optimize the services by improving operational efficiency and enable predictive maintenance measures by assessing data anomalies through creating, accessing, and visualizing the asset's environment (Khajavi et al., 2019; Nasaruddin et al., 2018). Also, DTw can strengthen the information management process over the lifecycle of a built asset and in turn enables an improved performance and a better decision making (Moretti et al., 2023). In addition, there is a huge business value to be gained from the twin. Siemens suggests that the superfluous data can be leveraged to create new applications with little effort/cost. These applications can include tracking the utility of spaces in a facility, tracking dynamic locations of equipment and people in a facility, quickly identify security/liability issues, simulate what if scenarios, and improve the design of new projects (Siemens, 2018).

2.7.2 Where does BIM end and Digital Twin Begin?

The above literature review can be summarized in the below table:

Characteristic	BIM	DTw
Definition	collaborative, data-rich approach that involves creating a digital representation of a facility's geometry and attributes, integrating multidisciplinary information, and enabling informed decision-making across all phases of a project's lifecycle	Digital Twins are virtual replicas of physical assets, vital in AECO for real-time control and predictive insights; they consist of digital models linked to physical assets, including product, construction, and performance twins,

	in the architecture, engineering, and construction (AEC) industry	while also integrating machine learning and big data for advanced analysis
Origin	Charles Eastman	NASA's Apollo Program
Lifecycle Phase	Concept, Design, Construction, Commissioning	Operation, Maintenance
Users	Architects, Engineers, Contractors	Facility Managers
Simulation of Operation Concept	Static information, no real-time synchronization	Real-time operational response
Core Benefits	Strengthen stakeholder communication and collaboration, reduce errors in design, improve construction efficiency, and construction cost and schedule planning.	Predictive maintenance, improve occupant comfort, what if risk analysis, and enhance decision making process

Table 8: Differences Between BIM and Digital Twin

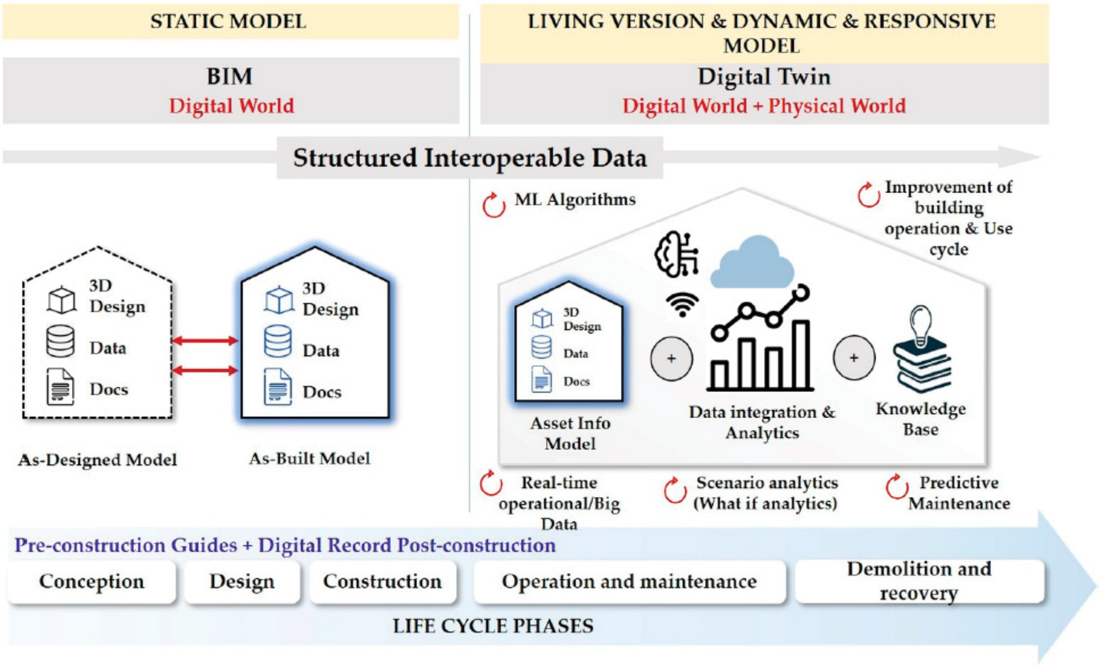


Figure 3: BIM and DTw processes and supporting technologies (Megahed & Hassan, 2022, p. 9)

There has been a lot of research performed on the relationship between BIM and DTw. Radzi discusses that there is a gap of industry understanding of this relationship, with many opinions on the boundaries of BIM and DTw. Moreover, out of 54 journal articles reviewed 8% believed that DTw is a subset of BIM, 15% believed that BIM is DTw, 18% believed that there is no relationship between BIM and DTw, and a majority of 60% believe that BIM is a subset of DTw (Radzi et al., 2023). In a way BIM is one of the first building blocks towards industry 4.0, where the AEC industry leverages the geometrical and non-geometrical information to create a DTw that can integrate static and dynamic real-time information (Antonino et al., 2019; Porsani et al., 2021; Rausch et al., 2021).

2.7.3 Relevant BIM for FM - Digital Twin Workflows

There have been many attempts at developing a successful BIM for FM workflow. Liu et al. developed a framework that integrates BIM, IoT, and support vector machines to strengthen the intelligence level of indoor safety management (Tian & Liu, 2014). Also, Desogus et al. suggested another method that integrates BIM and IoT through a single data platform that enables the visualization of energy consumption and indoor conditions (Desogus et al., 2021). Similarly, Villa et al. discusses the same concept but in an open source architecture (Villa et al., 2021). Moreover, Rasys et al. introduced the information integration framework that facilitates the management of oil and gas facilities through using Web3D technology to visualize asset's 3D components and their semantic FM information using class libraries (Rašys et al., 2014). In addition, Anderson et al. developed a BIM-FM workflow that employs standardized data collection to integrate BIM information with FM systems (Anderson et al., 2012). Furthermore, Tian and Liu suggested a semiotics-inspired framework that utilizes IFC models to include relevant facility information a useable format (Tian & Liu, 2014). Also, Borhani et al. reviewed the best current information exchange practices in the industry and accordingly built a workflow for data transfer from BIM to asset management systems (Borhani et al., 2017). Another BIM-based workflow is the developed by Orr et al., where object attributes were captured and data was transferred from BIM models into FM systems, with the system being assessed for its effectiveness in support of O&M practices and its applicability by a university's FM department (Orr et al., 2014). Lin and Su created an integrated information system for BIM and FM that focuses on enabling maintenance workers to review and update BIM models and their semantic maintenance records (Lin & Su, 2013). Also, Edmondson et al. introduced a prototype for a Smart Sewer AIM that enables real-time reporting of sewer asset performance by integrating IFC models with smart sensors (Edmondson et al., 2018). Moreover, Chen et al. highlighted the data integration challenges and their effect on productivity by developing a pilot study based on BIM for highway tunnels facility management system (L. Chen et al., 2020).

However, many of these workflows ignore a core part of the process, which is the BIM model development during the design and construction phases. Studies show that improper storage of facility information leads to the failure of optimization of the facility management systems. Therefore, the project teams must utilize a new BIM based process that correctly captures project information and then transfers it via open data formats that are interoperable with FM software. An effective BIM-FM workflow can be accomplished by clearly defining what information the facility manager requires to be included in the BIM model, capturing and storing the FM information in the BIM model throughout the project phases, and executing an interoperability plan for the data exchange between BIM and facility management systems (Pishdad-Bozorgi et al., 2018).

3 METHODOLOGY

3.1 Desired BIM to Digital Twin Framework

Workflow Goals	Details
Integrating client facility management requirements and organization requirements	Develop in coordination with the client and facility manager a set of requirements for the AIM that allows it to be utilized for the use of facility management.
Standardized naming convention	Develop a naming convention for the digital twin environment that is straightforward, user friendly, and follows open standards.
Adopting a CDE	Choosing the appropriate CDE that will act as a cybersecure digital twin environment, where it is expected to be accessible, support open standard formats, host the AIM with its static and dynamic information, visualize the model, allow customization, facilitate project handover, and satisfy facility management objectives such as predictive, preventive, and reactive maintenance methods.
Static information model (BIM) structure	Translate client requirements to define what geometric and non-geometric information should be available in the model.
Dynamic information model (RDS) structure	Translate client requirements to define what dynamic information is required and how it will be stored.
Compliance checking	Leverage the semantic properties of elements in the BIM model to develop effective compliance checking that upgrades the quality of the AIM and enhances the handover process.

Table 9: BIM to Digital Twin Workflow Goals

3.2 Overall Proposed BIM to Digital Twin Framework

Throughout the project lifecycle, there is continuous collaboration of documents from different stakeholders and therefore it is essential that information handling standards are followed to ensure proper **interoperability**. Moreover, they also enhance the **quality of work** and reduce the chances of risk and errors by ensuring a consistent predefined criterion is being followed, this further allows easier quality checking and document control. Also, the **amount of time and cost it saves** in the long run by simplifying the handling of information and risk mitigation is immeasurable. Furthermore, ISO in specific is an internationally accredited standard that is globally acknowledged and COBie is an exchange format that is generally used by facility managers. Both standards boast **credibility** and collaboration.

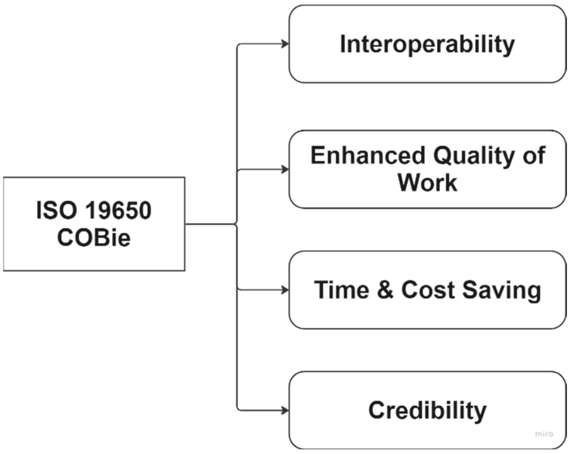


Table 10: Benefits of ISO 19650 & COBie for Facility Managers

3.2.1 Integrating client facility management requirements and organization requirements

This stage is what is defined by ISO as the information management process. It starts from the owner/client's side, where the first step is to appoint the individuals that are responsible to oversee the process. Then, the OIR – Organizational Information Requirements is established, followed by the PIR – Project Information Requirements and the AIR – Asset Information Requirements, which include identifying the standards followed and the assets to be managed along with the type of management and maintenance expected. This is all then organized into what is defined as an EIR – Exchange Information Requirements (delivery and operational) which then contributes to creating the LOIN - Level of Information Need (delivery and operational), which is considered as the designer and contractor's blueprint. A Common Data Environment (CDE) is established, considering the suitability of existing information systems, the ability to integrate project information models, legal storage requirements, separation of information for analysis and reporting, and a security-focused approach to CDE design and operation.

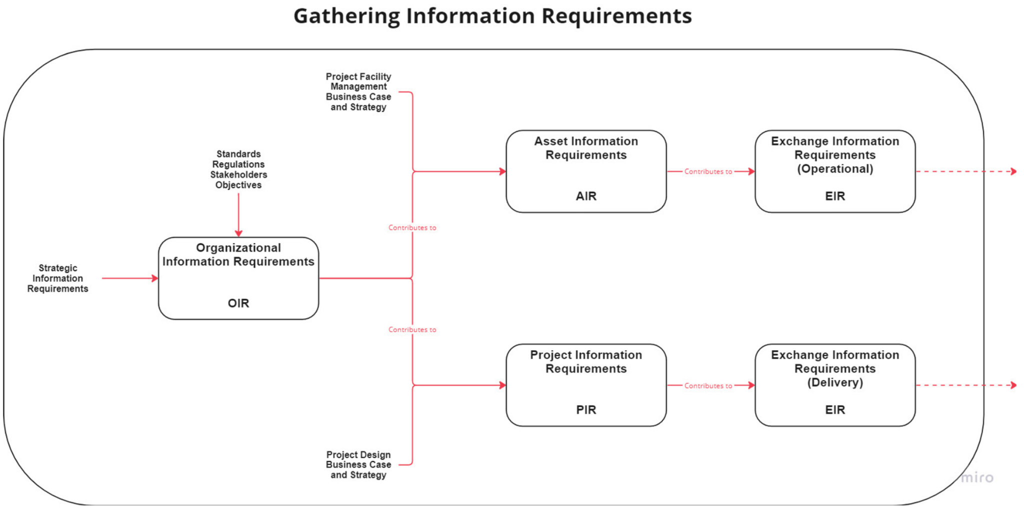


Figure 4: Step 1 - Gathering Information Requirements

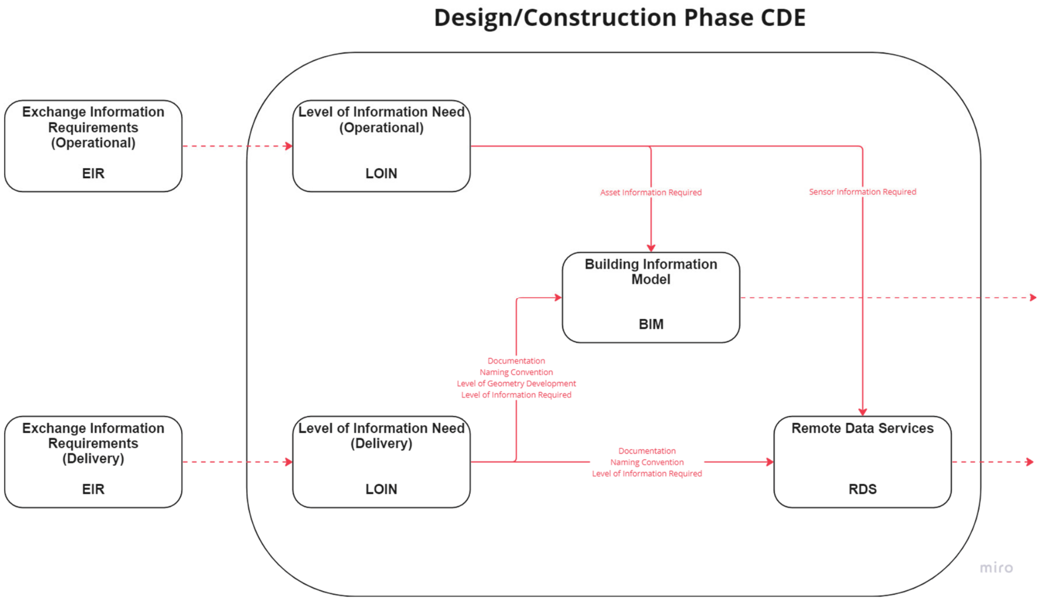


Figure 5: Step 2 - Design/Construction Phase

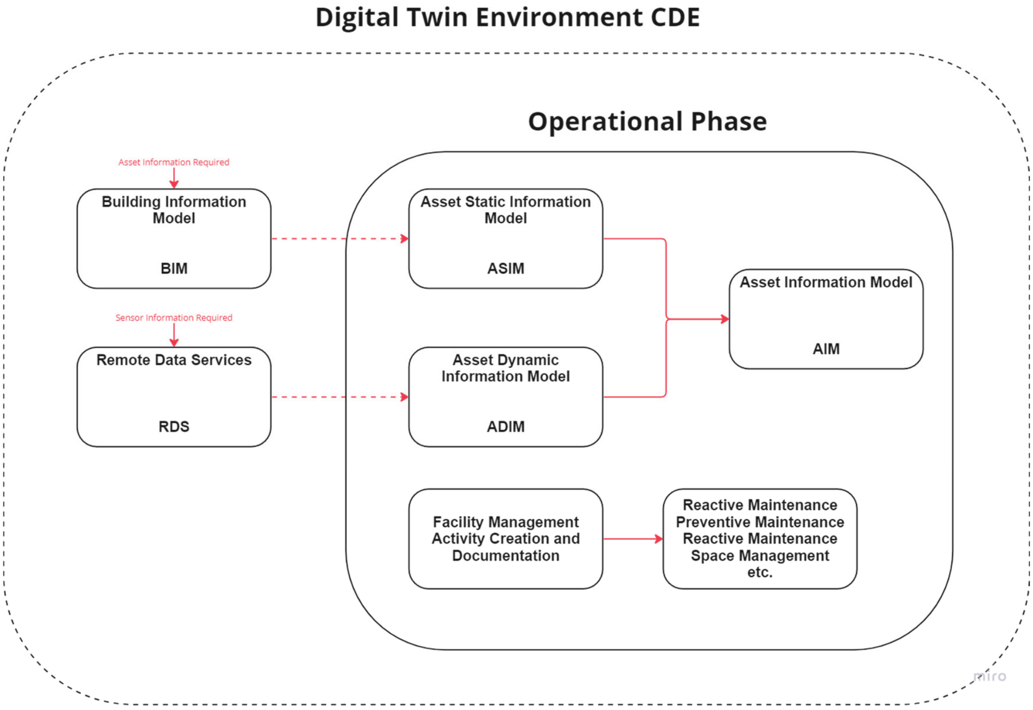


Figure 6: Step 3 - Setting Up The Digital Twin Environment

3.2.2 Standardized Naming Convention

The first building block of developing any standardized workflow is defining a naming convention. Specifically, this naming convention should follow an internationally recognized standard, such as ISO 19650 and COBie. Consequently, it should provide **unique identifiers** for all kinds of information types. Also, these identifiers should also follow a well defined **heirarchy** that clearly describes information relevant to this information type. In addition, this heirarchy should utilize **clear abbreviations** that are comprehendable by all stakeholders.

- Drawing Naming: For drawings, its important to keep track of the party that was responsible for producing them at a specific stage. Also, a clear seperation of disciplines, drawing types, and versions through the discipline code, sequence number, and revision.

Drawing Owner	Drawing Originator	Facility Name	Project Stage	Discipline Code	Sequence Number	Revision
DO	DD	FFF	PP	DC	XXXXXX	RR

Table 11: Drawing Naming Convention

  - DO: Client abbreviation
  - DD: Stakeholder abbreviation
  - FFF: Facility name abbreviation
  - PP: Project stage abbreviation (e.g. CD for concept design, DD for design development)

  - DC: Refer to discipline table
  - XXXXXX: Six-digit unique serial number (e.g. 001001, 001002…)
  - RR: Two-digit revision number (e.g. 00, 01…)

DO-DD-FFF-PP-DC-XXXXXX-RR

- Document Naming: Similar to the drawings, but with document type as an added parameter to account for the different possible type of documents.

Document Owner	**Document Originator**	**Facility Name**	**Project Stage**	**Discipline Code**	**Document Type**	**Sequence Number**	**Revision**
DO	DD	FFF	PP	DC	TTT	XXXXXX	RR

Table 12: Document Naming Convention

  - DO: Client abbreviation
  - DD: Stakeholder abbreviation
  - FFF: Facility name abbreviation
  - PP: Project stage abbreviation (e.g. CD for concept design, DD for design development)
  - DC: Refer to discipline table
  - TTT: Refer to document type table (e.g. BOQ for bill of quantities, M3D for BIM model …)
  - XXXXXX: Six-digit unique serial number (e.g. 001001, 001002…)
  - RR: Two-digit revision number (e.g. 00, 01…)

DO-DD-FFF-PP-DC-TTT-XXXXXX-RR

- Room Naming: Rooms are defined with a unique serial number that is associated with each level.

Level	**Department**	**Room Number**
Floor Name	**DD**	XXX

Table 13: Room Naming Convention

  - Floor Name
  - DD: Department abbreviation – text or numerical (e.g. 00,01, A, B, etc.)
  - XXX: Three-digit unique serial number (e.g. 101, 102, 201…)

Floor Name-DD-XXX

- Asset Type Naming: The asset type name is a combination of the family name and the family type name. It is important to develop the asset names with the end in mind, which is how can the naming of the asset be as straightforward and organized for the facility manager to properly handle the assets that are in the facility.

"Family Name: Family Type Name"

  - Family Name: The family name is the main identifier of the asset and it is necessary that this name is unique or else it would be hard for the facility manager to identify the assets needed. The hierarchy describing the asset can be defined as discipline code > subdiscipline code > origin Type > subtype > manufacturer > model name > description.

Type Originator	Discipline Code	Subdiscipline Code	Origin Type	Subtype	Manufacturer	Model Name	Description
TO	DC	SSS	OOO	SS	Manufacturer	Model Name	Description

Table 14: Family Naming Convention

- TO: Originator abbreviation
- DC: Refer to discipline table
- SSS: Refer to subdiscipline table
- OOO: Origin of family type abbreviation (e.g. FCU for fan coil unit, AHU for air handling unit…)
- SS: Subtype of the origin type abbreviation (e.g. IU for indoor unit, OU for outdoor unit…)
- Manufacturer: Manufacturer abbreviated name (e.g. YORK for York Manufacturing Services)
- Model Name: Name of the selected model the family is modelled after
- Description: Relevant information describing the model

TO-DC-SSS-OOO-SS-Manufacturer-Model Name-Description

- Family Type Name: The family type name is just meant to specify which series/model of the defined "Model Name"

Model Type
Model Type

Table 15: Family Type Naming Convention

TO-DC-SSS-OOO-SS-Manufacturer-Model Name-Description: Model Type

- Remote Data Service - Sensor Naming: The sensor naming is meant to convey where the sensor is, and more importantly what the sensor is measuring.

Level	Department	Room Number	Measurement	Type	Sequence Number
Floor Name	DD	XXX	MMM	TTT	ZZZ

Table 16: Remote Data Service Naming Convention

- Floor Name
- DD: Two-digit department number
- XXX: Three-digit unique serial number (e.g. 101, 102, 201…)
- MMM: Measurement abbreviation (e.g. TMP for temperature, HUM for humidity, FLW for flow…)
- TTT: Type of measurement (e.g. AIR for air, WTR for water…)
- ZZZ: Sensor sequence number according to the type of measurement (e.g. 001, 002, etc.)

FFF-LL-XXX-MMM-TTT

- Sample Discipline Table

Discipline Name	Discipline Code
Architecture	AR

Structure	ST
Mechanical	ME
Electrical	EL

Table 17: Sample Discipline Table Abbreviations

- Sample Document Type Table

Discipline Name	**Discipline Code**
BIM Execution Plan	BEP
BIM Model	M3
Drawing	DWG
Bill of Quantities	BOQ
Request for Information	RFI
Calculation	CAL

Table 18: Sample Document Type Abbreviations

- Sample Subdiscipline Table

Mechanical Discipline	
Subdiscipline Name	**Subdiscipline Code**
Mechanical Equipment	EQU
Air Terminal	AT
Duct	DT
Duct Accessory	DTA

Table 19: Sample Subdiscipline Abbreviations

3.2.3 Common Data Environment (CDE):

When it comes to handling projects throughout their different lifecycle, having all the relevant information in one reference point is of crucial importance. This reference point is called the common data environment (CDE). The main goals of this is to facilitate the collaboration and documentation of information throughout the entire lifecycle of a building or infrastructure project, where it acts as the single source of truth for all relevant stakeholders in a secure environment. In addition, a CDE is usually expected to comply with organization and employer requirements, where a certain standard is expected to be followed such as ISO 19650. Moreover, when it comes to facility management and maintenance, the CDE can greatly enhance the process if it provides the following features:

- **Security Measures:** This can be achieved through implementing strict access controls to ensure that only authorized individuals can access and interact with the data. For example, the role-based access control (RBAC) can be used to assign specific permissions to users based on their roles and responsibilities. Moreover, it is essential to have strong authentication methods, such as multi-factor authentication (MFA), to ensure that users are who they claim to be. Furthermore, data encryption is key in cybersecurity, where encryption protocols need to be in place to safeguard the data in the case of unauthorized access.

- **Web access and Mobile Interface:** Access to the digital twin environment through the web and through a mobile application to enhance facility manager accessibility and improve efficiency.
- **Customizable:** Customizability in a Common Data Environment (CDE) is pivotal as it aligns seamlessly with an organization's workflows, reducing disruptions and boosting user adoption. It caters to diverse projects by accommodating differences in data structures, document types, and collaboration approaches.
- **BIM Integration:** being able to import IFC BIM models to the CDE allows facility managers to link the assets that are in the BIM model with external FMM scenarios. In addition, it saves up time with regards the transfer of relevant static asset information and provides a geospatial reference to where the assets are in the facility.
- **RDS Integration:** being able to accommodate dynamic data coming from sensors that are monitoring asset performance and visualize it enables facility managers to perform preventive/predictive maintenance, carry out more optimized space management, and make better informed decisions.
- **Linking BIM and RDS:** Linking static BIM information and dynamic RDS information together allows the FMM manager to perform required tasks more efficiently. Where live performance information regarding an asset can be linked to its model, which allows for direct assessment of asset performance and consequently gives facility managers the capability to react faster to possible asset malfunction/failures.
- **Facility Portfolio Management:** giving the facility manager the proper tools to initiate, track, and document management and maintenance tasks within the same CDE saves up time and minimizes the loss of documents and data. Such tasks include but are not limited to producing reports tailored for standardization bodies, recordings for maintenance checkups, equipment inspection orders, alerts for required equipment checks, data from inspections and warranty certificates, and a bulletin board for information display.
- **Organize Handover to Facility Manager:** offering streamlined and secure approach to managing project-related information during transitions. By centralizing data and documentation, a CDE ensures that critical handover materials, such as design specifications, maintenance manuals, and compliance records, are easily accessible to relevant stakeholders. This organized platform facilitates seamless communication, reduces data duplication, and enhances collaboration between project teams and operational personnel, ultimately leading to efficient and well-coordinated handovers.

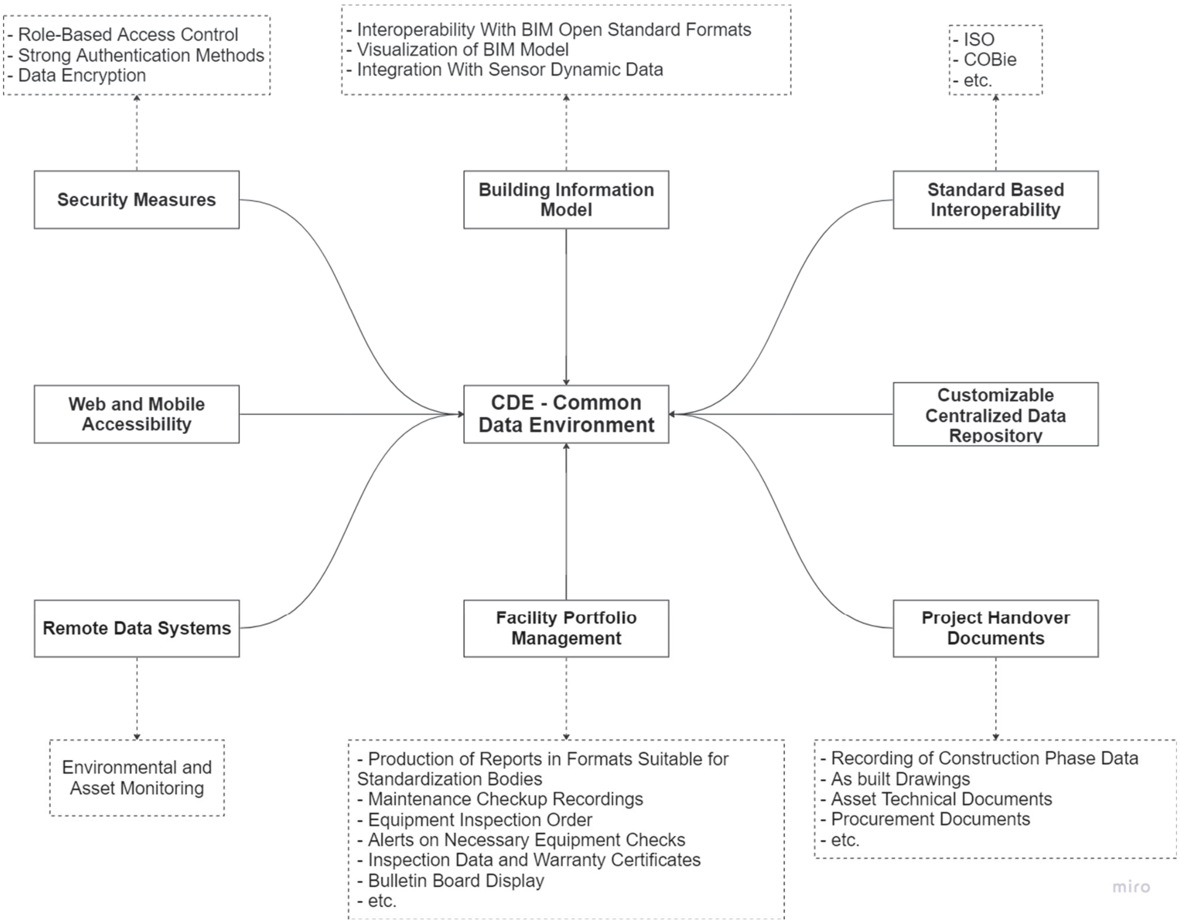


Table 20: Facility Management Common Data Environment Requirements

3.2.4 Asset Static Information Model (BIM) Structure

This model contains all necessary static information (geometric and non-geometric) that allow facility managers to effectively manage/maintain their assets. Static information encompasses all instances of information that do not necessitate real-time updates, such as equipment tag, manufacturer information, environmental requirements, etc. Moreover, this information serves the purpose of facilitating the systematic organization of assets within a facility management building portfolio. Such organization is crucial for executing seamless facility management operations, including passive scheduled maintenance that does not rely on dynamic data updates.

The ASIM – Asset Static Information Model is a derivative of the building information model that is developed throughout the building lifecycle, where it builds on the geospatial locations of the assets with relevant required F&M information. A pivotal factor in defining the ASIM is the Level of Information Need (LOIN) matrix, this matrix results from the intersection of facility manager information requirements and industry-standard mandates like COBie. Furthermore, the LOIN specifies what relevant F&M information is required at each step of the project's lifecycle and in turn what information parameter that will be needed in the model. These parameters are not all required to be filled from the start, however; they will be filled by the responsible parties at the relevant project stage i.e. manufacturer information should only be filled out after the contractor has completed procurement.

When exporting the ASIM from BIM, it is important to only export the information that is relevant to the facility manager. The LOIN is a guide for information will be exported, this prevents an overflow of data and makes it easier for the facility manager to locate the information needed for organizing the facility management portfolio.

The ASIM is made up of three main categories: Project, Asset, and Space Information. Each category is expanded on in the following sections. Each of these categories plays a critical role in enhancing the comprehensive understanding and management of assets within the facility. Project information pertains all necessary parameters that describe a project's general information. Whereas asset information delves into the parameters that describe the specifics of an asset's geometric and non-geometric information. Finally, the space information includes the parameters that mainly describe the environmental operating conditions of the space. This strategic categorization ensures that all facets of facility management are well-addressed within the ASIM framework, optimizing efficiency and effectiveness across the lifecycle of the building.

Legend: This legend will be followed in the following parameter matrices.

Expected Action	Color
Parameter to be verified or updated at this phase	🟧
Parameter to be filled at this phase	🟩

Table 21: LOIN Legend

Any parameter that cannot be filled due to any reason can be filled with the "n/a" term for text, and "0" for numbers.

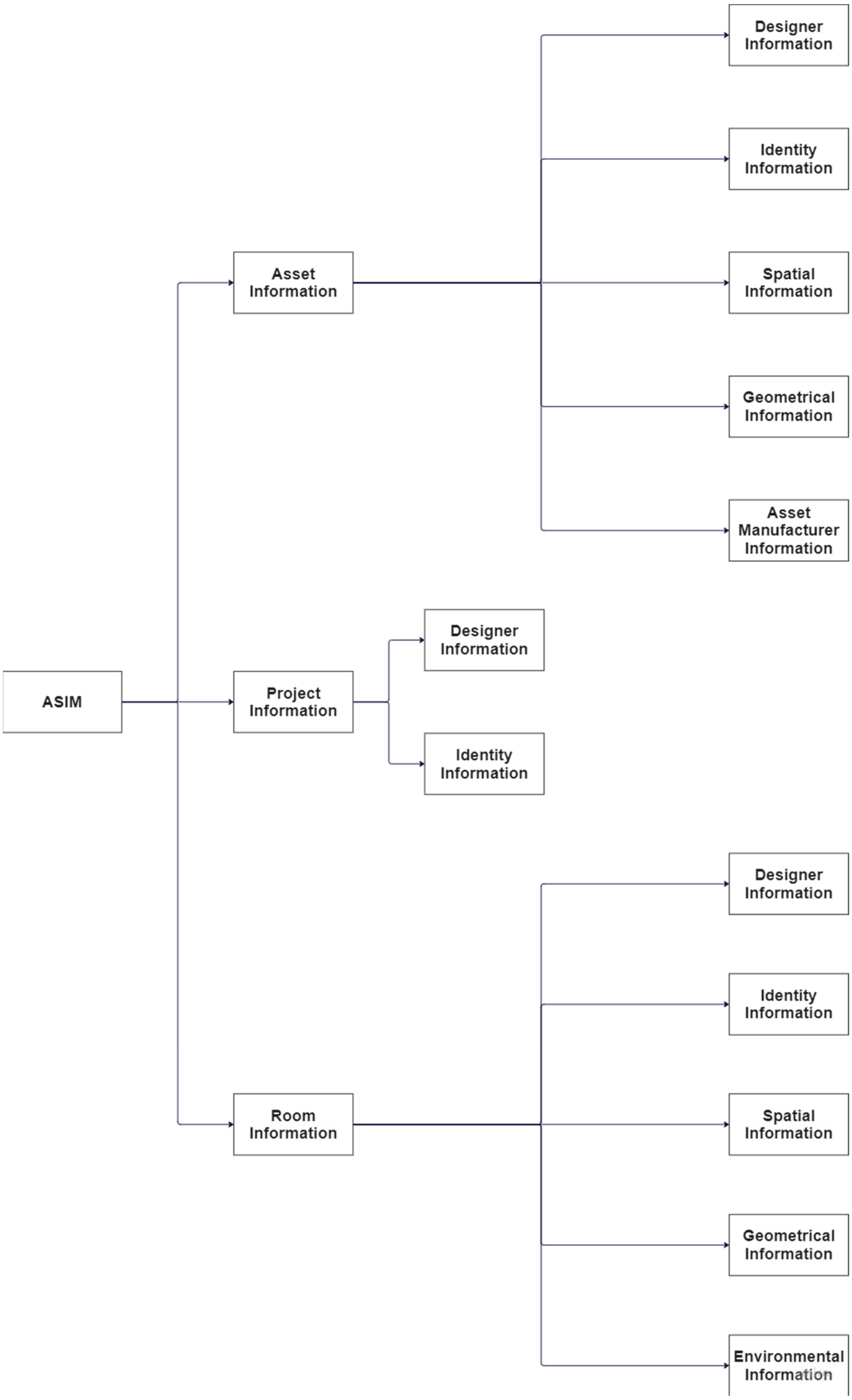


Figure 7: Asset Static Information Model Structure

3.2.4.1 Project Information

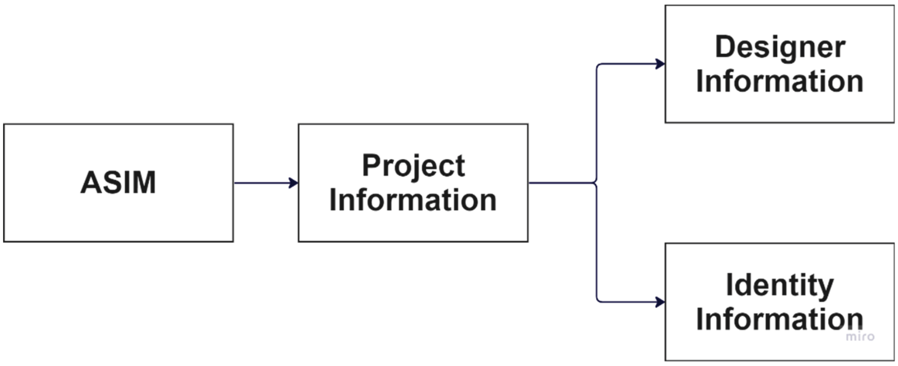


Figure 8: Project Information Structure

3.2.4.1.1 Designer Information

Designer information is mainly inspired from COBie and it offers benefits in improving the management and maintenance of building information by providing important metadata about the origin and time of information creation. The two parameters that are associated with this section are the “CreatedBy” and “CreatedOn” parameters. These parameters contribute to better traceability of information, accountability, and quality assurance throughout a building’s lifecycle through creating a clear history of ownership for the information element. Also, they fortify the handover process by making sure effective communication is carried out with the associated personnel. This information is expected to be filled at the design phase, and then continuously validated and updated throughout every phase of the project.

Designer Information				
Parameter Name	Parameter Type	Design Phase	Construction Phase	Operation
CreatedBy	Text	🟩	🟧	🟧
CreatedOn	Text	🟩	🟧	🟧

Table 22: Project Designer Information Requirements

3.2.4.1.2 Identity Information

This group of parameters focus on defining the project framework in terms of general project description, information, measurement standards, and quantity calculations. The parameters “ProjectName”, “Phase”, and “ProjectDescription” provide a clear and basic understanding of the project and its scope. Moreover, the parameters “LinearUnits”, “AreaUnits”, “VolumeUnits”, “CurrencyUnit”, and “AreaMeasurement” establish the measurements methods used in the model. All these parameters are expected to be filled at the design phase, and then continuously validated and updated throughout every phase of the project.

Identity Information				
Parameter Name	Parameter Type	Design	Construction	Operation
ProjectName	Text	🟩	🟧	🟧
Phase	Text	🟩	🟧	🟧
ProjectDescription	Text	🟩	🟧	🟧
LinearUnits	Text	🟩	🟧	🟧
AreaUnits	Text	🟩	🟧	🟧
VolumeUnits	Text	🟩	🟧	🟧
CurrencyUnit	Text	🟩	🟧	🟧
AreaMeasurement	Text	🟩	🟧	🟧

Table 23: Project Identity Information Requirements

3.2.4.2 Asset Information - Level of Development

In terms of assets, COBie makes a clear distinction between types and components within the framework of facility management.

- **Types** refer to standardized classifications or categories of building elements. The purpose of a type is to group together a specific set of elements that share the common template of asset information. In a way, the type acts as a carrier of “parent” data, for example a fan coil unit asset type will have certain manufacturer information, geometrical information, etc. and all elements that belong to this type will inherit the same information. This provides a semantic structural approach in data organization that boasts consistency and facilitates asset maintenance and management planning.
- **Components** refer to instances of elements within a project. These components are the tangible elements that exist in the facility. The purpose of a component is to individualize an element with unique information that is associated with this specific element. Going back to the “parent” description of the type, the component would be the “child” that inherits all the type properties as a base and then builds on them with more specific information. For example, a fan coil unit component would carry all the information that the fan coil type has, but with additional information that make it unique such as a serial number, installation date, etc. Components ensure that each element in the facility is accounted for and effectively maintained/managed throughout the building’s lifecycle.

In terms of Revit language, a family type would translate into the "type", and a family type instance would translate into the "component".

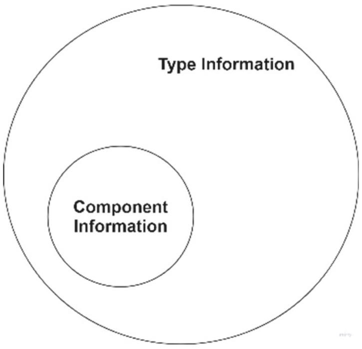


Figure 9: Type and Component Information Hierarchy

For assets, there are several types of information: designer, identity, spatial, geometric, and manufacturer information.

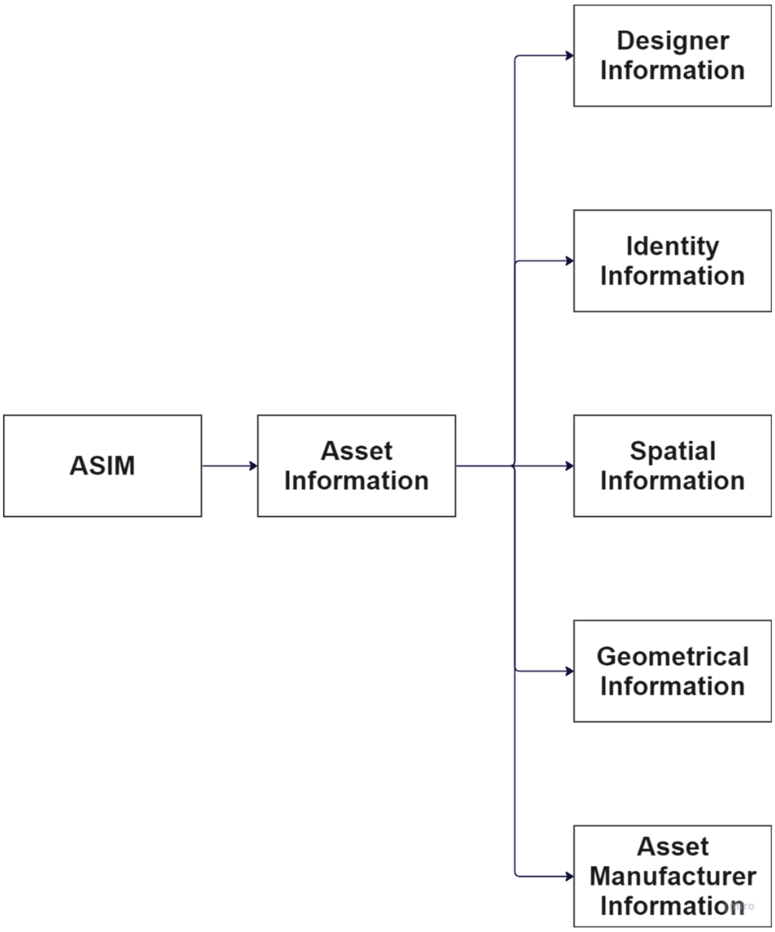


Figure 10: Asset Information Structure

3.2.4.2.1 Asset Designer Information

Like the project designer information, the two parameters that feature here are “CreatedBy” and “CreatedOn”. The added detail is that these parameters are required to be created for both the type and component part of the asset. Also, these parameters should be filled out for the design phase of the project and then updated according to each project phase.

Designer Information					
Parameter Name	Type/Component	Parameter Type	Design	Construction	Operation
CreatedBy	Type & Component	Text	🟩	🟧	🟧
CreatedOn	Type & Component	Text	🟩	🟧	🟧

Table 24: Asset Designer Information Requirements

3.2.4.2.2 Asset Identity Information

The parameters that are used to identity the assets are “IfcGUID”, “Description”, “Family”, “Type”, “Category”, “Constituents”, “Features”, and “AssetType”. Each of these parameters play an important role in organizing the asset information in the facility building portfolio.

- The “IfcGUID” is a global unique identifier that is automatically assigned to each element in the BIM model, meaning no two elements in any BIM model will have the same identifier. It serves the function of a unique serial number that can be used to identify, reference, and track an asset or a type of an asset throughout the lifecycle of the project. The IfcGUID is a reliable tool for interoperable data management and facility maintenance as it remains consistent even if elements are moved, modified, or transferred to different BIM software applications. Both asset types and components have their own GUID.
- The “Description” parameter is a straightforward parameter that is supposed to provide a brief explanation of what the asset type or component’s purpose and characteristics are. This parameter aims at clarifying any relevant information to the facility manager. Both asset types and components have the description parameter.
- The “ComponentName” parameter combines the GUID of the component with the family and type parameters to create a unique identifier for all instances of assets.
- The “Family” and “Type” parameters define the respective category and subcategory of the asset in the model. When it comes to facility management, they serve a crucial purpose in supporting the facility manager in identifying what assets are available in the model or are in a certain room. These parameters should be following the naming convention established earlier, which makes organizing and navigating the elements in the model easier. Both these parameters are considered type parameters.

- The “Category” parameter assigns assets to specific categories which belong to a standardized classification system, such as Uniclass, Omniclass, Uniformat, etc. This parameter is a concatenation of the classification number and description. The main goal of this parameter is to aid the facility manager in filtering and organizing elements based on their classification. Moreover, this parameter is a type parameter.
- The “AssetType” parameter is inspired directly from COBie and describes the type of the asset as either “Fixed” or “Moveable”. This information is important for the facility manager to know which of the assets are fixed such as a fan coil unit or moveable such as furniture. Fixed and moveable assets are treated differently in FMM scenarios, where the former require long term maintenance planning and the latter require efficient tracking and management, among other differences. Moreover, “AssetType” is a type parameter.
- The “Constituents” parameter plays a role in identifying any important subcomponents that a certain asset may have. It helps the maintenance team pay attention to parts of the asset that require a checkup or that may require any special attention. For example, a fan coil unit would have the filter, coil, and fan as its constituents. This improves efficiency of any maintenance operation and the lifecycle management of the assets. “Constituents” is a type parameter.
- The “Features” parameter’s purpose is to indicate any unique features that the asset has. These features would help identify the asset or would indicate any special handling procedure required. Overall, this parameter is supposed to add information to the facility manager and improve the maintenance and handling process of an asset. “Features” is a type parameter.
- The “ModelReference” parameter specifies the reference model after which the family was modelled after. This helps the contractor in procuring the asset in the market or find something similar.

  All these parameters should be filled out in the design phase, and then regularly updated and verified throughout the following project phases.

Identity Information					
Parameter Name	Type/Component	Parameter Type	Design	Construction	Operation
IfcGUID	Type & Component	Text	🟩	🟧	🟧
Description	Type & Component	Text	🟩	🟧	🟧
ComponentName	Component	Text	🟩	🟧	🟧
Family	Type	Text	🟩	🟧	🟧
Type	Type	Text	🟩	🟧	🟧
Category	Type	Text	🟩	🟧	🟧
AssetType	Type	Text	🟩	🟧	🟧
Constituents	Type	Text	🟩	🟧	🟧
Features	Type	Text	🟩	🟧	🟧
ModelReference	Type	Text	🟩	🟧	🟧

Table 25: Asset Identity Information Requirements

3.2.4.2.3 Asset Spatial Information

The parameters associated with the spatial information are "SpaceDepartment", "SpaceNumber", and "Level". These parameters are the basics that any facility manager would need to locate an asset in a facility. It is crucial that the geospatial location the assets are modelled at reflect their location in the built facility. This would help with locating an asset's location faster for any maintenance or management operation, ensuring a faster response time, smoother workflows, and a better operational efficiency of the facility. These three parameters should be automatically read from the room and level there are modelled in. This helps reduce errors and makes the data filling process smoother.

These parameters are all component parameters, and they need to be filled out in the design phase of the project then validated and updated throughout the lifecycle of the building.

Spatial Information					
Parameter Name	Type/Component	Parameter Type	Design	Construction	Operation
SpaceDepartment	Component	Text	🟩	🟧	🟧
SpaceNumber	Component	Text	🟩	🟧	🟧
Level	Component	Text	🟩	🟧	🟧

Table 26: Asset Spatial Information Requirements

3.2.4.2.4 Asset Geometrical Information

From a facility manager's point of view, the required geometric information is the one that is relevant to the asset's size and volumetric dimensions. Therefore, a high level of geometrical detail would be irrelevant for facility management scenarios and rather the focus should be on properly allocating the assets in their proper geospatial location and the physical space they occupy. For example, an air handling unit can be modelled as a rectangle that reflects its size, with no need to show all the components of an air handling unit.

The parameters that are associated with the geometrical information are "NominalLength", "NominalWidth", NominalHeight", "NominalDiameter", "Shape", "Color", "Finish", "Grade", and "Material". By geometrical information, it is meant to cover the information that is related to the physical characteristics of the asset.

The first five parameters are associated with the spatial space the asset occupies and are therefore required to be filled at the design stage, and then updated and validated throughout the project lifecycle. However, the last four parameters are associated with information that is revealed once the asset has been procured by the contractor, and there it is only required for this information to be filled at the construction phase, and then validated in the as built phase.

Geometrical/Physical Information

Parameter Name	Type/Component	Parameter Type	Design	Construction	Operation
NominalLength	Type	Number	🟩	🟧	🟧
NominalWidth	Type	Number	🟩	🟧	🟧
NominalHeight	Type	Number	🟩	🟧	🟧
NominalDiameter	Type	Number	🟩	🟧	🟧
Shape	Type	Text	🟩	🟧	🟧
Color	Type	Text		🟩	🟧
Finish	Type	Text		🟩	🟧
Grade	Type	Text		🟩	🟧
Material	Type	Text		🟩	🟧

Table 27: Asset Geometrical Information Requirements

3.2.4.2.5 Asset Manufacturer Information

The asset manufacturer information is arguably the most important information for a facility manager. The parameters involved are the "Manufacturer", "ModelNumber", "WarrantyGuarantorParts", "WarrantyDurationParts", "WarrantyGuarantorLabor", "WarrantyDurationLabor", "WarrantyDurationUnit", "UnitCost", "ReplacementCost", "ExpectedLife", "DurationUnit", "WarrantyDescription", "SerialNumber", "InstallationDate", and "WarrantyStartDate". This information provides a comprehensive summary regarding an asset's warranty, financial aspects, identification, and expected lifespan.

- "Manufacturer", "WarrantyGuarantorParts", "WarrantyGuarantorLabor", and "WarrantyDescription" are mainly responsible for the identification of the originator of the asset and the entity appointed with the warranty of the asset. This is important when it comes to sourcing asset replacement parts and maintenance guidelines.
- "ModelNumber" and "SerialNumber" support the facility manager in the identification of the asset and its categorization within the facility.
- The rest of the parameters "WarrantyDurationParts", "WarrantyDurationLabor", "WarrantyDurationUnit", "UnitCost", "ReplacementCost", "ExpectedLife", "DurationUnit", "InstallationDate" and "WarrantyStartDate" are instrumental in the maintenance and management process of assets. They provide the tools that enable scheduled maintenance and organize the relationship between the assets, the facility manager, and the warranty guarantors. Only the "SerialNumber", "InstallationDate", and the "WarrantyStartDate" are component parameters given their individuality in the assets, and the rest are type parameters. Moreover, since these parameters require information about the manufacturer and the warranty guarantors, then they are only required to be filled from the construction phase onwards.

Manufacturer Information

Parameter Name	Type/Component	Parameter Type	Design	Construction	Operation
Manufacturer	Type	Text		🟩	🟧
ModelNumber	Type	Text		🟩	🟧
WarrantyGuarantorParts	Type	Text		🟩	🟧
WarrantyDurationParts	Type	Number		🟩	🟧
WarrantyGuarantorLabor	Type	Text		🟩	🟧
WarrantyDurationLabor	Type	Number		🟩	🟧
WarrantyDurationUnit	Type	Text		🟩	🟧
UnitCost	Type	Number		🟩	🟧
ReplacementCost	Type	Number		🟩	🟧
ExpectedLife	Type	Number		🟩	🟧
DurationUnit	Type	Text		🟩	🟧
WarrantyDescription	Type	Text		🟩	🟧
SerialNumber	Component	Text		🟩	🟧
InstallationDate	Component	Text		🟩	🟧
WarrantyStartDate	Component	Text		🟩	🟧

Table 28: Asset Manufacturer Information

3.2.4.3 Room Information

The room information is crucial when it comes to facility space management. It provides insight on the identity of the room, its location, its dimensions, and its requirements.

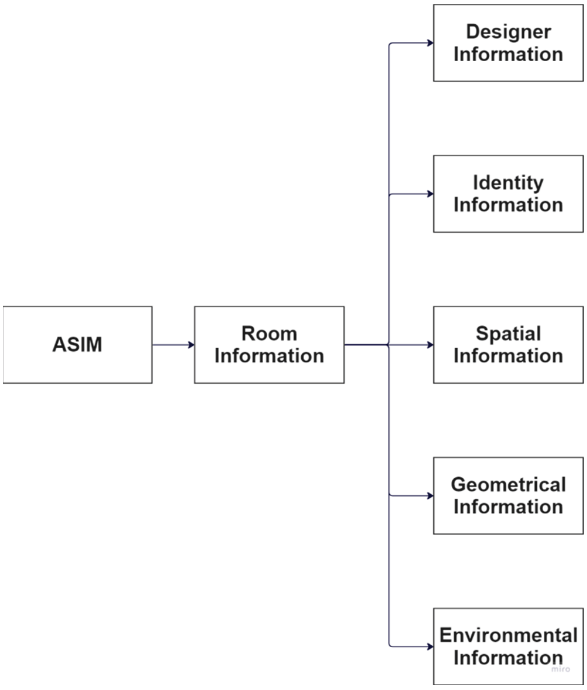


Figure 11: Room Information Structure

3.2.4.3.1 Designer Information

Like the previous designer information, the two parameters that feature here are "CreatedBy" and "CreatedOn". These parameters should be filled out for the design phase of the project and then updated according to each project phase.

Designer Information				
Parameter Name	Parameter Type	Design	Construction	Operation
CreatedBy	Text	🟩	🟧	🟧
CreatedOn	Text	🟩	🟧	🟧

Table 29: Room Designer Information

3.2.4.3.2 Identity Information

There are four parameters that are concerned with the room identity, which are "IfcGUID", "RoomName", "RoomNumber", and "Description".

- As mentioned before, the “IfcGUID” is a global unique identifier that is also automatically assigned to rooms in the BIM model.
- “RoomName” is not unique and provides insight on the function of the room, such as “Office”, “Meeting Room”, etc.
- “RoomNumber” is unique per level and follows the naming convention defined in previous section. This parameter together with the “Level” and the “ProjectName” makeup the comprehensive room name defined in the naming convention (FFF-LL-XXX = ProjectName-Level-RoomNumber).
- The “Description” parameter aims to provide further details regarding the room function. This information is not necessary to be provided and is usually only added if it adds relevant information to the facility manager’s role in room and space management.

  All these parameters are generally filled in the design stage and then verified and updated throughout the project’s lifecycle.

Identity Information				
Parameter Name	Parameter Type	Design	Construction	Operation
IfcGUID	Text	🟩	🟧	🟧
RoomName	Text	🟩	🟧	🟧
RoomNumber	Number	🟩	🟧	🟧
Description	Text	🟩	🟧	🟧

Table 30: Room Identity Information

3.2.4.3.3 Spatial Information

The spatial information concerned with the rooms is limited to two parameters, the “Level” and “Zone”.

- “Level” parameter is read automatically from the level the room is modelled in.
- “Zone” parameter is filled according to what zone the room belongs to, assuming the facility is composed of different zones. Knowing the zoning of each room supports the facility manager in locating the rooms in a facility and allows better room management.

  Both parameters are filled since the design stage, then updated and validated throughout the project lifecycle.

Spatial Information				
Parameter Name	Parameter Type	Design	Construction	Operation
Level	Text	🟩	🟧	🟧
Zone	Text	🟩	🟧	🟧

Table 31: Room Spatial Information

3.2.4.3.4 Geometrical Information

The geometrical information required are the “Area” and “Height” parameters. The “Area” should provide the net usable area in a space, which supports the facility manager in maintenance planning, tenant allocation, and optimizing the ongoing use of spaces in the building. Moreover, the “Height” is particularly important to determine the passageway of assets and their maintenance parts.

Both parameters are filled in the design phase and then updated and validated throughout the construction process.

Geometrical Information				
Parameter Name	Parameter Type	Design	Construction	Operation
Area	Number	🟩	🟧	🟧
Height	Number	🟩	🟧	🟧

Table 32: Room Geometrical Information

3.2.4.3.5 Environmental Information

The parameters that are concerned with the environmental management of the room are “MaxTemperatureCooling”, “MinTemperatureCooling”, “MaxTemperatureHeating”, “MinTemperatureHeating”, “MaxHumidity”, “MinHumidity”, “MaxCO2Level”, “RequiredLuxLevel”, and “MaxDbLevel”. These parameters support the facility manager in analyzing dynamic data coming from remote data services, enable better space management, enhance occupant wellbeing, optimize energy efficiency, improve performance monitoring of equipment, and allow better and faster decision making.

- ““MaxTemperatureCooling”, “MinTemperatureCooling”, “MaxTemperatureHeating”, “MinTemperatureHeating”, “MaxHumidity”, and “MinHumidity” tackle the occupant’s thermal comfort. Thermal comfort is usually defined between a range of temperatures and humidity, which prompts parameters that check for upper and lower ranges of these measurements.
- “MaxCO2Level” is a parameter that is concerned with the air quality of the space. Spaces have a maximum threshold of allowable percentage of CO2 in the air that is recoded using sensors. Having this parameter makes it easier to check if the sensor readings are acceptable and helps make sure all spaces are designed up to acceptable air quality standards.
- “RequiredLuxLevel” is a parameter that defines what the lighting requirements of a space is. This helps making sure all spaces are designed up to lighting standard requirements and facilitates the checking of live LUX readings. It also gives insights on possible out of service or underperforming lighting fixtures that require maintenance or replacement.

- The “MaxDbLevel” parameter is concerned with the acceptable sound level in a space. This helps make sure all the spaces are designed up to acceptable noise standard requirements. It also prompts the facility manager to identify unacceptable Db readings and therefore address them by either adding insulation, changing space function, etc.

All these parameters should be developed in the design stage, then updated and validated throughout the rest of the project lifecycle.

Environmental Information				
Parameter Name	Parameter Type	Design	Construction	Operational
MaxTemperatureCooling	Number	🟩	🟧	🟧
MinTemperatureCooling	Number	🟩	🟧	🟧
MaxTemperatureHeating	Number	🟩	🟧	🟧
MinTemperatureHeating	Number	🟩	🟧	🟧
MaxHumidity	Number	🟩	🟧	🟧
MinHumidity	Number	🟩	🟧	🟧
MaxCO2Level	Number	🟩	🟧	🟧
RequiredLuxLevel	Number	🟩	🟧	🟧
MaxDbLevel	Number	🟩	🟧	🟧

Table 33: Room Environmental Information

3.2.5 Dynamic Information Model Structure

The ADIM - Asset Dynamic Information Model contains all necessary dynamic information that gives facility managers insight on asset performance and room environmental conditions. Dynamic information encompasses all instances of information that are recorded in real-time, such as water flow, room temperature, etc.

Moreover, this information play an important role in enabling the facility manager to perform predictive and preventive maintenance, in addition to enhanced space management to ensure optimal occupant comfort and energy consumption.

The ADIM records information coming from IoT sensors, or what is described as RDS – Remote Data Services. Furthermore, using the proper CDE allows the integration of the ASIM and ADIM to create the comprehensive AIM, which provides the facility manager with the appropriate amount of information that can be leveraged to perform better asset maintenance, space management, and decision making. What defines this appropriate information is again the LOIN, where the requirements of what the facility manager wants to measure are translated into measurement requirements in the facility’s operational phase.

The structure of the ADIM is composed of three main parts, the Identity Information, Measurement Information, and Network Information. Each of these parts specify a layer of the RDS information, and together they provide the facility manager with a comprehensive picture of what information is measured and how it is connected. First, the Identity Information breaks down the information that is needed to identify the remote data service and referencing it with the asset its monitoring. Second, the Measurement Information describes the content of the information being monitored and its frequency. Third, the Network Information explains where the information is stored and how it is transferred.

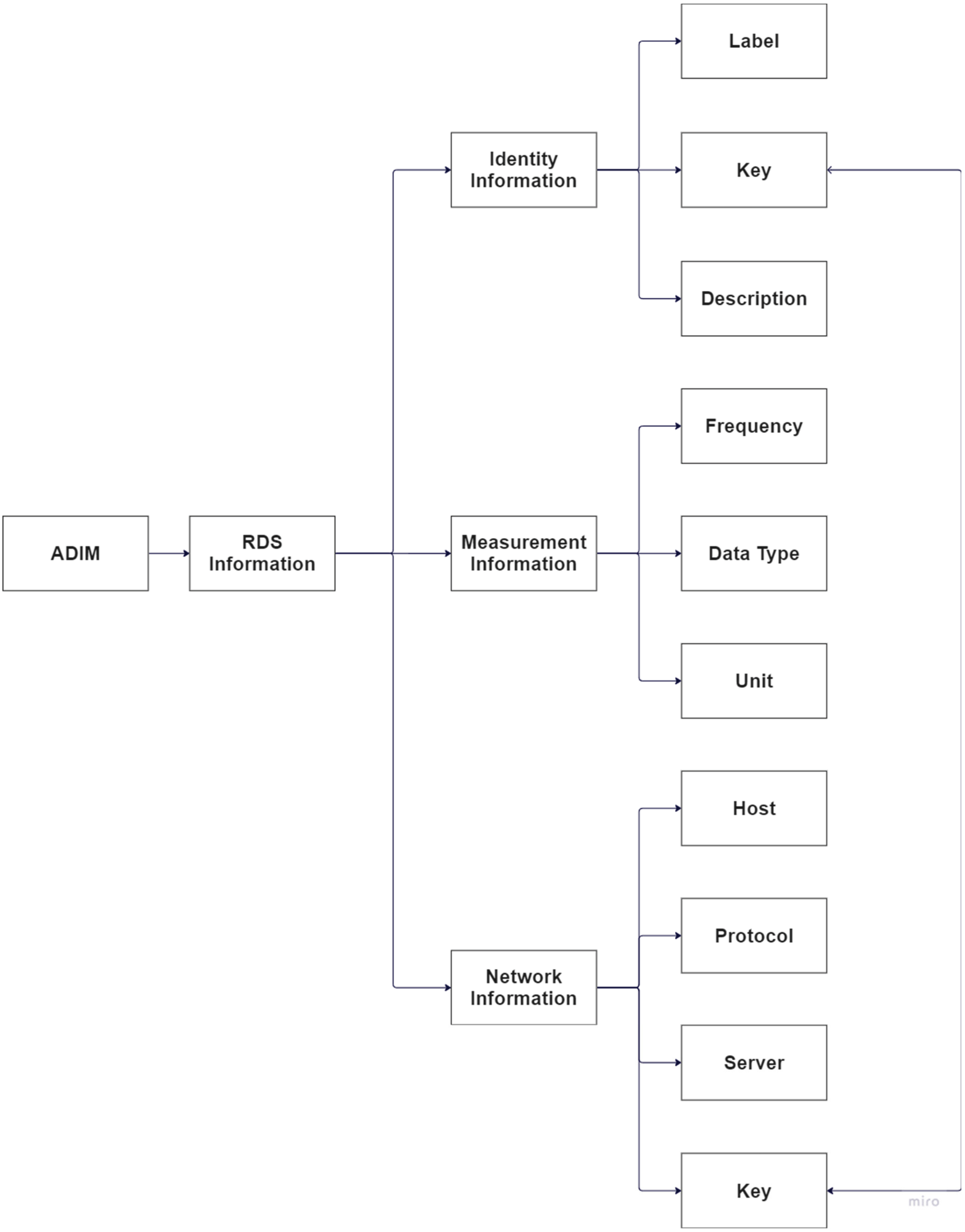


Figure 12: Asset Dynamic Information Model Structure

3.2.5.1 Identity Information

Identity information is divided into three main parts, the “Key”, “Label” and “Description”. These parameters play a role in identifying the role and location of the remote data service.

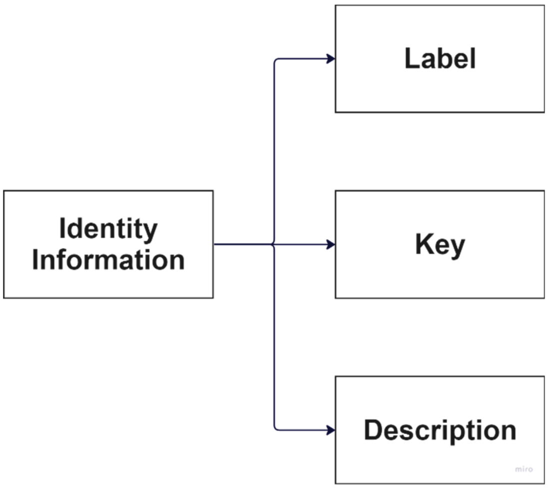


Figure 13: RDS Identity Information Structure

Here the spatial information is integrated into the identity information, where the “Key” parameter contains within it the facility, level, and room number. Moreover, it should be complying with the naming convention established earlier: Floor Name-DD-XXX-MMM-TTT-ZZZ, where:

Level	Department	Room Number	Measurement	Type	Sequence Number
Floor Name	DD	XXX	MMM	TTT	ZZZ

Table 34: RDS Naming Convention

- Floor Name-DD-XXX are enough to identify the location of the remote data service.
- MMM-TTT define what is being measured

The “Key” parameter is the connection between the value readings from the controller and the address which the readings are recorded at. Moreover, “Label” is meant to convey a short title that describes the measurement of the RDS. This title plays a role in quickly identifying the RDS and facilitates the organization of the information within the facility portfolio. For example, a label can be “Room Temperature”, “Pump Flow”, etc. Furthermore, the “Description” parameter is meant to deliver any additional information that would add relevant context to the facility manager in the operational phase.

Identity Information				
Parameter Name	Parameter Type	Design	Construction	Operation
Key	Text		🟩	🟧
Label	Text		🟩	🟧
Description	Text		🟩	🟧

Table 35: RDS Identity Information

3.2.5.2 Measurement Information

Measurement information is composed of three parameters: “DataType”, “Frequency”, and “Unit”.

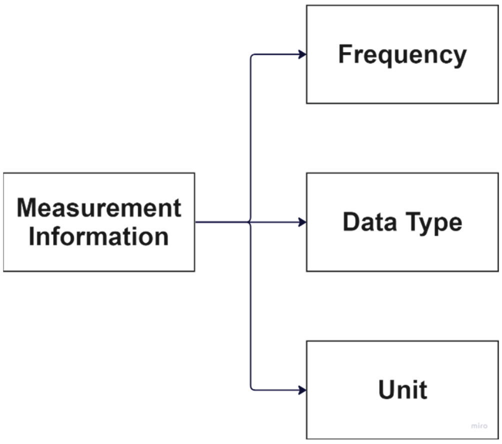


Figure 14: RDS Measurement Information Structure

These parameters cover the details of the measured information on a more qualititative lense and provide the facility manager with an understanding on how to store this information.

First, the “DataType” parameter defines the type of data being stored, which can be boolean, integer, double, etc. which helps the facility manager understand the nature of the data being recorded and how to make use of it. Second, the “Frequency” parameter is important to know how often information is being recorded and stored, as different assets require different monitoring methods. This is instrumental when it comes to mointoring, analysing, and handling the incoming information and their correlated assets. Also, it is important to take note the impact this has on database size, as too much information could compromise performance. Third, the “Unit” parameter gives context to the scale and magnitude of the recorded information, such as “Celsius”, “Pascal”, “m^3/s” , etc. This helps ensure consistency and accuracy in measurements.

Measurement Information				
Parameter Name	Parameter Type	Design	Construction	Operation
Frequency	Text		🟩	🟧
DataType	Text		🟩	🟧
Unit	Text		🟩	🟧

Table 36: RDS Measurement Information

3.2.5.3 Network Information

The netowrk information is mainly composed of four parameters: “Host”, “Protocol”, “Server”, and “Key”.

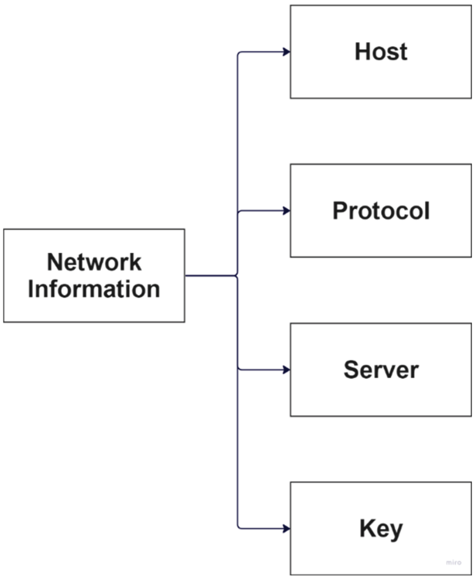


Figure 15: RDS Network Information Structure

These parameters define how the recorded information is transferred from the remote controller to the CDE. First, the "Host" parameter refers to a specific system within the network that is a part of the common data environment and is considered the intended destination, which could be an IP address, hostname, etc. Second, the "Protocol" parameter defines the communication rules or set of conventions that devices within the network follow to trasnmit data and establish connections. Such protocols include HTTP/HTTPS, TCP/IP, etc. Knowing the protocol is important to determine how data is being exchanged and provides insight into the level os security and reliability of the communication Third, the "Server" parameter defines the node within the network that stores the information before its transferred to the Host environment. This server plays a significant role in the data transfer process, ensuring efficient and reliable transmission. Lastly, the "Key" parameter is the relational parameter that was introduced in the identity information section, and it points to where the recorded information is stored at in the host CDE environment. These parameters are crucial for the facility manager to be able to understand how information is transferred and accordingly how to better be prepared for it.

Network Information				
Parameter Name	Parameter Type	Design	Construction	Operation
Host	Text		🟩	🟧
Protocol	Text		🟩	🟧
Server	Text		🟩	🟧
Key	Text		🟩	🟧

Table 37: RDS Network Information

4 CASE STUDY

4.1 Project Description

4.1.1 Project Brief

The client intends to construct an administration building for its own needs, on the parcel of land that is located near current production facility. The final solution must ensure functionality and represent the overall architectural image of the company. It must include internal and external landscaping, all in keeping with the existing layout of the area. It will be predominantly office space with an accompanying program of business activities. Moreover, the client wants to manage the facility using a BIM model.

Indicative areas of the building:

- Total area of the building plot: 5,220 m2
- Gross floor area: 4,672 m2
- Elevation: assumed 1+2
- Employees: approx. 105 seats

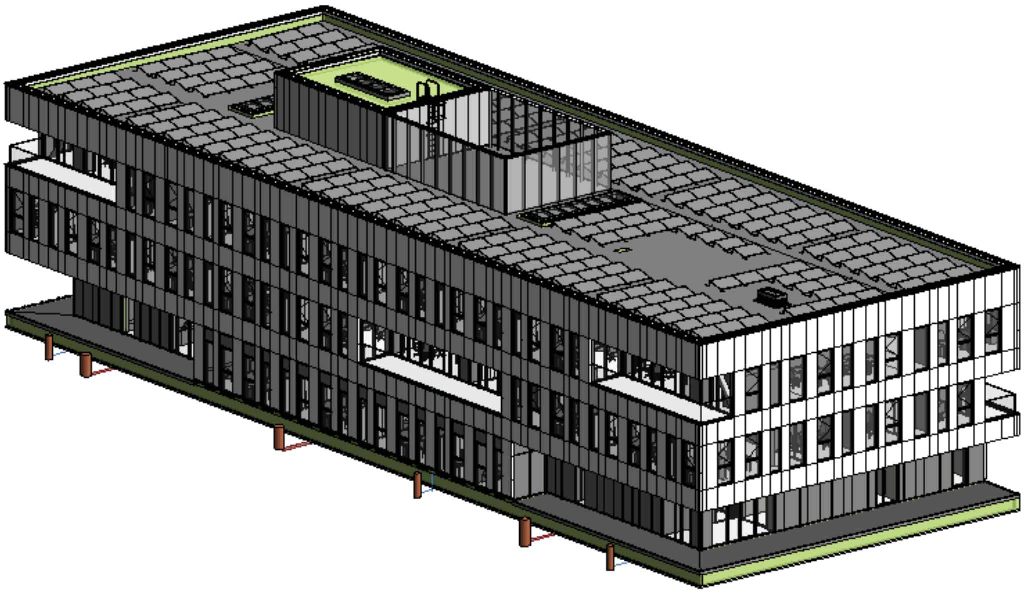


Figure 16: Revit 3D View of Case Study

4.1.2 Facility Manager Requirements

Facility manager requirements were developed in coordination with the client facility management representatives.

Requirements Category	Details
ISO Compliant Documentation	Production of reports and collection of documentation for ISO 9001, ISO 14001, ISO 45001.
	Recording of construction phase data.
	Recording of construction subcontractor records.
	Production of reports in formats suitable for standardization bodies.
Facility Management Requirements	Monitoring of environmental conditions.
	Recording of external illuminance measurements.
	Recording of ambient noise measurements.
	Recording of tests on the operation of security lighting and fire detectors.
	Recording of inspections of the MEP systems.
	Recording of leakage checks of gas installations.
	Recording of fire extinguishing system inspections.
	Providing alerts on necessary equipment inspections (preventive and reactive maintenance).
	Providing equipment inspection order.
	Inputting and storing of inspection certificate data, warranty certificates, and invoices.
	Allowing the digital signing of completed jobs.
	Recording of subcontractor trail.
	Recording of facility visits.
	Reserving facility premises.
	Displaying information in a bulletin board display.
BMS Requirements	Connecting to the BMS system via BACnet, ModBus, etc.
	Monitoring and control of lighting, shading, space cooling/heating, Air quality, ventilation.
	Collecting information from all subsystems, sensors, and devices into a central facility server system. Accessing information from the central system and allowing the configuration and editing of database parameters.
General Requirements	Eliminating the need for physical file storage.
	Allowing access to the API. Integrating data with enterprise resource planning.
	Viewing of 2D schematics simultaneously along with 3D viewing of the model.

Table 38: Facility Manager Requirements

4.1.3 Software and Standards Used

The standards followed in this workflow are:

- ISO 19650
- Uniclass Classification
- COBie
- IFC Schema

The BIM models are developed mainly using Revit, and they are to be exported into IFC format to be integrated into the digital twin environment. Moreover, the digital twin environment selected is Ecodomus, which will act as the common data environment for the facility manager.

4.2 Naming Convention

4.2.1 Document Naming:

Drawing Naming Convention: DO-DD-FFF-PP-DC-TTT-XXXXXX-RR

Models are accordingly named:

- Architectural Model: WS-RP-PZI-DD-AR-M3-000001-00
- Electrical Model: WS-RP-PZI-DD-EL-M3-000001-00
- Mechanical Model: RP-RP-PZI-DD-ME-M3-000001-00

4.2.2 Family and Family Type Naming:

One sample asset will be followed in each model to display the transfer of these assets from the BIM to the ASIM.

Family Naming Convention: TO-DC-SSS-OOO-SS-Manufacturer-Model Name-Description

- Sample Architectural Asset:

The asset discussed is an office chair.

Family Name: RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO

Family Type: 2210

- Sample Mechanical Asset:

The asset discussed is a Fan coil Unit.

Family Name: RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE

Family Type: 130

- Sample Electrical Asset:

The asset discussed is a Lighting Fixture

Family Name: RP-EL-LF-SUSPENDED-INTRALIGHTING-SUSPENDED

Family Type: 2001

4.2.3 Room Naming

A sample room will be used that contains all the previously mentioned sample assets.

Room Identifier: Floor Name-DD-XXX

Pritličje-01-001

Room Name: Meeting Room

4.2.4 Sensor Naming

A sample sensor will be used, which is a room temperature sensor.

Sensor Naming Convention: Floor Name-DD-XXX-MMM-TTT-ZZZ
Pritličje-01-001-TMP-AIR-001

4.3 Choosing CDE

Ecodomus is a BIM-enabled CDE that integrates the PIM and AIM together and serves as a comprehensive tool for the facility manager.

Building Information Model Interoperability	• Model geometry can be uploaded to Ecodomus directly through the interface. Format can be .ecd, which is generated through the Ecodomus connector, or the standard IFC file format. • Model information is uploaded to Ecodomus through the BIM connector Ecodomus plug-in, where the information is then associated with the previously uploaded geometry. • Different models can be federated in the CDE, allowing 3D model navigation, asset geometry and data visualization, locating systems and components, and facilitating tasks around the building.

Standard Based Interoperability	• COBie: Ecodomus allows the import and export of COBie spreadsheets to facilitate the transfer of information for its use in other facility management software if needed. • ISO 19650: Ecodomus is ISO19650 certified as it facilitates seamless information transfer among stakeholders, ensuring compliance with BIM information management guidelines through integrated data and document management. • Ecodomus offers a set of APIs to enable integrations with BMS, such as Desigo CC, or other third-party lifecycle systems, such as SAP, and supports open standards like OPC, MQTT, BACnet, etc.
Customizable Centralized Data Repository	Ecodomus provides a comprehensive EDMS interface for managing facility information, including building and asset data. Customizability however is limited to certain functionalities.
Remote Data Systems Functionality	Ecodomus can be connected via APIs to interfaces that are on the operational side of the facility, such as CMMS, CAFM, BMS, and IoT systems. Live information can be accessed through Ecodomus and even integrated with the uploaded static facility information.
Project Handover Documents	Ecodomus organizes the handover of facility information and documentation across different project lifecycles by allowing facilities and their information to be categorized into their respective phase. In addition, compliance checks can be enforced to ensure that certain phase requirements are validated.
Web and Mobile Accessibility	Ecodomus operates through a web-based interface and is also available as a dedicated mobile app for tablets and smartphones (iOS and Android devices). This supports the personnel on the field by providing them with access to live data, markups, etc. and allowing them to update any information as needed.
Security Measures	Ecodomus employs RBAC methods to ensure access is only given to the relevant parties that are cleared for access of this information. In addition, authentication and strong password policies are used to ensure safety of information.
Facility Management Portfolio Functionality	Ecodomus provides document management, asset management, issue management, data quality control, and 3D model navigation.

Table 39: Ecodomus CDE Functionalities

Although having the major drawback of not being open source, Ecodomus software itself supports different open standard formats such as IFC, COBie, BACnet, etc. and provides a degree of functionality for all previously described CDE requirements.

4.4 Populating ASIM

The project at hand is at the design development phase, therefore the information required to be in the model needs to follow the LOIN requirements for that stage.

The main priority in this process is to populate the building information model in the fastest and most organized way possible. To do so, multiple tools were utilized such as AUTODESK INTEROPERABILITY TOOLS.

- AUTODESK INTEROPERABILITY TOOLS are free Autodesk apps that are designed to facilitate BIM workflows for architects, engineers, contractors, and owners. The tools used for this case study are:

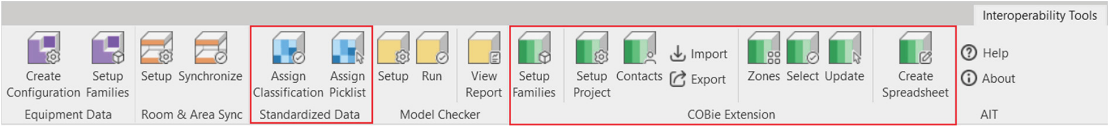


Figure 17: Autodesk Interoperability Tools

    - AUTODESK STANDARDIZED DATA TOOL FOR REVIT:
      This tool allows applying data from multiple classification systems to the elements in the model. Specifically, in this project the Uniclass classification system will be used.

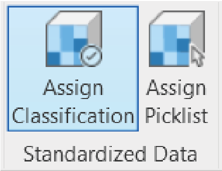


Figure 18: Autodesk Standardized Data Tool

        - Assign Classification: this tab works by selecting the element type that classification is required to be assigned to and then selecting the "Assign Classification" tab.

          Example: the below chair is selected

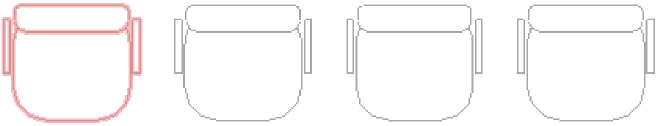
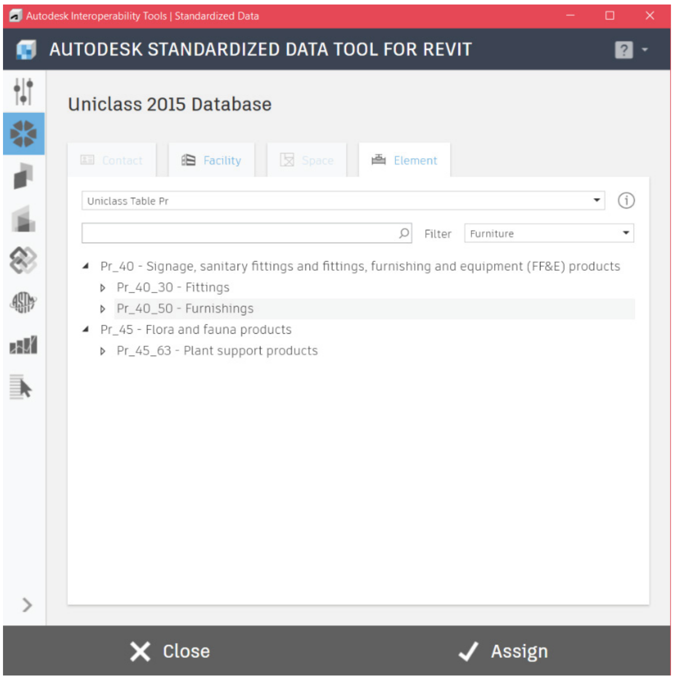


Figure 19: Sample Selection of Chair in Revit

Then the respective classification is assigned by selecting "Pr_40_30 – Furnishings"



Uniclass 2015 Database

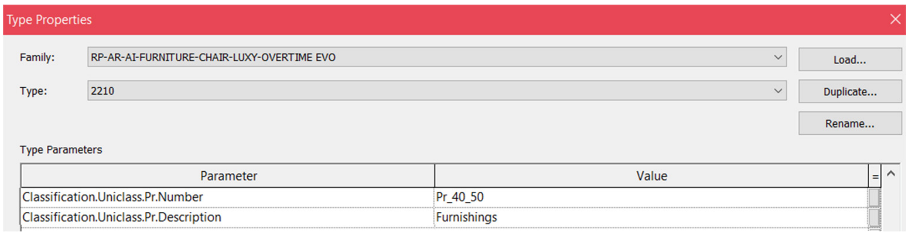
Uniclass Table Pr

Filter: Furniture

- Pr_40 - Signage, sanitary fittings and fittings, furnishing and equipment (FF&E) products
  - Pr_40_30 - Fittings
  - Pr_40_50 - Furnishings
- Pr_45 - Flora and fauna products
  - Pr_45_63 - Plant support products

Figure 20: Assigning Uniclass Classification Data

The result is parameters that are created in the family type and populated with the selected classification.



Family: RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO

Type: 2210

Type Parameters

Parameter	Value
Classification.Uniclass.Pr.Number	Pr_40_50
Classification.Uniclass.Pr.Description	Furnishings

Figure 21: Result of Assigned Classification

- AUTODESK COBie EXTENSION FOR REVIT:

  This tool allows setting up the Revit models to capture COBie data and set it up for interoperability with facility management software.

- Setup Project: sets up the COBie extension and configures the settings for the active model.

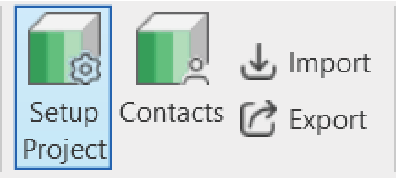
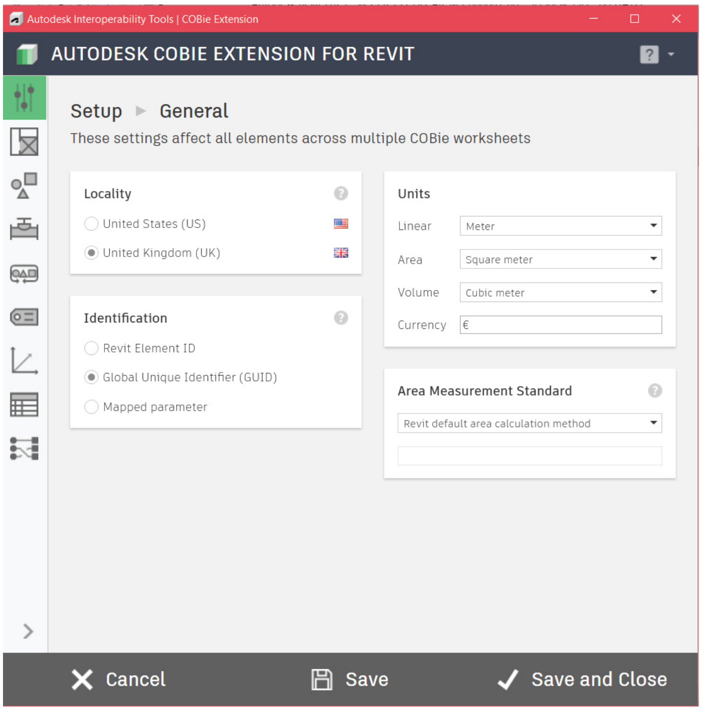


Figure 22: Autodesk Interoperability Tool Project Setup

- General:



Setup ▶ General

These settings affect all elements across multiple COBie worksheets

Locality
○ United States (US)
● United Kingdom (UK)

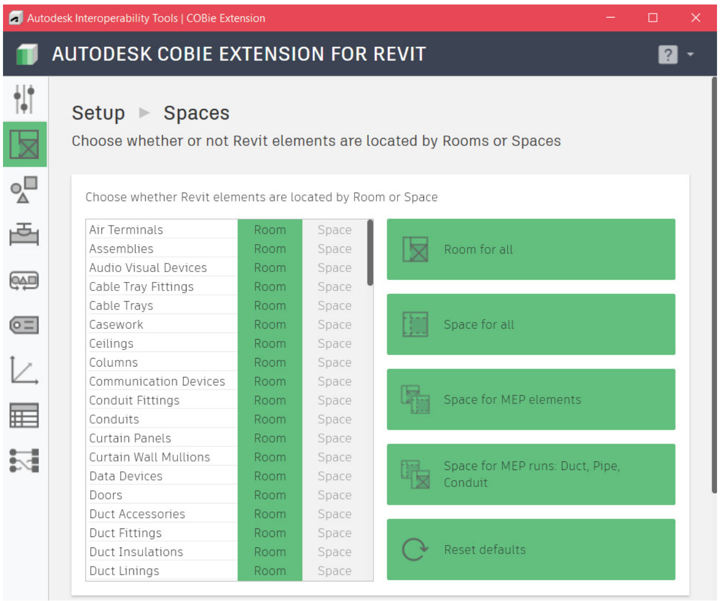
Identification
○ Revit Element ID
● Global Unique Identifier (GUID)
○ Mapped parameter

Units
Linear: Meter
Area: Square meter
Volume: Cubic meter
Currency: €

Area Measurement Standard
Revit default area calculation method

Figure 23: Autodesk Interoperability Tool Project General Setup

- Spaces: in this case study, Revit rooms will be used to identify asset location. Also, COBie treats rooms as spaces so the parameter COBie.Space.Name will be assigned to rooms as well.


Autodesk Interoperability Tools | COBie Extension

AUTODESK COBIE EXTENSION FOR REVIT

Setup ▶ Spaces

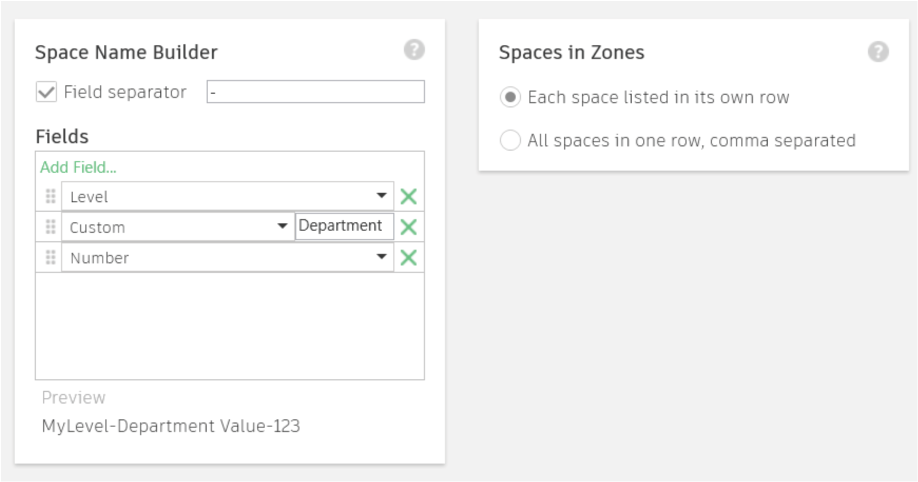
Choose whether or not Revit elements are located by Rooms or Spaces

Choose whether Revit elements are located by Room or Space

Air Terminals	Room	Space
Assemblies	Room	Space
Audio Visual Devices	Room	Space
Cable Tray Fittings	Room	Space
Cable Trays	Room	Space
Casework	Room	Space
Ceilings	Room	Space
Columns	Room	Space
Communication Devices	Room	Space
Conduit Fittings	Room	Space
Conduits	Room	Space
Curtain Panels	Room	Space
Curtain Wall Mullions	Room	Space
Data Devices	Room	Space
Doors	Room	Space
Duct Accessories	Room	Space
Duct Fittings	Room	Space
Duct Insulations	Room	Space
Duct Linings	Room	Space

Figure 24: Autodesk Interoperability Tool Space Setup

The space name builder will update the space name parameter with the defined structure. This structure will be defined according to the defined naming convention for rooms: Level-Department-Number


Space Name Builder

☑ Field separator -

Fields

Add Field...

Level

Custom Department

Number

Preview

MyLevel-Department Value-123

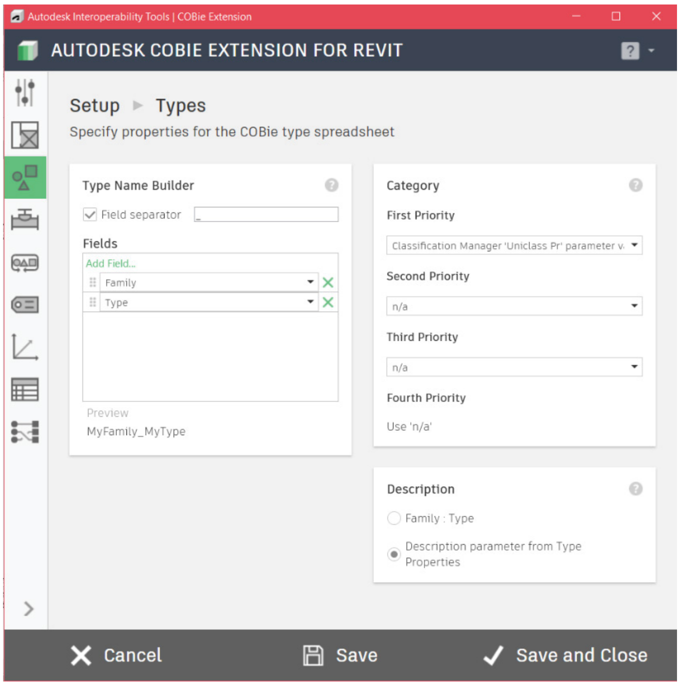
Spaces in Zones

● Each space listed in its own row

○ All spaces in one row, comma separated

Figure 25: Autodesk Interoperability Tools Name Builder

- Types: the type names will be built from the family name and family type name, which both should be following the defined naming convention.



Specify properties for the COBie type spreadsheet

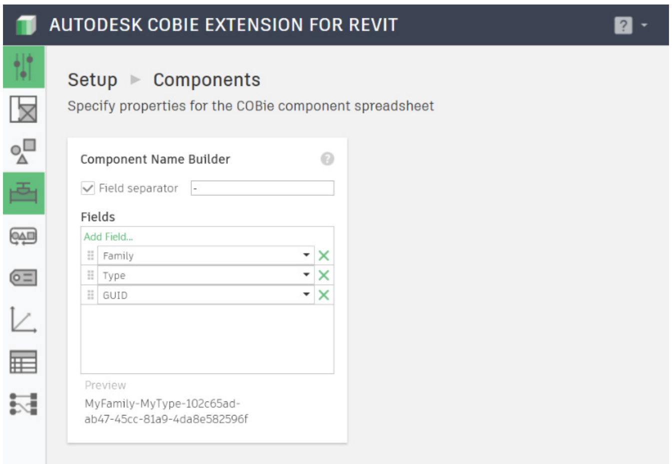
Type Name Builder
☑ Field separator: _
Fields
Add Field...
Family
Type
Preview
MyFamily_MyType

Category
First Priority: Classification Manager 'Uniclass Pr' parameter v
Second Priority: n/a
Third Priority: n/a
Fourth Priority: Use 'n/a'

Description
○ Family : Type
● Description parameter from Type Properties

Figure 26: Autodesk Interoperability Tools Type Setup

- Components: component names will follow the type name but with an added GUID for identification.



Specify properties for the COBie component spreadsheet

Component Name Builder
☑ Field separator: -
Fields
Add Field...
Family
Type
GUID
Preview
MyFamily-MyType-102c65ad-ab47-45cc-81a9-4da8e582596f

Figure 27: Autodesk Interoperability Tools Component Setup

- Contacts

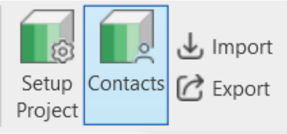
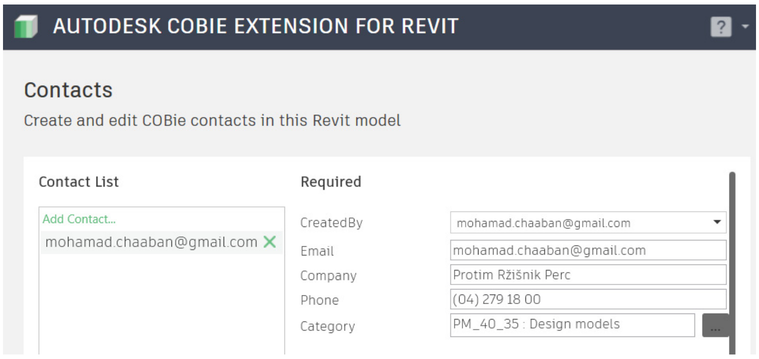


Figure 28: Asset Interoperability Tools Contacts Button

The contacts tab is what will be used to populate the CreatedBy parameter, where stakeholders are defined will all the necessary details.



Contacts

Create and edit COBie contacts in this Revit model

Contact List

Add Contact...

mohamad.chaaban@gmail.com ✕

Required

CreatedBy: mohamad.chaaban@gmail.com

Email: mohamad.chaaban@gmail.com

Company: Protim Ržišnik Perc

Phone: (04) 279 18 00

Category: PM_40_35 : Design models

Figure 29: Autodesk Interoperability Tools Contacts Setup

- Select

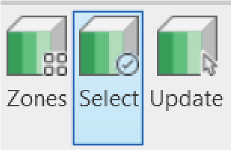
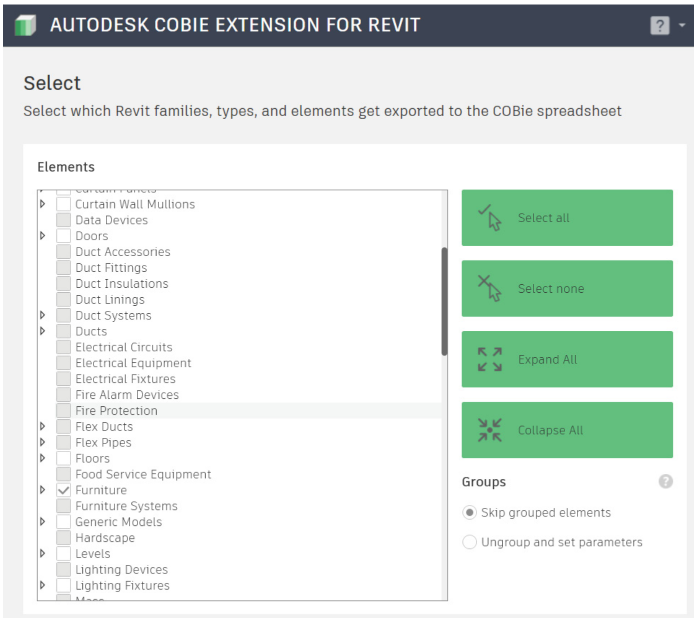


Figure 30: Autodesk Interoperability Tools Asset Selection Button

The select tab is for selecting which project elements will be populated with the previously defined information.


AUTODESK COBIE EXTENSION FOR REVIT

Select

Select which Revit families, types, and elements get exported to the COBie spreadsheet

Elements

- ☐ Curtain Wall Mullions
- ☐ Data Devices
- ☐ Doors
- ☐ Duct Accessories
- ☐ Duct Fittings
- ☐ Duct Insulations
- ☐ Duct Linings
- ☐ Duct Systems
- ☐ Ducts
- ☐ Electrical Circuits
- ☐ Electrical Equipment
- ☐ Electrical Fixtures
- ☐ Fire Alarm Devices
- ☐ Fire Protection
- ☐ Flex Ducts
- ☐ Flex Pipes
- ☐ Floors
- ☐ Food Service Equipment
- ☑ Furniture
- ☐ Furniture Systems
- ☐ Generic Models
- ☐ Hardscape
- ☐ Levels
- ☐ Lighting Devices
- ☐ Lighting Fixtures

Groups

- ● Skip grouped elements
- ○ Ungroup and set parameters

Figure 31: Autodesk Interoperability Tools Asset Selection

- Update

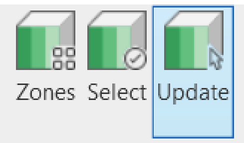
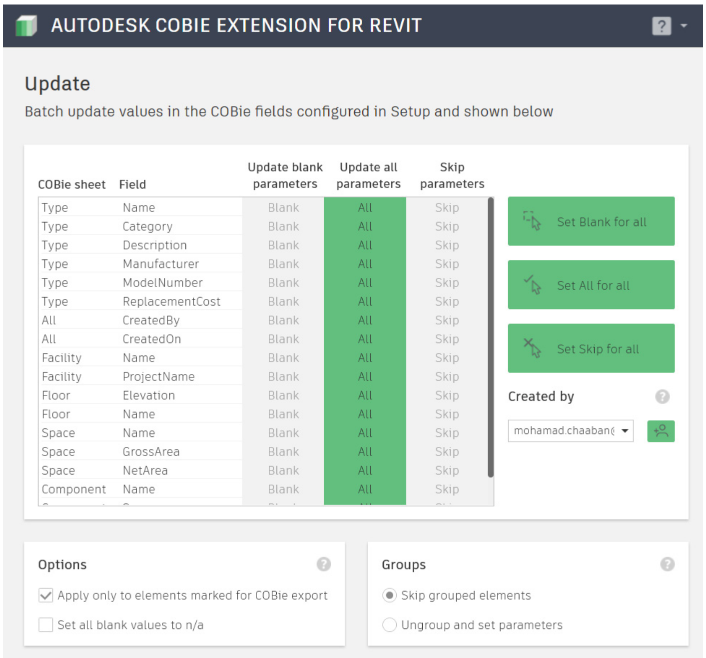


Figure 32: Autodesk Interoperability Tools Update Button

The update tab executes the defined project setup onto the selected assets.



Update

Batch update values in the COBie fields configured in Setup and shown below

COBie sheet	Field	Update blank parameters	Update all parameters	Skip parameters
Type	Name	Blank	All	Skip
Type	Category	Blank	All	Skip
Type	Description	Blank	All	Skip
Type	Manufacturer	Blank	All	Skip
Type	ModelNumber	Blank	All	Skip
Type	ReplacementCost	Blank	All	Skip
All	CreatedBy	Blank	All	Skip
All	CreatedOn	Blank	All	Skip
Facility	Name	Blank	All	Skip
Facility	ProjectName	Blank	All	Skip
Floor	Elevation	Blank	All	Skip
Floor	Name	Blank	All	Skip
Space	Name	Blank	All	Skip
Space	GrossArea	Blank	All	Skip
Space	NetArea	Blank	All	Skip
Component	Name	Blank	All	Skip

Created by: mohamad.chaaban(

Options

☑ Apply only to elements marked for COBie export

☐ Set all blank values to n/a

Groups

● Skip grouped elements

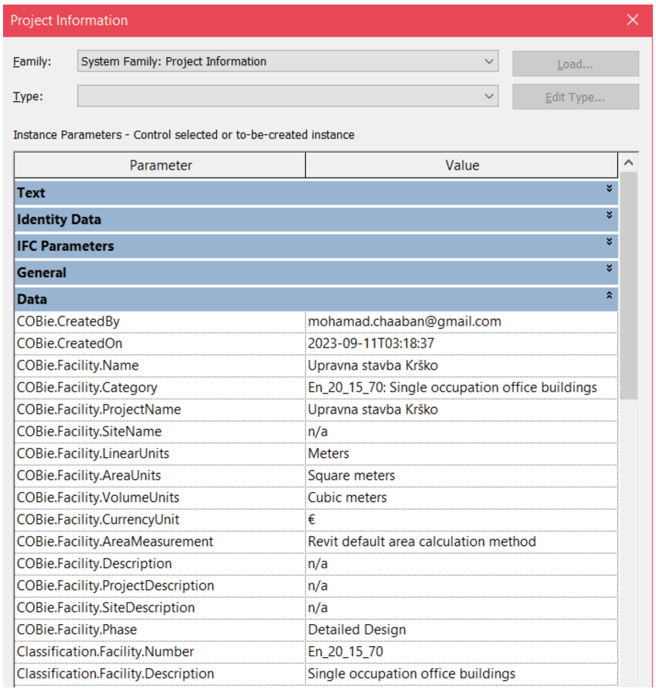
○ Ungroup and set parameters

Figure 33: Autodesk Interoperability Tools Asset Parameter Update Selection

Results of the population of the building information model are displayed in the following sections.

4.4.1 Project Information

Designer and Identity Information:



Family: System Family: Project Information

Type:

Instance Parameters - Control selected or to-be-created instance

Parameter	Value
Text	
Identity Data	
IFC Parameters	
General	
Data	
COBie.CreatedBy	mohamad.chaaban@gmail.com
COBie.CreatedOn	2023-09-11T03:18:37
COBie.Facility.Name	Upravna stavba Krško
COBie.Facility.Category	En_20_15_70: Single occupation office buildings
COBie.Facility.ProjectName	Upravna stavba Krško
COBie.Facility.SiteName	n/a
COBie.Facility.LinearUnits	Meters
COBie.Facility.AreaUnits	Square meters
COBie.Facility.VolumeUnits	Cubic meters
COBie.Facility.CurrencyUnit	€
COBie.Facility.AreaMeasurement	Revit default area calculation method
COBie.Facility.Description	n/a
COBie.Facility.ProjectDescription	n/a
COBie.Facility.SiteDescription	n/a
COBie.Facility.Phase	Detailed Design
Classification.Facility.Number	En_20_15_70
Classification.Facility.Description	Single occupation office buildings

Figure 34: Project Information in Revit

4.4.2 Asset Information

4.4.2.1 Sample Architectural Asset

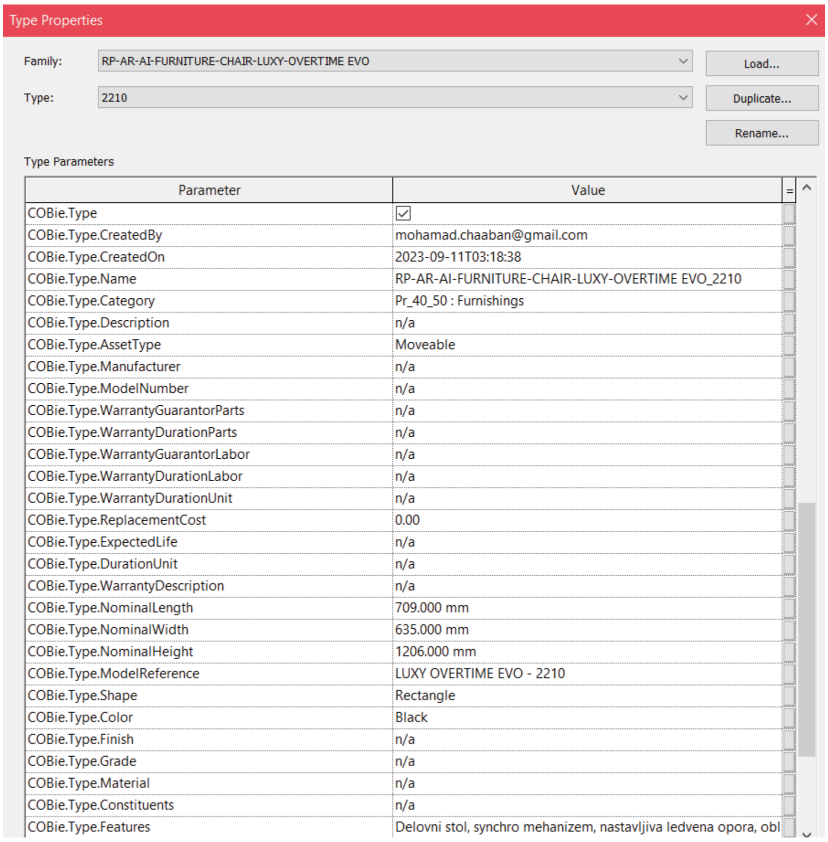
The asset discussed is an office chair.

Family Name: RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO

Family Type: 2210

Figure 35: Sample Architectural Chair 3D-View in Revit

Type Information:



Family: RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO

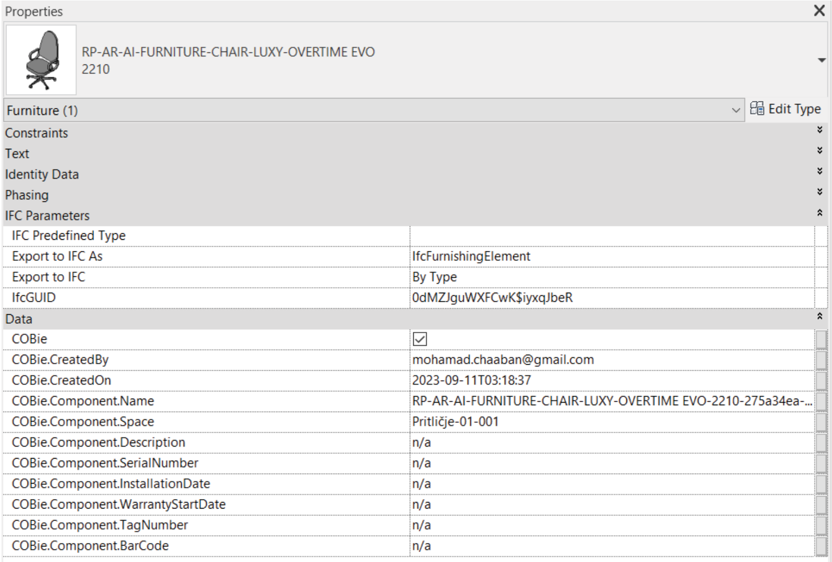
Type: 2210

Type Parameters

Parameter	Value
COBie.Type	☑
COBie.Type.CreatedBy	mohamad.chaaban@gmail.com
COBie.Type.CreatedOn	2023-09-11T03:18:38
COBie.Type.Name	RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO_2210
COBie.Type.Category	Pr_40_50 : Furnishings
COBie.Type.Description	n/a
COBie.Type.AssetType	Moveable
COBie.Type.Manufacturer	n/a
COBie.Type.ModelNumber	n/a
COBie.Type.WarrantyGuarantorParts	n/a
COBie.Type.WarrantyDurationParts	n/a
COBie.Type.WarrantyGuarantorLabor	n/a
COBie.Type.WarrantyDurationLabor	n/a
COBie.Type.WarrantyDurationUnit	n/a
COBie.Type.ReplacementCost	0.00
COBie.Type.ExpectedLife	n/a
COBie.Type.DurationUnit	n/a
COBie.Type.WarrantyDescription	n/a
COBie.Type.NominalLength	709.000 mm
COBie.Type.NominalWidth	635.000 mm
COBie.Type.NominalHeight	1206.000 mm
COBie.Type.ModelReference	LUXY OVERTIME EVO - 2210
COBie.Type.Shape	Rectangle
COBie.Type.Color	Black
COBie.Type.Finish	n/a
COBie.Type.Grade	n/a
COBie.Type.Material	n/a
COBie.Type.Constituents	n/a
COBie.Type.Features	Delovni stol, synchro mehanizem, nastavljiva ledvena opora, obl

Figure 36: Sample Architectural Chair Type Information in Revit

Component Information:



RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO
2210

Furniture (1)

Constraints
Text
Identity Data
Phasing
IFC Parameters

IFC Predefined Type	
Export to IFC As	IfcFurnishingElement
Export to IFC	By Type
IfcGUID	0dMZJguWXFCwK$iyxqJbeR
Data	
COBie	☑
COBie.CreatedBy	mohamad.chaaban@gmail.com
COBie.CreatedOn	2023-09-11T03:18:37
COBie.Component.Name	RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO-2210-275a34ea-...
COBie.Component.Space	Pritličje-01-001
COBie.Component.Description	n/a
COBie.Component.SerialNumber	n/a
COBie.Component.InstallationDate	n/a
COBie.Component.WarrantyStartDate	n/a
COBie.Component.TagNumber	n/a
COBie.Component.BarCode	n/a

Figure 37: Sample Architectural Chair Component Information in Revit

4.4.2.2 Sample Electrical Asset

The asset discussed is a LED suspended lighting fixture.

Family Name: RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED

Family Type: 2001

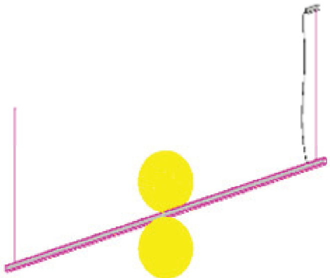
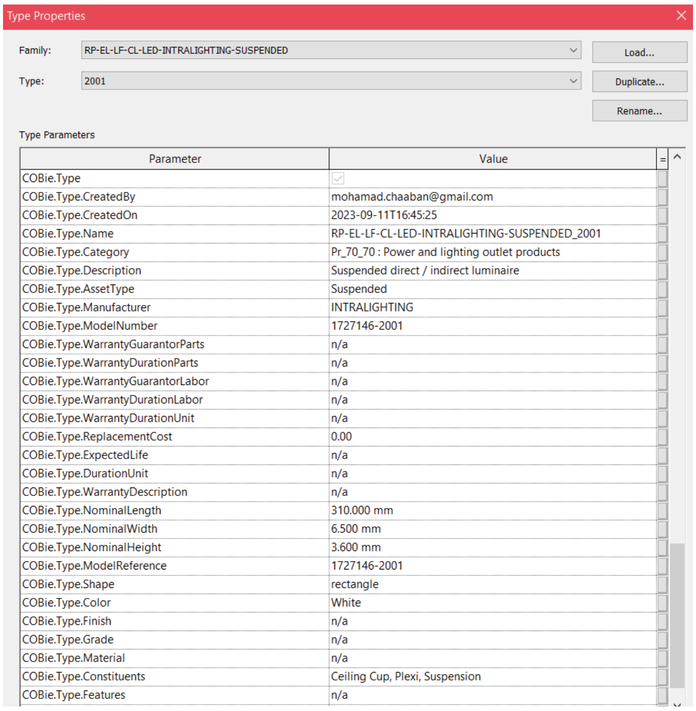


Figure 38: Sample Electrical Lighting Fixture 3D-View in Revit

Type Information:



Family: RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED

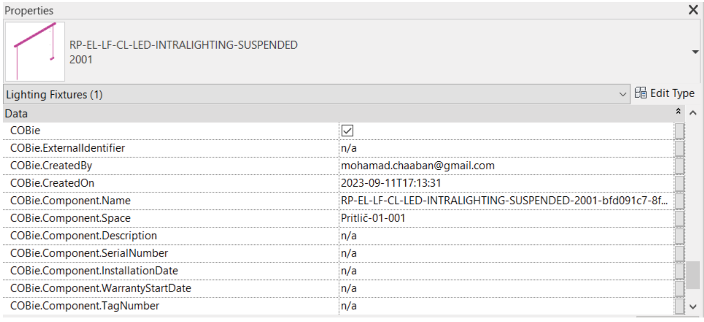
Type: 2001

Type Parameters

Parameter	Value
COBie.Type	☑
COBie.Type.CreatedBy	mohamad.chaaban@gmail.com
COBie.Type.CreatedOn	2023-09-11T16:45:25
COBie.Type.Name	RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED_2001
COBie.Type.Category	Pr_70_70 : Power and lighting outlet products
COBie.Type.Description	Suspended direct / indirect luminaire
COBie.Type.AssetType	Suspended
COBie.Type.Manufacturer	INTRALIGHTING
COBie.Type.ModelNumber	1727146-2001
COBie.Type.WarrantyGuarantorParts	n/a
COBie.Type.WarrantyDurationParts	n/a
COBie.Type.WarrantyGuarantorLabor	n/a
COBie.Type.WarrantyDurationLabor	n/a
COBie.Type.WarrantyDurationUnit	n/a
COBie.Type.ReplacementCost	0.00
COBie.Type.ExpectedLife	n/a
COBie.Type.DurationUnit	n/a
COBie.Type.WarrantyDescription	n/a
COBie.Type.NominalLength	310.000 mm
COBie.Type.NominalWidth	6.500 mm
COBie.Type.NominalHeight	3.600 mm
COBie.Type.ModelReference	1727146-2001
COBie.Type.Shape	rectangle
COBie.Type.Color	White
COBie.Type.Finish	n/a
COBie.Type.Grade	n/a
COBie.Type.Material	n/a
COBie.Type.Constituents	Ceiling Cup, Plexi, Suspension
COBie.Type.Features	n/a

Figure 39: Sample Electrical Lighting Fixture Type Information in Revit

Component Information:



RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED
2001

Lighting Fixtures (1)

Data

COBie	☑
COBie.ExternalIdentifier	n/a
COBie.CreatedBy	mohamad.chaaban@gmail.com
COBie.CreatedOn	2023-09-11T17:13:31
COBie.Component.Name	RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED-2001-bfd091c7-8f...
COBie.Component.Space	Pritlič-01-001
COBie.Component.Description	n/a
COBie.Component.SerialNumber	n/a
COBie.Component.InstallationDate	n/a
COBie.Component.WarrantyStartDate	n/a
COBie.Component.TagNumber	n/a

Figure 40: Sample Electrical Lighting Fixture Component Information in Revit

4.4.2.3 Sample Mechanical Asset

The asset discussed is an indoor part of a split fan coil unit.

Family Name: RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE

Family Type: 130

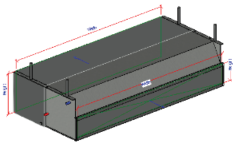
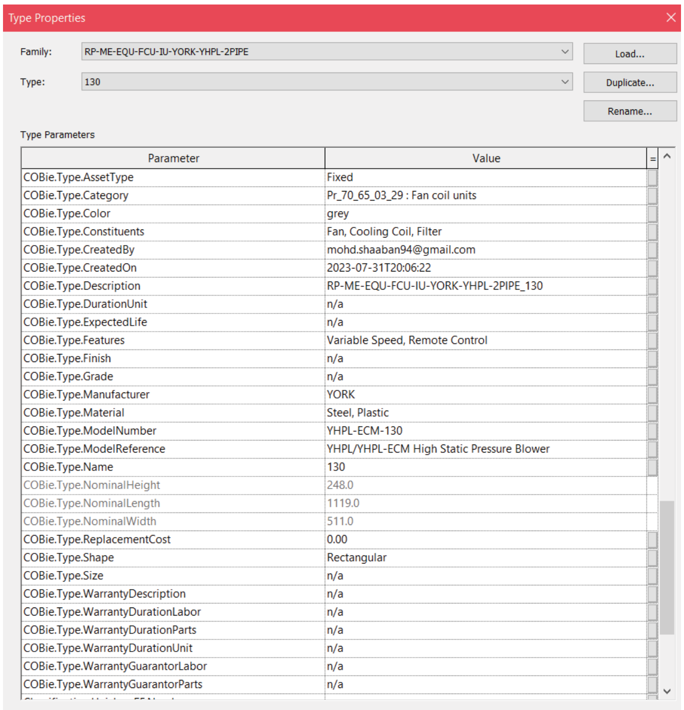


Figure 41: Sample Mechanical Fan Coil Unit 3D-View in Revit

Type Information:



Family: RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE

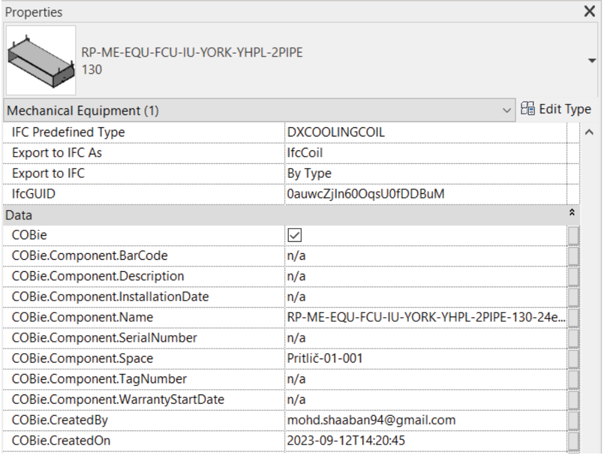
Type: 130

Type Parameters

Parameter	Value
COBie.Type.AssetType	Fixed
COBie.Type.Category	Pr_70_65_03_29 : Fan coil units
COBie.Type.Color	grey
COBie.Type.Constituents	Fan, Cooling Coil, Filter
COBie.Type.CreatedBy	mohd.shaaban94@gmail.com
COBie.Type.CreatedOn	2023-07-31T20:06:22
COBie.Type.Description	RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE_130
COBie.Type.DurationUnit	n/a
COBie.Type.ExpectedLife	n/a
COBie.Type.Features	Variable Speed, Remote Control
COBie.Type.Finish	n/a
COBie.Type.Grade	n/a
COBie.Type.Manufacturer	YORK
COBie.Type.Material	Steel, Plastic
COBie.Type.ModelNumber	YHPL-ECM-130
COBie.Type.ModelReference	YHPL/YHPL-ECM High Static Pressure Blower
COBie.Type.Name	130
COBie.Type.NominalHeight	248.0
COBie.Type.NominalLength	1119.0
COBie.Type.NominalWidth	511.0
COBie.Type.ReplacementCost	0.00
COBie.Type.Shape	Rectangular
COBie.Type.Size	n/a
COBie.Type.WarrantyDescription	n/a
COBie.Type.WarrantyDurationLabor	n/a
COBie.Type.WarrantyDurationParts	n/a
COBie.Type.WarrantyDurationUnit	n/a
COBie.Type.WarrantyGuarantorLabor	n/a
COBie.Type.WarrantyGuarantorParts	n/a

Figure 42: Sample Mechanical Fan Coil Unit Type Information in Revit

Component Information:



RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE
130

Mechanical Equipment (1)

IFC Predefined Type	DXCOOLINGCOIL
Export to IFC As	IfcCoil
Export to IFC	By Type
IfcGUID	0auwcZjIn60OqsU0fDDBuM
Data	
COBie	☑
COBie.Component.BarCode	n/a
COBie.Component.Description	n/a
COBie.Component.InstallationDate	n/a
COBie.Component.Name	RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE-130-24e...
COBie.Component.SerialNumber	n/a
COBie.Component.Space	Pritlič-01-001
COBie.Component.TagNumber	n/a
COBie.Component.WarrantyStartDate	n/a
COBie.CreatedBy	mohd.shaaban94@gmail.com
COBie.CreatedOn	2023-09-12T14:20:45

Figure 43: Sample Mechanical Fan Coil Unit Component Information in Revit

4.4.2.4 Sample Room Information

The sample room discussed is

Pritličje-01-001

Room Name: Meeting Room

2D View:

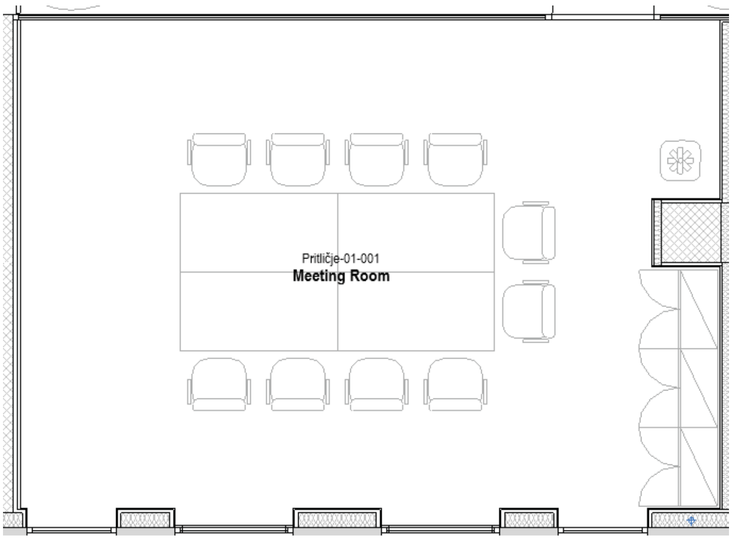


Figure 44: Sample Room 2D-View in Revit

3D View:

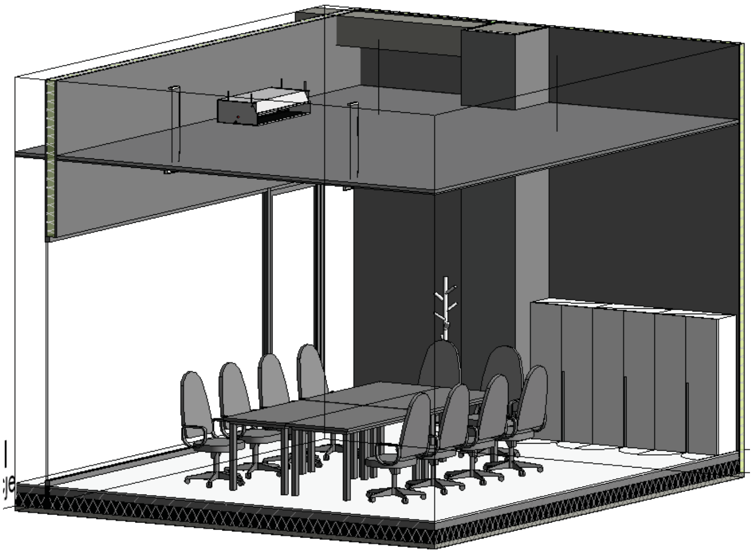
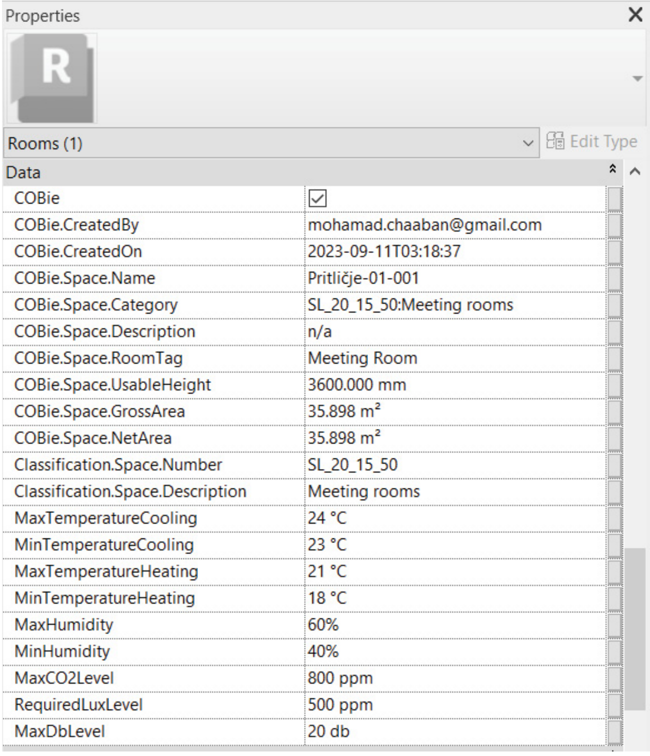


Figure 45: Sample Room 3D-View in Revit

Room Information:



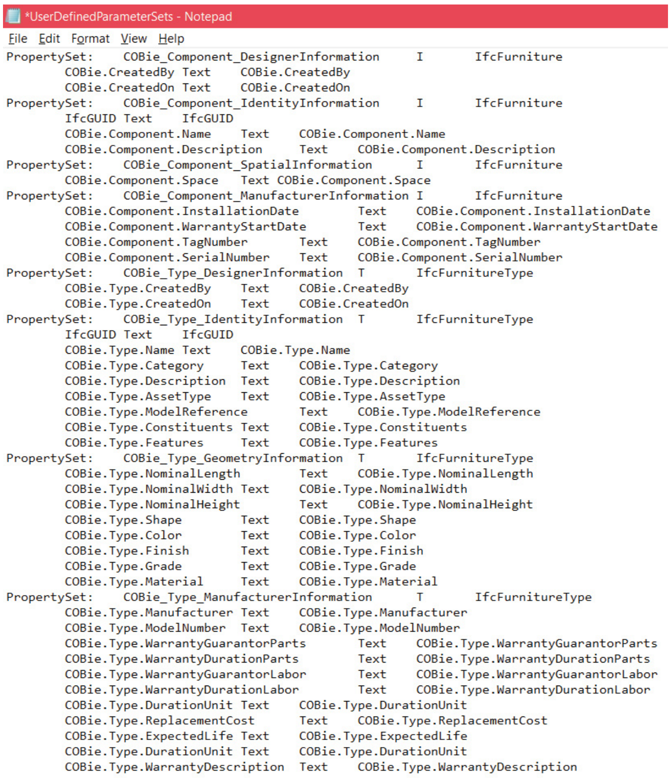
Data	
COBie	☑
COBie.CreatedBy	mohamad.chaaban@gmail.com
COBie.CreatedOn	2023-09-11T03:18:37
COBie.Space.Name	Pritličje-01-001
COBie.Space.Category	SL_20_15_50:Meeting rooms
COBie.Space.Description	n/a
COBie.Space.RoomTag	Meeting Room
COBie.Space.UsableHeight	3600.000 mm
COBie.Space.GrossArea	35.898 m²
COBie.Space.NetArea	35.898 m²
Classification.Space.Number	SL_20_15_50
Classification.Space.Description	Meeting rooms
MaxTemperatureCooling	24 °C
MinTemperatureCooling	23 °C
MaxTemperatureHeating	21 °C
MinTemperatureHeating	18 °C
MaxHumidity	60%
MinHumidity	40%
MaxCO2Level	800 ppm
RequiredLuxLevel	500 ppm
MaxDbLevel	20 db

Figure 46: Sample Room Information in Revit

4.4.3 Exporting ASIM

User defined parameter sets were used to export a filtered IFC file that only contains relevant information for the facility manager as defined by the LOIN.

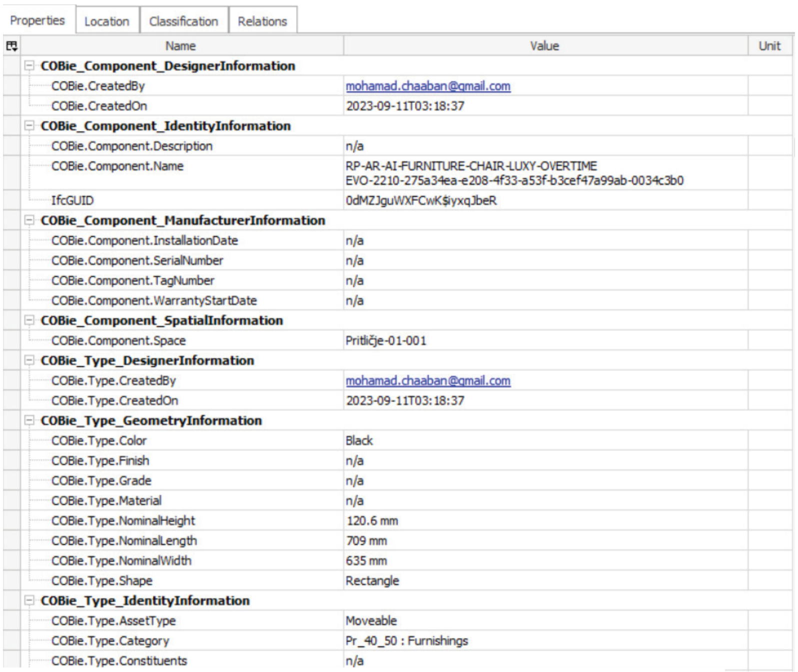
Sample Architectural File User Defined Parameter Sets:



```
PropertySet:    COBie_Component_DesignerInformation     I       IfcFurniture
        COBie.CreatedBy Text    COBie.CreatedBy
        COBie.CreatedOn Text    COBie.CreatedOn
PropertySet:    COBie_Component_IdentityInformation     I       IfcFurniture
        IfcGUID Text    IfcGUID
        COBie.Component.Name    Text    COBie.Component.Name
        COBie.Component.Description     Text    COBie.Component.Description
PropertySet:    COBie_Component_SpatialInformation      I       IfcFurniture
        COBie.Component.Space   Text COBie.Component.Space
PropertySet:    COBie_Component_ManufacturerInformation I       IfcFurniture
        COBie.Component.InstallationDate        Text    COBie.Component.InstallationDate
        COBie.Component.WarrantyStartDate       Text    COBie.Component.WarrantyStartDate
        COBie.Component.TagNumber       Text    COBie.Component.TagNumber
        COBie.Component.SerialNumber    Text    COBie.Component.SerialNumber
PropertySet:    COBie_Type_DesignerInformation  T       IfcFurnitureType
        COBie.Type.CreatedBy    Text    COBie.CreatedBy
        COBie.Type.CreatedOn    Text    COBie.CreatedOn
PropertySet:    COBie_Type_IdentityInformation  T       IfcFurnitureType
        IfcGUID Text    IfcGUID
        COBie.Type.Name Text    COBie.Type.Name
        COBie.Type.Category     Text    COBie.Type.Category
        COBie.Type.Description  Text    COBie.Type.Description
        COBie.Type.AssetType    Text    COBie.Type.AssetType
        COBie.Type.ModelReference       Text    COBie.Type.ModelReference
        COBie.Type.Constituents Text    COBie.Type.Constituents
        COBie.Type.Features     Text    COBie.Type.Features
PropertySet:    COBie_Type_GeometryInformation  T       IfcFurnitureType
        COBie.Type.NominalLength        Text    COBie.Type.NominalLength
        COBie.Type.NominalWidth Text    COBie.Type.NominalWidth
        COBie.Type.NominalHeight        Text    COBie.Type.NominalHeight
        COBie.Type.Shape        Text    COBie.Type.Shape
        COBie.Type.Color        Text    COBie.Type.Color
        COBie.Type.Finish       Text    COBie.Type.Finish
        COBie.Type.Grade        Text    COBie.Type.Grade
        COBie.Type.Material     Text    COBie.Type.Material
PropertySet:    COBie_Type_ManufacturerInformation      T       IfcFurnitureType
        COBie.Type.Manufacturer Text    COBie.Type.Manufacturer
        COBie.Type.ModelNumber  Text    COBie.Type.ModelNumber
        COBie.Type.WarrantyGuarantorParts       Text    COBie.Type.WarrantyGuarantorParts
        COBie.Type.WarrantyDurationParts        Text    COBie.Type.WarrantyDurationParts
        COBie.Type.WarrantyGuarantorLabor       Text    COBie.Type.WarrantyGuarantorLabor
        COBie.Type.WarrantyDurationLabor        Text    COBie.Type.WarrantyDurationLabor
        COBie.Type.DurationUnit Text    COBie.Type.DurationUnit
        COBie.Type.ReplacementCost      Text    COBie.Type.ReplacementCost
        COBie.Type.ExpectedLife Text    COBie.Type.ExpectedLife
        COBie.Type.DurationUnit Text    COBie.Type.DurationUnit
        COBie.Type.WarrantyDescription  Text    COBie.Type.WarrantyDescription
```

Figure 47: User Defined Parameter Sets for AIM Export

Sample Architecture IFC File Information:



Name	Value	Unit
COBie_Component_DesignerInformation		
COBie.CreatedBy	mohamad.chaaban@gmail.com	
COBie.CreatedOn	2023-09-11T03:18:37	
COBie_Component_IdentityInformation		
COBie.Component.Description	n/a	
COBie.Component.Name	RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO-2210-275a34ea-e208-4f33-a53f-b3cef47a99ab-0034c3b0	
IfcGUID	0dMZJguWXFCwK$iyxqJbeR	
COBie_Component_ManufacturerInformation		
COBie.Component.InstallationDate	n/a	
COBie.Component.SerialNumber	n/a	
COBie.Component.TagNumber	n/a	
COBie.Component.WarrantyStartDate	n/a	
COBie_Component_SpatialInformation		
COBie.Component.Space	Pritličje-01-001	
COBie_Type_DesignerInformation		
COBie.Type.CreatedBy	mohamad.chaaban@gmail.com	
COBie.Type.CreatedOn	2023-09-11T03:18:37	
COBie_Type_GeometryInformation		
COBie.Type.Color	Black	
COBie.Type.Finish	n/a	
COBie.Type.Grade	n/a	
COBie.Type.Material	n/a	
COBie.Type.NominalHeight	120.6 mm	
COBie.Type.NominalLength	709 mm	
COBie.Type.NominalWidth	635 mm	
COBie.Type.Shape	Rectangle	
COBie_Type_IdentityInformation		
COBie.Type.AssetType	Moveable	
COBie.Type.Category	Pr_40_50 : Furnishings	
COBie.Type.Constituents	n/a	

Figure 48: Sample Exported AIM Information

4.5 Uploading Information to AIM

The BIM connector feature of Ecodomus is used to upload the information from the IFC ASIM model to the CDE.

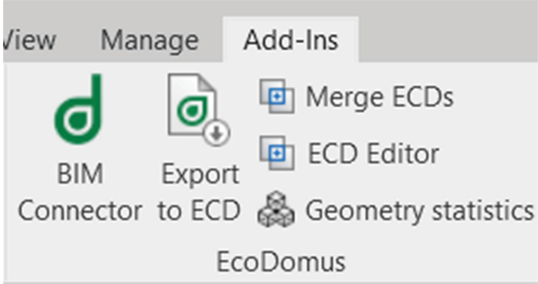
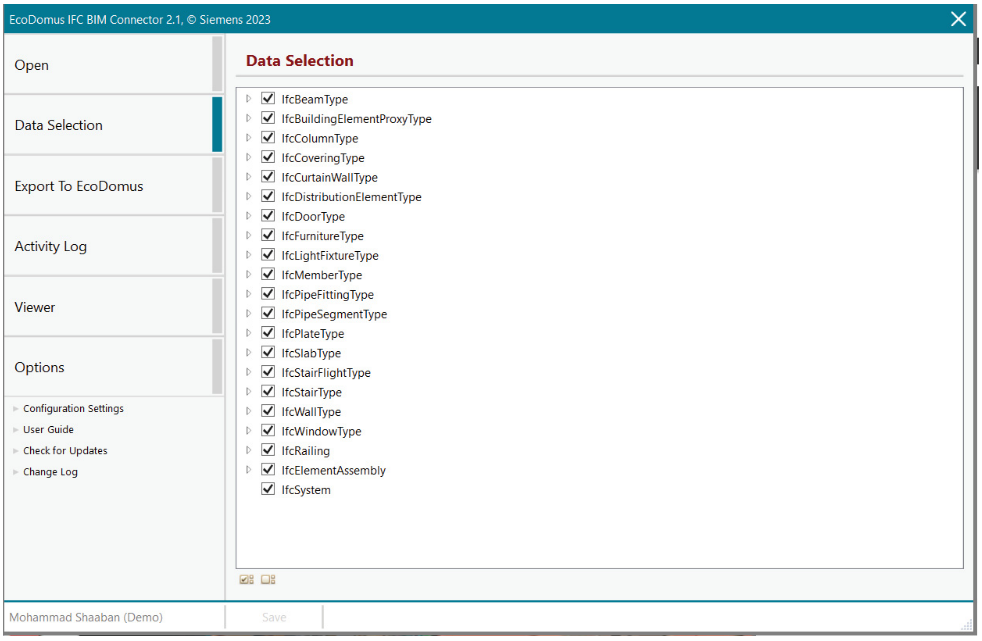


Figure 49: Ecodomus Revit Add-In

To export the model information to the Ecodomus server, the information is first selected using the “Data Selection” button, where assets can be specified using the IFC schema.

Warning: The computer program is protected by copyright law and international treaties. Unauthorized reproduction or distribution of this program, or any portion of it, may result in severe civil and criminal penalties, and will be prosecuted under the maximum extent possible under law.

Figure 50: BIM Connector Interface



Data Selection

- ☑ IfcBeamType
- ☑ IfcBuildingElementProxyType
- ☑ IfcColumnType
- ☑ IfcCoveringType
- ☑ IfcCurtainWallType
- ☑ IfcDistributionElementType
- ☑ IfcDoorType
- ☑ IfcFurnitureType
- ☑ IfcLightFixtureType
- ☑ IfcMemberType
- ☑ IfcPipeFittingType
- ☑ IfcPipeSegmentType
- ☑ IfcPlateType
- ☑ IfcSlabType
- ☑ IfcStairFlightType
- ☑ IfcStairType
- ☑ IfcWallType
- ☑ IfcWindowType
- ☑ IfcRailing
- ☑ IfcElementAssembly
- ☑ IfcSystem

Figure 51: Selection of Assets

Then the IFC model is uploaded to the CDE from the Ecodomus menu, where it gets associated with the information previously uploaded through the BIM connector.

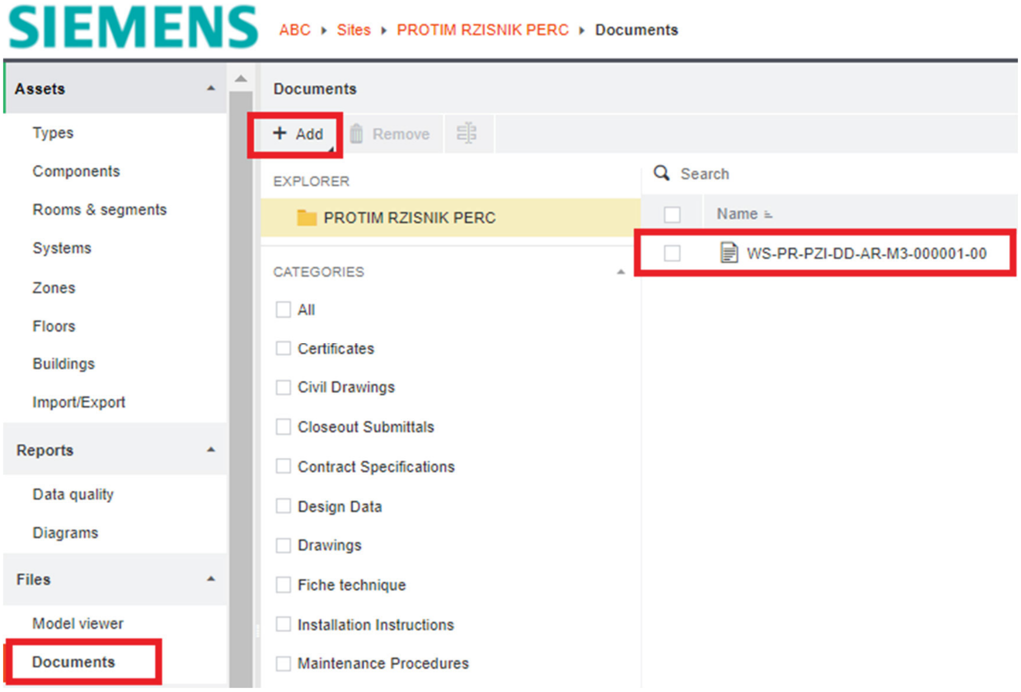
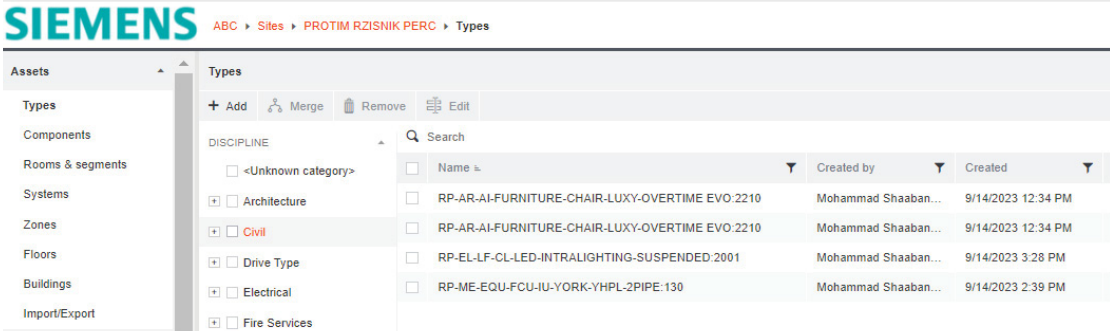


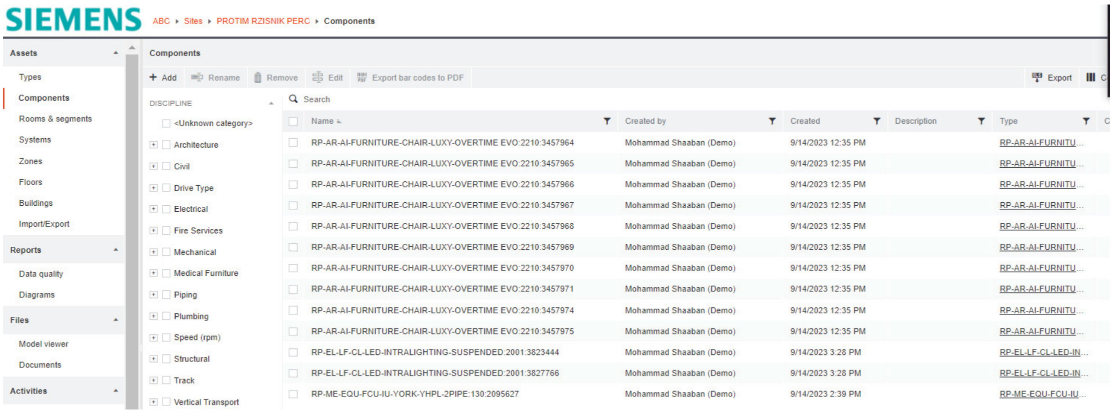
Figure 52: Uploading the IFC Model to Ecodomus

Figure 53: 3D-Model Geometry Viewing in Ecodomus



Name	Created by	Created
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210	Mohammad Shaaban...	9/14/2023 12:34 PM
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210	Mohammad Shaaban...	9/14/2023 12:34 PM
RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED:2001	Mohammad Shaaban...	9/14/2023 3:28 PM
RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE:130	Mohammad Shaaban...	9/14/2023 2:39 PM

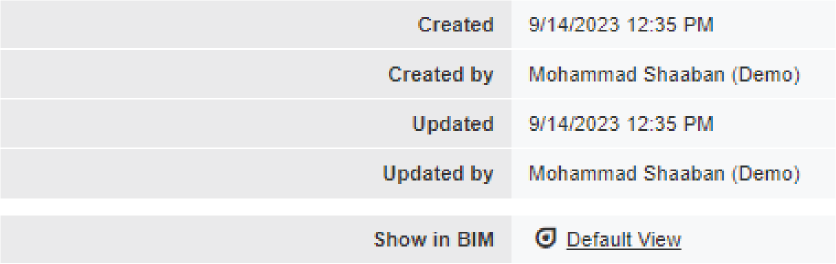
Figure 54: Uploaded Asset Types Displayed in Ecodomus



Name	Created by	Created	Description	Type
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457964	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457965	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457966	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457967	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457968	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457969	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457970	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457971	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457974	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457975	Mohammad Shaaban (Demo)	9/14/2023 12:35 PM		RP-AR-AI-FURNITU...
RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED:2001:3823444	Mohammad Shaaban (Demo)	9/14/2023 3:28 PM		RP-EL-LF-CL-LED-IN...
RP-EL-LF-CL-LED-INTRALIGHTING-SUSPENDED:2001:3827766	Mohammad Shaaban (Demo)	9/14/2023 3:28 PM		RP-EL-LF-CL-LED-IN...
RP-ME-EQU-FCU-IU-YORK-YHPL-2PIPE:130:2095627	Mohammad Shaaban (Demo)	9/14/2023 2:39 PM		RP-ME-EQU-FCU-IU...

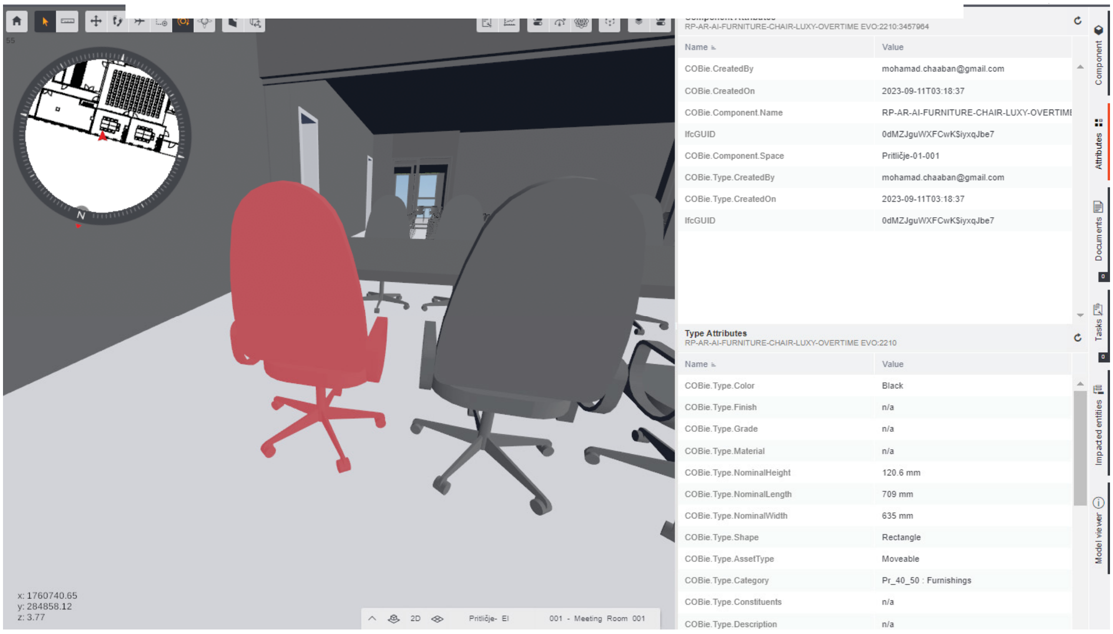
Figure 55: Uploaded Asset Components Displayed in Ecodomus

Assets have a "Show in BIM" functionality that takes the user to the asset's location in the model.



Created	9/14/2023 12:35 PM
Created by	Mohammad Shaaban (Demo)
Updated	9/14/2023 12:35 PM
Updated by	Mohammad Shaaban (Demo)
Show in BIM	Default View

Figure 57: "Show in BIM" Feature in Ecodomus



RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210:3457964

Name	Value
COBie.CreatedBy	mohamad.chaaban@gmail.com
COBie.CreatedOn	2023-09-11T03:18:37
COBie.Component.Name	RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME
IfcGUID	0dMZJguWXFCwK$iyxqJbe7
COBie.Component.Space	Pritličje-01-001
COBie.Type.CreatedBy	mohamad.chaaban@gmail.com
COBie.Type.CreatedOn	2023-09-11T03:18:37
IfcGUID	0dMZJguWXFCwK$iyxqJbe7

Type Attributes
RP-AR-AI-FURNITURE-CHAIR-LUXY-OVERTIME EVO:2210

Name	Value
COBie.Type.Color	Black
COBie.Type.Finish	n/a
COBie.Type.Grade	n/a
COBie.Type.Material	n/a
COBie.Type.NominalHeight	120.6 mm
COBie.Type.NominalLength	709 mm
COBie.Type.NominalWidth	635 mm
COBie.Type.Shape	Rectangle
COBie.Type.AssetType	Moveable
COBie.Type.Category	Pr_40_50 : Furnishings
COBie.Type.Constituents	n/a
COBie.Type.Description	n/a

Figure 56: Viewing the Asset and Its Corresponding Information in Ecodomus

4.6 Defining ADIM

A sample sensor will be used, which is a room temperature sensor, is defined in Ecodomus with the below parameters:

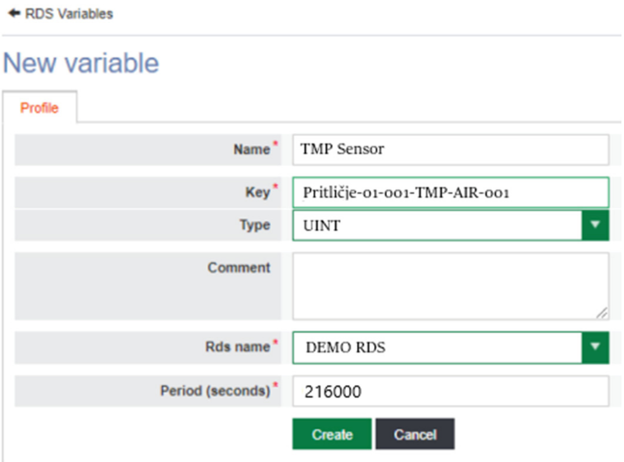
Name: TMP Sensor

Key: Pritličje-01-001-TMP-AIR-001

Type: UINT

RDS name: Demo RDS

Period: 216,000



New variable

Name*	TMP Sensor
Key*	Pritličje-01-001-TMP-AIR-001
Type	UINT
Comment	
Rds name*	DEMO RDS
Period (seconds)*	216000

Figure 58: Defining the Sample RDS in Ecodomus

The rest of the information required for the ADIM is to be completed at the construction phase, where it is only possible to information such as the "Host", "Server", "Protocol", etc. once the sensors have been procured and the BMS system has been established.

4.7 Integrating ASIM and ADIM Within AIM

Ecodomus has multiple features that allow integration between static and dynamic asset information.

- Remote data service labels can be placed in the model viewer, which allows for functionalities such as placing the value of the temperature sensor that is monitoring this room in the actual room itself.

Figure 59: Integrating RDS with BIM Model

- Diagrams can be created to overlay remote data service labels with 2D design drawings or riser diagrams, where information coming from ASIM can be integrated with sensor data. Having this kind of integrated approach allows the live comparison of operational information with required designed information.

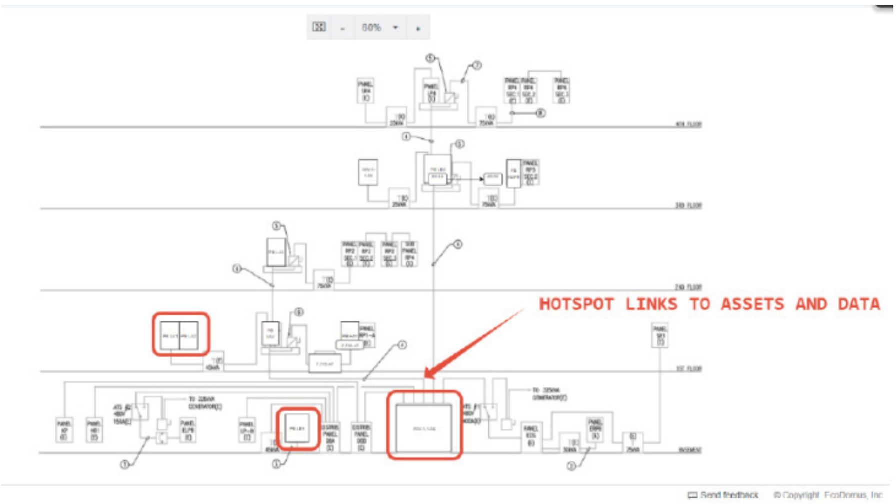


Figure 60: Integrating RDS with 2D-Diagrams and Schedules

5 RESULTS, ASSESSMENT, AND FUTURE WORKS

5.1 Results

Requirements Category	Details	Achievement Status
ISO Compliant Documentation	Production of reports and collection of documentation for ISO 9001, ISO 14001, ISO 45001.	Achieved through Ecodomus. All kinds of documents and information can be uploaded to Ecodomus in addition to the generation of different kinds of reports.
	Recording of construction phase data.	
	Recording of construction subcontractor records.	
	Production of reports in formats suitable for standardization bodies.	
Facility Management Requirements	Monitoring of environmental conditions.	Partially achieved through developing proper information requirements for the asset dynamic information models. The RDS instances are integrated in Ecodomus where all information is recorded. Setting up the RDS is only possible in the construction phase which is why this feature was not implemented fully.
	Recording of external illuminance measurements.	
	Recording of ambient noise measurements.	
	Recording of tests on the operation of security lighting and fire detectors.	
	Recording of inspections of the MEP systems.	
	Recording of leakage checks of gas installations.	
	Providing alerts on necessary equipment inspections (preventive and reactive maintenance).	Achieved through the proper development of ASIM. The integration of the ASIM with Ecodomus allows the organization of the maintenance of assets in addition to enabling preventive maintenance by being able to set alerts on dynamic asset information according to the designed performance static information.
	Providing equipment inspection order.	

	Inputting and storing of inspection certificate data, warranty certificates, and invoices.	Achieved through Ecodomus. All kinds of documents can be uploaded and organized in one centralized common data environment. Also, Information is organized in the home page of the facility where customizable information can be displayed as a summary of asset notifications, activity schedule, etc.
	Allowing the digital signing of completed jobs.	
	Recording of subcontractor trail.	
	Recording of facility visits.	
	Reserving facility premises.	
	Displaying information in a bulletin board display.	
BMS Requirements	Connecting to the BMS system via BACnet, ModBus, etc.	Not achieved in this phase as it is only possible to implement this once the facility has been constructed. However, Ecodomus does have the feature that allows the integration of the BMS system into the common data environment.
	Monitoring and control of lighting, shading, space cooling/heating, Air quality, ventilation.	
	Collecting information from all subsystems, sensors, and devices into a central facility server system. Accessing information from the central system and allowing the configuration and editing of database parameters.	
General Requirements	Eliminating the need for physical file storage.	Achieved through using Ecodomus as a centralized CDE.
	Allowing access to the API. Integrating data with enterprise resource planning.	Not achieved as Ecodomus is a propriety software with closed source API.
	Viewing of 2D schematics simultaneously along with 3D viewing of the model.	Achieved through Ecodomus model and document navigation mode.

Table 40: Achievement Status of Facility Manager Requirements

5.2 Workflow Assessment

Workflow Goals	**What Was Achieved**	**Obstacles Faced**	**Oppurtunities For Furture Solutions**
Integrating client facility management requirements and organization requirements	AIM requirements were successfully developed in coordination with facility manager	FMM functionalities are very broad and are hard to define at an early stage due to lack of understanding of what exact FMM functions are required for a certain facility.	FMM functionalities and their respective BIM requirements need to be better standardized and translated into BIM uses in a more specfic manner. Having a more detailed and standardized format will help facility managers better define what their requirements are and accordingly what BIM information requirements are
Standardized naming convention	Naming convention was developed according to ISO standards.	There is a lack of standardization of discipline name abbreviation, asset name abbreviation, space naming, etc. This comes from the fact that each organiziation has its own requirements and workflows. The result is too many naming standards which hinders interoperability between different stakeholders and compliance checking rules.	Universalizing naming standards for the AECO industry by an internationally reconigzed institue such as ISO would address this issue and minimize discrepancies between different naming conventions.

Static information model (BIM) structure	Adopting a CDE
Client requirements were successfully translated into asset information requirements, with a level of information need properly developed for project information, asset information, and room information. Also parameters were successfully created and filled with required information. The Autodesk BIM interoperability tool was used to create the parameters and populate the model with the information required.	The required functionalities of the CDE were defined and accordingly Ecodomus was chosen as the designated CDE for the case study.
The problem with Autodesk BIM interoperability tools is mainly with the lack of customization and flexibility with what parameters should be added and how they are mapped to exisitng parameters, resulting in some necesssary workarounds and manual input of information.	Being a propriety software is a major drawback as it requires licensing costs, dependency on vendor, lack of source code transparency, limited customization, etc.
Using Dynamo to create the parameters and map them to the existing Revit properties is more flexible and allows for more a more customized and streamlined work.	Given that the requirements of what a digital twin CDE should provide are well defined, developing an open source CDE that is based on open standards is a strongly viable solution that would address the cost issue, customization, transparency, and demand community collaboration.

Compliance checking	Dynamic information model (RDS) structure
Semantic compliance checks are enabled through following a well structured naming convention. Heirachal rule checks that are built on the semantics of asset information structures can be created in Ecodomus.	Client requirements were successfulyl translated into RDS information requirements with a level of information need properly developed for identity, network, and measurement information.
Creating compliance checks takes up alot of time as the interface does not allow batch creation of rules. This is somehow managed as compliance checks can be imported from one project to another; however, the initial creation of the rules is tedious.	Sensor information had to be created and populated manually on Ecodomus. This could be very tedious when it comes to large project as a huge numebr of RDS would need to be defined and manually inputted, which is not very efficieny, is prone to error, and takes alot of time.
Through the development of an open source CDE, important features such as batch creation of compliance rule checks or importing rules from spreadsheets, etc.	Through the development of an open source CDE, important features such as automating the creation and population of sensor information by either parameter mapping or allowing the import of data from spreadsheets would streamline the RDS information process.

Table 41: Workflow Assessment

5.3 Future Works

The main obstacle in this entire workflow was being limited with the proprietary features of Ecodomus. Although it provided most of the required features; however, the limited customizability, license requirement, and lack of feature flexibility complicates the process and hinders the overall smoothness and efficiency of such a workflow. This can be addressed in the future by developing open source digital twin environment that is community driven and can perform all required features, given that such features are now in high demand in the market and the operation phase of a building lifecycle garnering a lot of attention in the industry.

6 CONCLUSION

The literature reviewed spans the ontology of BIM, FM, IoT and is meant to capture the core enabling information components and CDE requirements that allow them to be integrated into what is known as a digital twin. Although there is a decent amount of research regarding the integration of BIM and FM, there is a lack of standardized workflows for stakeholders to adopt that can improve their current practices. This thesis sets out to develop a structured standard-adhering workflow that sets the groundwork for developing a BIM model rich with relevant FM-information that facilitates its integration into a digital twin environment.

The methodology proposes the BIM to DTw framework in a hierarchal step by step process that aims to leverage the semantic properties of assets in BIM for facility management operations. The first step in developing this framework was to define the requirements that would ensure meeting its goals. These requirements are achieved in a step by step process that is summarized in the following figure:

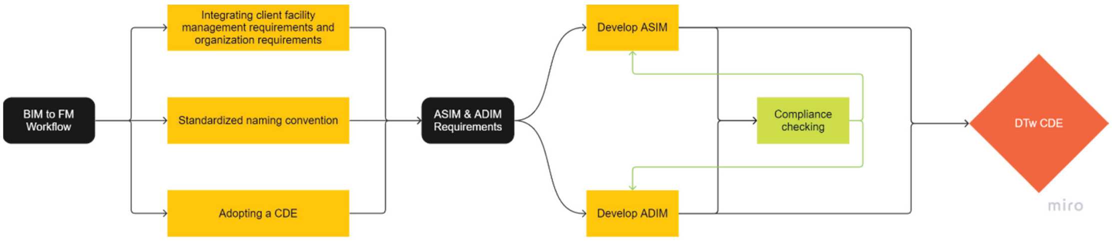


Figure 61: BIM to FM Workflow Process Summary

The main pillar of this workflow is the different standards (ISO, COBie, OpenBIM) used that enhance the quality of work, facilitate interoperability, provide time and cost saving, and boast credibility. Moreover, these standards were used to organize the process of information requirements exchange with the client's facility manager, develop a standardized naming convention, and define DTw CDE requirements. Then, a standardized naming convention was developed that characterized all kinds of documents and assets with unique identifiers that follow a hierarchical structure with clear abbreviations, which adds a layer of structure and organization when uploading the documents to the CDE and allows the facility manager to properly manage facility information. This was followed with defining the requirements for the CDE that enable it to act as a successful DTw environment, which can be summarized by acting as a customizable centralized data repository, integrating ASIM (BIM Models) and ADIM (RDS information), providing standard based interoperability, organizing project handover documents, issuing and storing facility management and maintenance tasks, having web and mobile accessibility, and sufficient security measures. The next step was to define the ASIM and ADIM requirements, covering all kind of information that could be required for an asset by the facility manager to properly cover its management and maintenance process, which includes project information, designer information, identity information, spatial information, geometrical information, manufacturer information, environmental information, measurement information, and network information.

The above was then applied onto a case study, showcasing the importance of having such a workflow in the organization of information and the management and maintenance of assets for a DTw environment.

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