# Data Quality Assessment of BIM Models for Facility Management

by

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## RÉSUMÉ

Malgré les avantages potentiellement importants que la modélisation des données du bâtiment (BIM) a à offrir dans la phase d'exploitation des installations (O&M), l'industrie n'a jusqu'à présent principalement mis en œuvre le BIM que dans les phases de conception et de construction. Cela peut être dû aux problèmes suivants: même si les modèles BIM tels que construits sont transmis à la livraison du projet, les propriétaires et les opérateurs possèdent rarement l'expertise nécessaire pour les utiliser et les mettre à jour efficacement; ensuite, les normes de l'industrie ne contiennent pas de lignes directrices précises pour assurer la facilité d'utilisation, l'interopérabilité et la maintenabilité, pour une utilisation efficace des modèles; enfin, comme ces modèles sont principalement développés pour les phases de conception et de construction, ils contiennent généralement trop de détails superflus et manquent d'informations nécessaires à l'exploitation du bâtiment.

Ainsi, ce projet étudie une méthode pour faire correspondre les modèles tels que construits avec les exigences O&M, en utilisant des procédures et des outils automatisés pour faciliter les activités de gestion de la qualité en créant des modèles BIM pour la gestion des installations (FM-BIM). Pour ce faire, une liste de contrôle complète des informations qui doivent être présentes dans les modèles BIM à la livraison et des éléments inutiles pouvant être purgés a été créée. Cette liste de contrôle fait partie d'un cadre de qualité global qui combine l'assurance qualité et le contrôle qualité pour fournir des modèles utilisables pour les opérations. De plus, une procédure et un ensemble d'outils ont été étudiés pour appliquer automatiquement les éléments de la liste de contrôle aux modèles tels que construits. Enfin, un flux de processus est présenté pour aider dans les activités de gestion de la qualité pendant le développement des modèles et pour les préparer à leur transfert.

Pour vérifier l'applicabilité des outils développés et des procédures proposées, des modèles de projets de construction réels ont été utilisés dans des expériences conçues.

**Mots-clés :** BIM, Gestion des Installations, Contrôle Qualité, Assurance Qualité, Requis d’Information

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## ABSTRACT

Despite the potentially significant benefits Building Information Modeling (BIM) has to offer in the facility operation and maintenance (O&M) phase, the industry has thus far only mainly implemented BIM in the design and construction phases. This may be due to the following issues: even though as-built BIM models are delivered at the handover stage, owners and operators rarely possess the expertise needed to efficiently use and update them; industry standards do not contain precise guidelines to ensure the ease of use, interoperability, and maintainability, for an efficient and effective utilization of models; and, as these models are mainly developed for the design and construction phases, they usually contain too many superfluous details and lack information required for the building's operations.

Thus, this research investigates delivering correspondences between as-built models and O&M requirements, using procedures and automated tools to facilitate quality management activities for creating BIM models for Facility Management (FM-BIM). To achieve this, a comprehensive checklist of information that must be present in the BIM models at the handover stage and of the unnecessary items that can be purged was created. This checklist is part of an overall quality framework that combines quality assurance and quality control to deliver usable models for operations. Additionally, a procedure and a set of tools have been investigated to automatically apply the items of the checklist on as-built models. Finally, a process flow is presented to assist in quality management activities during the development of the models and to prepare them for handover.

To verify the applicability of the developed tools and the proposed procedures, models of real construction projects were used in designed experiments.

**Keywords:** BIM, Facility Management, Quality Control, Quality Assurance, Information Requirements

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| | |
|---|---|
| ABAB | Australian BIM Advisory Board |
| AIQS & NZIQS | Australian/New-Zealand Institute of Quantity Surveyors |
| AIR | Asset Information Requirements |
| AIM | Asset Information Model |
| AM | Asset Management |
| BEP | BIM Execution Plan |
| BIM | Building Information Modelling |
| BMP | BIM Management Plan |
| CAFM | Computer Aided Facility Management |
| CMMS | Computerized Maintenance Management System |
| COBie | Construction Operation Building information exchange |
| EIR | Exchange Information Requirements |
| FM | Facility Management |
| FMS | Facility Management System |
| GSA | General Service Administration |
| IAM | Institute of Asset Management |
| IFC | Industry Foundation Classes |
| IR | Information Requirements |
| IWMS | Integrated Workplace Management System |
| LOD | Level of Detail |
| LOI | Level of Information |

| | |
|---|---|
| MEPF | Mechanical, Electrical, Plumbing, Fire Protection |
| MVD | Model View Definition |
| NIBS | National Institute of Building Sciences |
| NIST | National Institute of Standards and Technology |
| O&M | Operations and Maintenance |
| OIR | Owner Information Requirements |
| PAS | Publicly Available Standards |
| PIM | Project Information Model |
| PIR | Project Information Requirements |
| PM | Project Management |
| PSU | Penn State University |
| QA | Quality Assurance |
| QC | Quality Control |
| QM | Quality Management |

# INTRODUCTION

Building Information Modeling (BIM) consists of the creation of a digital representation of the physical and functional characteristics of a facility (National Institute of Building Sciences, 2015b). As an integrated database of coordinated, consistent, and computable information (Ramesh, 2016), BIM can drastically improve the quality of construction projects by bringing together technology, process improvements and digital information (Fallon et al., 2007).

BIM-models include objects whose properties describe geometrical dimensions, materials, finishes, specifications, manufacturer, price, and also relationships with other objects, such as the location of the objects within rooms of the facility (ADEB-VBA, 2015). Additionally, since BIM information is reused throughout the lifecycle as a single source of truth, it results in less errors and greater consistency, clarity, and accuracy (Kivits & Furneaux, 2013). Provided that BIM capabilities are correctly exploited and explicitly defined, BIM enables improved collaboration between designers, engineers, constructors, and facility managers across the life cycle (Kivits et al., 2013), which results in maximized efficiency, improved information exchanges, and a reduction of costs (Vega Völk, 2017).

This is why many governmental and public organizations (e.g., Smithsonian, 2018; Société Québécoise des Infrastructures, 2016; The Ohio State University, 2019a; US Department of Veterans Affairs, 2017a) have started to mandate the use of BIM for new projects to improve productivity and information management.

According to the NIST (Gallaher et al., 2004), the major benefit of BIM lies in the cross-platform interoperability it offers for data transfer and its ability to centralize asset management information. The report identifies a current lack of integration between project management (PM) and asset management (AM) and sees the lack of information capture and transfer as one of the main reasons why owners are unable to carry out proper maintenance activities. The objectives, operation modes, disciplines and practices associated with PM and AM differ in several aspects (IAM, 2015), mainly due to the fact that the project (temporary) is traditionally separated from the operation (permanent).

BIM has thus far mainly been used in the design and construction phases (Heaton et al., 2019). However, major benefits could be obtained during the Operation and Maintenance (O&M) phase by improving various processes (Motamedi et al., 2018) and providing a repository of detailed information of the built asset. BIM can be used during operations to populate facility operations databases with both geometry and parameters, thus supporting information technology used by owners' organizations (Pishdad-Bozorgi et al., 2018). Other useful features provided by BIM for O&M are visual information on the location of assets, relationships between these assets, and a history of maintenance activities (Motamedi et al., 2014).

Given that BIM can be used for O&M, an increasing number of owners would like to have complete and useful BIM models at the end of the construction project (Becerik-Gerber et al., 2012). However, while the commissioning and handover processes of delivering physical assets is very well defined, there is a lack of standards, guidelines, or procedures for digital project delivery. This makes it difficult for owners to, for instance, defining deliverables (Thabet & Lucas, 2017).

Although owners are increasingly aware of the BIM opportunities for facility operations, they seldom know which information should be required (Cavka et al.,2017). On the other hand, designers are not familiar with operations requirements, consequently, they too do not know what information they should deliver (Kensek, 2015). Additionally, the gap in the definition of the requirements makes the quality management process inefficient, as there is no adequate reference to define and assess the quality of the model's content. As a result, the delivered models often lack relevant information and contain superfluous data, thus cannot be readily used by the operators.

A lack of guidelines can lead to a loss of important data such as information from the design and construction phases. For the models to be useful, it is crucial that the information and quality requirements be thoroughly defined and meet quality management processes. In fact, the designers and engineers will benefit from having standard procedures and tools as these will help them create useful models for operations and make it possible for them to perform quality control (QC) before delivering digital information.

The abovementioned problems raise the following research questions:

**RQ1: What are the data quality dimensions related to BIM deliverables?**

Quality dimensions illustrates the general needs of owners in terms of model quality, for instance availability or accuracy.

**RQ2: What are the quality assessment items for BIM data?**

Quality dimensions are translated and refined in specific quality items that are used to design a thorough checklist of all required and unnecessary items in a BIM for Facility Management (FM-BIM).

**RQ3: What are the procedures to include necessary data and remove unnecessary data?**

A precise and explicit process is necessary to seamlessly include or purge data in the model.

**RQ4: How the control of BIM data for FM can be automated?**

Automated commercial tools and visual programming software offer opportunities to improve the control of the models and the modeling practices.

**RQ5: Will the quality control process improve the usability and reduce the overall QC effort?**

Case studies of real projects enable to assess the applicability of the checklist and tools designed, thus increasing the reliability and automation of quality assessment.

## Research Objectives and Contributions

The main goal of this research is to develop a framework to facilitate the usability of the delivered models for facility operations, and assist QC and improvements efforts for facility operators. This research aims to set the foundations for using BIM models as the basis to implement useful digital twins that will correspond to the needs of the stakeholders.

Therefore, the research objectives are to:

1) investigate a comprehensive list of data quality requirements that will facilitate BIM usability during the O&M phase through various resources, such as standards, guidelines, best practices and expert knowledge,
2) create a checklist to evaluate the quality of the delivered models,
3) propose processes to prepare and deliver high-quality models for facility operations,
4) provide automation methods and recommendations that can be used to apply the checklist to the as-built models, and
5) verify and validate the applicability of the proposed method in real projects and gather feedback for future improvements.

Hence, this study proposes the following contributions:

1) comprehensive capture of necessary information and quality requirements,
2) development of a complete checklist to evaluate the quality of delivered BIM models,
3) definition of quality assurance and quality control processes to ensure the delivery of usable models, and
4) development of automated quality control tools

## Thesis Organization

The introduction section elaborated the context of the research and identified the main questions that this research intends to answer. The objectives and contributions were also elaborated. Chapter One provides a review of the relevant literature and offers an academic and industrial context for this study. The chapter gives a detailed description of facility management, quality management, and information requirements. Chapter Two presents the proposed method to address the gaps discovered in the literature review, through the design of a quality management framework. Chapter Three describes the activities performed to implement the proposed framework using various commercial applications. Chapter Four details how the proposed method and the developed tools were applied and adapted in two case studies, followed by a discussion of the results in Chapter Five. Finally, the Conclusion chapter summarizes the conclusions and provides descriptions of the research limitations and suggestions for future work.

# CHAPTER 1

# LITERATURE REVIEW

To develop a method for improving the quality of BIM models used during the O&M phase, a literature review was performed to assess the current state of research on the related subjects. These include Facility Management, BIM, Information Requirements, Quality Assurance and Control, and Interoperability. The specific challenges of creating, assessing, and transferring BIM data for operations were investigated. This review helped to develop a framework for ensuring the delivery of optimal-quality BIM information at the time of handover.

## 1.1 Operations & Maintenance, Asset Management, Facility Management

### 1.1.1 Facilities Operations and Maintenance

Since the O&M phase accounts for the largest proportion of assets lifecycle costs (50–70% of the total annual operating costs, and 85% of the entire life cycle costs), effective management is crucial to obtain significant financial benefits (ABAB, 2018).

*Asset Management* is the coordinated activity of an organization to realize value from assets over the entire lifecycle. This is achieved by balancing costs, opportunities and risks against desired asset performance, technical and financial decisions aim to fulfill organizational objectives (Heaton et al., 2019). *Facility Management*, on the other hand, regroups various daily services to ensure functionality of the built environment by integrating people, place, process and technology (Ramesh, 2016). Among others, FM aims to provide safe and efficient environment for facility occupants by tracking facility components accurately, identify inefficiencies in building operations, and respond quickly to client requests (GSA, 2011).

### 1.1.2 Facility Information

AM and FM activities depend on the accuracy and accessibility of data created in the design and construction phases and updated throughout the O&M phase (GSA, 2011). Thus, information should be managed and analyzed in a structured and systematic way to facilitate decision-making.

A lack of information can result in cost overruns, inefficient building operations, and untimely resolution of client requests. Unfortunately, an owner's decision making often relies on a range of incomplete, inaccurate, or vaguely defined information leading to poor decisions Parsanezhad & Dimyadi, 2014).

On the other hand, an overload of information may saturate an operation's database and decrease its efficiency. Additionally, excessive unorganized information in non standard formats can simply become unused data (Lu, 2018). Defining and formalizing the required useful FM information before the design of an asset is the key to effective management of this vast quantity of information, which is critical to the success of facility operations (Lu, 2018).

Another issue is that designers and constructors seldom know what information is needed for the FM. Thus, the owner's input and requirements should be sought out at the initial stages of the project (Masania, 2015). However, most owners do not have precise requirements for information deliverable to ensure the usefulness of the closeout information (Liu & Issa, 2013).

### 1.1.3 Issues with Static Documentation

Facility Information is often delivered through static documents (e.g. CAD, PDF), which often do not leverage the potential benefits of digital technologies (ABAB, 2018). These static documents raise issues at the time of handover and throughout the O&M phase, such as manual search and retrieval of information and failure to carry-out any kind of data verification (Lu, 2018). Additional issues of static data include its low quality, the complexity of its organization, the search time-cost, and storage of paper documents (Whyte et al., 2010).

This issue of static data could be addressed by more precise guidelines regarding the delivery and use of standardized BIM information for O&M (Lu, 2018). Indeed, aside from 3D geometry, BIM can supply centralized and standardized assets and spaces data to FM databases to be used for activities such as maintenance and renovation planning (Akcamete et al., 2010). However, BIM data might still not be useful if it lacks rigorous structure and quality or does not correspond to actual needs. This gap is explored in Section 1.4.

## 1.2 BIM for Operations

### 1.2.1 Facility Management Systems

FM operators use a variety of software forming Facility Management Systems (FMS). Among them, Computerized Management Systems (CMMS) and Computer Aided Facility Management (CAFM) are used to manage facility assets, maintenance transactions, and store facility data during the O&M phase (GSA, 2011). CMMS are deployed for equipment inventories, generation of service requests, managing work orders of different types, tracking resources for maintenance, keeping employees' records, and inventory of managed assets, etc. CAFM systems are mainly used for space management, i.e. administering room numbers, departments, usable heights, room areas etc. (Parsanezhad et al., 2014).

### 1.2.2 Enabling BIM for the O&M Phase

The potential benefits of applying BIM applications to facility management was discussed by Pärn et al., (2017) in a thorough literature review. The use of BIM during operations can also be supported by various technologies, such as visual analytics (Motamedi et al., 2014), Virtual Reality (Motamedi et al., 2017), or RFID (Motamedi et al., 2016). These technologies are compatible with the FM platforms used by facility operators, such as CMMS and CAFM. At project closeout, facility information (data and geometry) can be extracted from the BIM models and transferred into these platforms. Data required by an FM platform can be imported at project handover either directly from the BIM model, or through an external format such as COBie (GSA, 2011).

Hence, BIM models can be used as the basis for information delivery between project management and asset management and in so doing, considerably reducing efforts in data transfer, restructuring, and management (Vega Völk, 2017). Facility Information provided by the BIM model can speed up the O&M of the facility (Vega Völk, 2017) and BIM data can be used for space management, to populate the FM database, anticipate maintenance needs, and provide background information for renovations (Kensek, 2015).

However, proper use of BIM models to populate the FM platforms requires that the designers and contractors provide the owner with models that contain complete, accurate, and actionable data on their assets to support efficient operations. To ensure the delivery of a high-quality BIM, owners should request the models to be adapted for FM and verify them. Yet, the analysis of owner standards and guidelines (e.g. AIQS & NZIQS, 2019; Georgia Tech University, 2016; University of South Florida, 2018) revealed that they rarely contain comprehensive guidelines to ensure the ease of use, efficiency, interoperability, and maintainability of FM models. As a result, the use of BIM during the O&M phase remains limited as the models are not readily usable and require extensive modifications and quality improvement, which is costly and time-consuming.

### 1.2.3 FM-BIM Creation and Model Evolution

Motamedi et al. (2018) showed that various types of BIM models are created and used throughout a building's lifecycle (Figure 1.1a). Each model is created based on the models in their preceding stage. Design professionals create a geometrically accurate *As-Designed Model* for project BIM execution, digital design mock-ups, decision support, and coordination. Construction professionals upgrade it into an *As-Built Model* to plan, schedule, coordinate, manufacture components and execute construction. Model elements are accurate and include fabrication, assembly, detailing, and non-geometric information. This model also captures the conditions at the time of completion of construction. However, the model used in each stage does not necessarily contain all the data from the preceding model. Figure 1.1a shows how the BIM data in models evolves during a current typical BIM project. While the data relevant to each phase is added, some data is filtered out between the various phases (e.g. Planning Options or Construction Details*)*, and Figure 1.1b illustrates the overlapping between BIM data throughout the lifecycle.

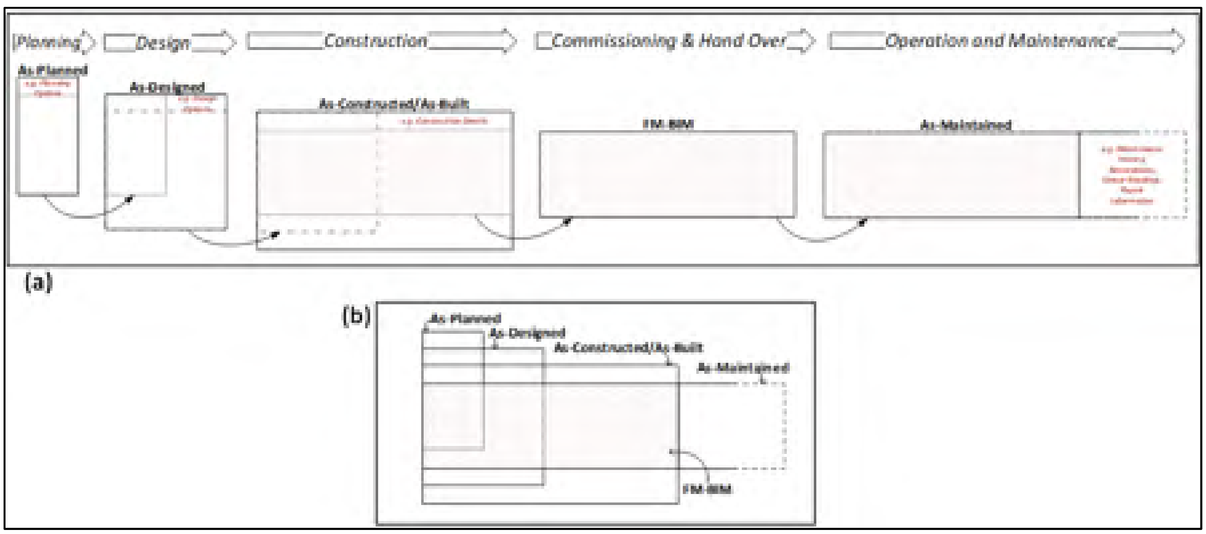


Figure 1.1 (a) Evaluation of BIM deliverables (b) Schematic view of overlapping BIM data
Taken from Motamedi et al. (2018)

Alternatively, since FM-BIM models can derive from either *As-Designed* or *As-Built* model, the owner can also choose to require from which is the FM-BIM created (PSU, 2013):

- *As-Designed* Model. Often considered the most beneficial for FM, it contains design level detail and lacks fabrication information. It may be the most cost-effective solution for renovation work and FM.
- *As-built* Model. This model contains much more detailed geometry and therefore requires a massive purging effort.
- Both *As-Designed* Model and *As-built* Model. Many owners choose to require both types of Record Models.

Motamedi et al. (2018) proposed that the FM-BIMs be the source of truth for facility information at the time of handover. The FM models evolve from As-Built and As-Designed Models: they must include as-built geometry and should be lightweight and interoperable. As-Built Models also include all relevant attributes for inspection, maintenance, and operation simulations – which are extracted from asset documents – as well as the relationship between elements (Figure 1.2). Indeed, to ensure the efficiency of FM models, these should only contain information valuable to FM; hence all unnecessary information needs to be purged (purging and cleanup bubble in Figure 1.2). The resulting FM-BIM model is integrated into the Integrated Workplace Management System (IWMS) platform and is expanded, as the building ages, to an *As-Maintained* Model, or a digital twin, by containing information about the ongoing O&M of the building. The *As-Maintained* Model information is synchronized with the CMMS and CAFM, which are populated either by the BIM model directly or through the export of a COBie spreadsheet, to become the source of truth during the operations of the facility.

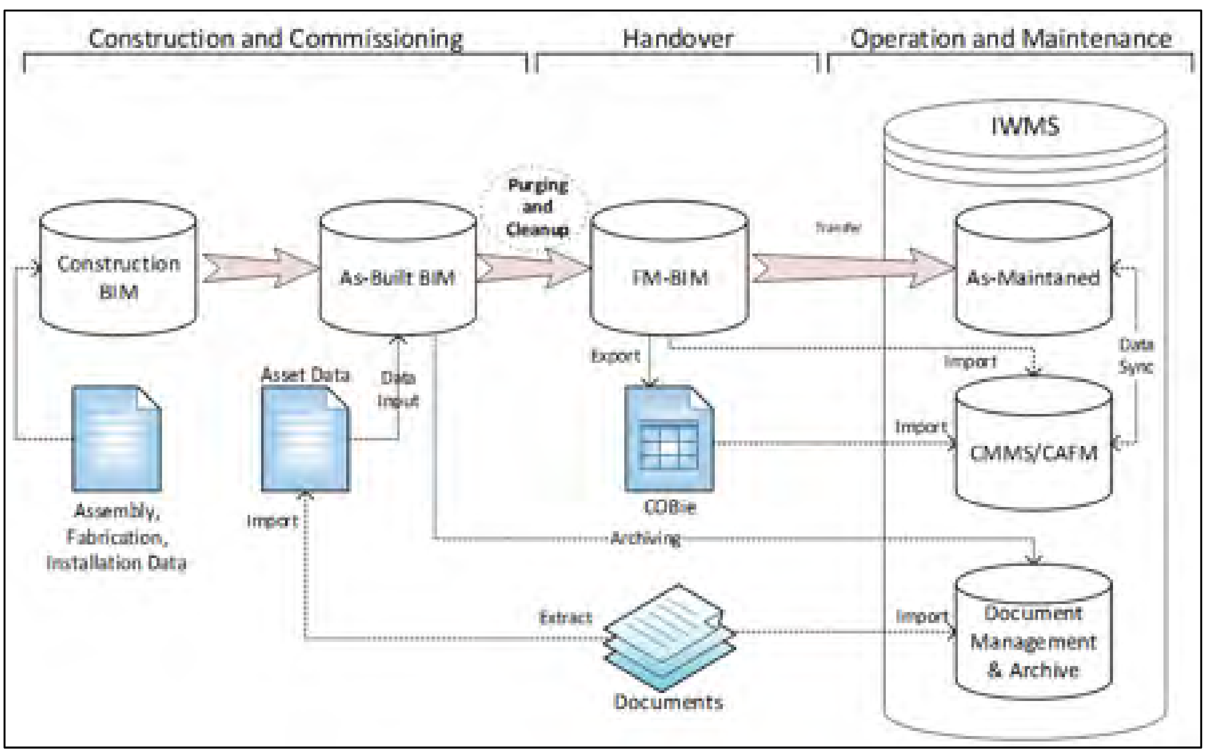


Figure 1.2 Creation of FM-BIM and IWMS integration
Taken from Motamedi et al. (2018)

The high-level process flow for the preparation of the FM-BIM from the *As-Built* model (Figure 1.3) includes model preparation and quality control steps to check whether all the owner's and the modeling requirements for an FM-BIM are met (Motamedi et al., 2018). Furthermore, since only the information valuable to FM needs to be extracted and the nonessential data should be removed, the model is cleaned up. In the next step, the model's interoperability is tested to verify that the produced model is vendor independent and interoperable. Exporting the model to the Industry Foundation Classes (IFC) file format and analyzing the resulting model is a common practice for the interoperability test. The interoperability test raises further issues, as it is dependant to the development of the IFC standard, and the supports provided by the BIM authoring platforms.

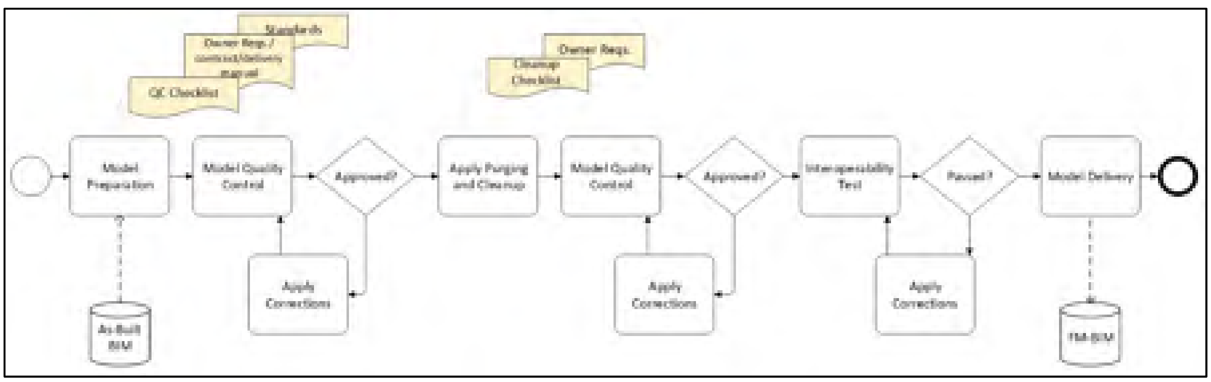


Figure 1.3 Process flow for quality control, cleanup and purging
Taken from Motamedi et al. (2018)

### 1.2.4 Updating FM Data

Maintaining FM information in a BIM model is comparable to maintaining the physical facility (Akcamete et al., 2010). As the components are replaced, repaired, or removed, those changes will need to be reflected in the BIM file (Kensek, 2015). Thus, a clear procedure for updating FM-BIMs shall be documented to ensure that the data reflects the current condition of the facility, regardless of the location of the data (either in the BIM model, or in an external FMS) (Jokela et al., 2012).

The update process depends on the type of information that needs to be updated:

1) update attributes in the external database since it is more accessible for operators than a BIM model,
2) update equipment and geometry both in the BIM and the external database, or
3) simply update the geometry in the BIM model.

## 1.3 BIM Information Requirements in the Industry

Requirements are based on the owner's expectations of how the model must be developed (Cavka, 2017). The Information Requirements are the basis from which the client's expectations can be defined in terms of the quality of the models delivered. Information Requirements can be categorized in various types, formalized in ISO 19650 (ISO, 2018), such as Organization Information Requirements (OIR), which are high level generic requirements, Asset Information Requirements (AIR), which relates to the objects and their properties, or Exchange Information Requirements (EIR), which includes all the details of the production and transfer of information (BrisBIM, 2020; UK BIM Alliance, 2019a).

Cavka et al. (2017) studied how the owner Information Requirements should ideally be identified and classified, based on project specifications. They proposed to classify the requirements in five categories: codes and design standards, organisational requirements, project requirements, personnel requirements, and BIM requirements. The research was done prior to the release of ISO 19605. Hence, although they identified multiple sources and examples of BIM requirements (e.g. standards, protocols, guidelines), the types of BIM requirements could not be mapped to the various IRs defined by the ISO. Further work is required to extend their proposal by considering the ISO standards in terms of relating BIM requirements with the different types of IR.

Additionally, they identified computable requirements for spaces and equipment and developed a framework that demonstrates relationships between the BIM model, the building, and the requirements. Yet, they only scarcely explored how the quality of the models can be assessed against the requirements, except for verifying whether elements' properties and attributes are populated. The Information Requirements, as defined by ISO, encompass items such as attributes required, level of details in the modeling, and information exchange practices. Clearly and thoroughly defining these requirements is crucial, both for Quality Assurance (i.e. defining the content of the models according to the requirements) and Quality Control (i.e. verifying the content of the models against the requirements). Thus, the quality assessment of the model per the requirements proposed by Cavka et al. (2017) could be further extended from simply verifying the population of attributes and the structure of the model, to designing a thorough quality control checklist based on model objects and quality dimensions (Section 1.4).

As Cavka et al. (2017) mentioned, Information Requirements are assembled in various types of documentation used in a project to clearly communicate expectations to the modeling team. Examples of documentation include: the project specifications serving as the only transcription of the client's wishes, in the form of text, diagrams and plans, Asset Attributes Matrix mapping the parameters and objects that are required to be part of the model (e.g. US Department of Veterans Affairs, 2017b), or Modeling Guidelines such as the one provided by The Smithsonian Institute (Smithsonian, 2018) to ensure model integrity.

Finally, BMP and BEP commonly accompany contractual documents to define the scope of the project, the uses of BIM, the roles and responsibilities, the expected deliverables, etc. Although references to AIR, PIR and EIR and corresponding documentations should be included in this document, current BEP and BMP seldom mention Information Requirements, even in the templates provided by ISO or Publicly Available Standards (PAS).

### 1.3.1 Information Requirements Types

Information Requirements (IR) are a collection of parameters and attributes required by the owner at various levels and for different purposes in the facility lifecycle. Various categories of IR are defined in standards such as ISO 19650 (UK BIM Alliance, 2019b) that PAS 1192 (Hansford & Bew, 2013) and their relationships are illustrated in Figure 1.4:

The Organisational Information Requirements (OIR) are information needed by an organisation to inform decision-making about high-level strategic objectives in relation to the built assets. OIR are generally not issued as part of tender documentation

The Project Information Requirements (PIR) are information needed in a specific project to inform decision-making about high level strategic objectives, in relation to a particular project throughout its duration. These requirements can include excerpts of construction and project management documents and/or purpose-written reports including cost and progress reports.
The Asset Information Requirements (AIR) contain detailed and computable information needed to answer the OIR. They primarily set out the technical aspects of the required asset information and are often computable.

The Exchange Information Requirements (EIR) include details of the roles and responsibilities of stakeholders, information production processes and procedures, data standards, file formats and timetables for information exchanges. The EIR are primarily concerned with who, how and when delivering the information.

The Project Information Model (PIM) and Asset Information Model (AIM) should not be mistaken as a virtual 3D model as they respectively contain methods, scheduling and costing, details of systems and components or documents, models, and structured data. The PIM supports the delivery of the project and contributes to the AIM, which is a deliverable provided by the delivery team in response to the AIR. The AIM supports the strategic and day to day FM processes. It can also provide information at the start of a refurbishment or extension of existing asset.

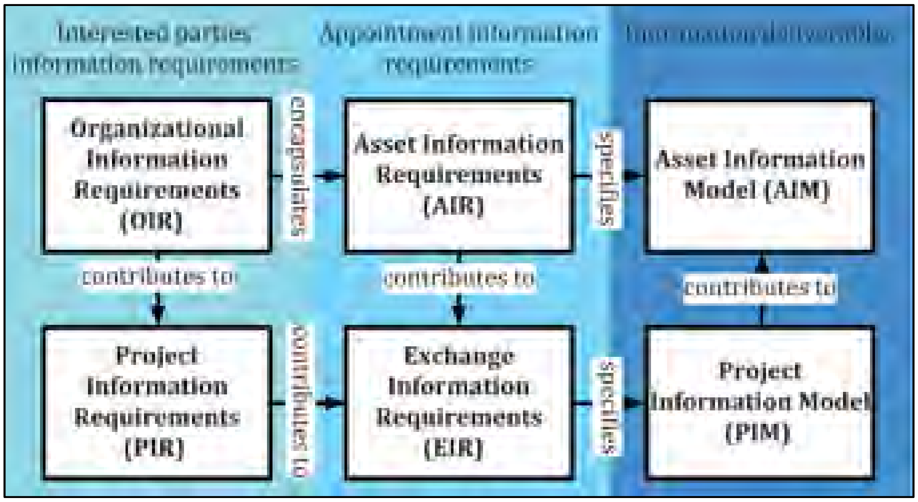


Figure 1.4 Relationships between information requirements
and information models
Taken from UK BIM Alliance (2019a)

The AIR and EIR form the basis to define client expectations regarding the quality of the models delivered. These types of IR set the reference in terms of attributes required, level of details in the modeling, information exchanges practices, etc.

### 1.3.2 Examples of Information Requirements Documentation

The various requirements in traditional construction are defined and described in the project specifications. This document is prepared and shared at the beginning of the project but as the amount of information grows during the project, the specifications are usually not updated and as a result, are unfaithful to the as-built building (Whyte et al., 2010). Additionally, this document does not contain any indication regarding BIM practices.

Asset Attributes Matrix are an example of documents that aim to support the project team in delivering information that complies with the requirements. The Veterans Affairs (US Department of Veterans Affairs, 2017) have designed an Excel sheet to help identifying attributes requirements by type of object and detailing the expectations regarding the required attribute (e.g. format, unit, provider).

Naming conventions are another common, yet crucial, type of documentation to follow to ensure consistency, readability, and compliance of the data. Likewise, Classification Systems such as those presented in Table 1.1 were designed in that regard to help categorizing objects. Popular systems include Uniformat for cost estimation, Masterformat for specifications and Omniclass 23 or Uniclass for facility management (Autodesk, 2016).

Table 1.1 Comparison between four classification systems
Adapted from Autodesk (2016)

| **Classification Systems** | **OmniClass** | **MasterFormat** | **UniFormat** | **Uniclass** |
|---|---|---|---|---|
| Origin | US | US | US | UK |
| Purpose and Properties | Product information for all objects throughout the project lifecycle. | Organizing construction work results, requirements, products, and activities. Mostly used in bidding and specifications. | Arranging construction information, organized around the functional elements, and mainly used for cost estimates. | For all aspects of the design and construction process. For structuring product literature and project information. |

Modeling Guidelines and Standards are essential documents provided by owners to guide the designers and help them delivering models that complies with the requirements. It is usually a collection of best practice to ensure model integrity. The Smithsonian Institute (Smithsonian, 2018) is an example of major owner organizations providing this documentation.

Additionally, LOD and LOI Matrix (e.g., NATSPEC, 2013) define respectively the level of geometric detail and attributes richness per category of objects. These levels and the corresponding quantity of data increase throughout the project lifecycle. The LOD and LOI are also indicated in Information Delivery Matrix, whose goal is to provide a timetable of the delivery of the model with the expected quantity of information at each milestone throughout the project. Scottish Future Trust provides templates and examples of such matrices (Scottish Future Trust, n.d.).

## 1.4 BIM Data Quality Assurance and Control

### 1.4.1 Definitions

ISO 8402:1994 and 9000:2000 define quality as the degree to which a set of characteristics of a product fulfills requirements from the client and is considered fit for use (ISO, 1994, 2000). Quality management is a process of attaining and satisfying high quality output by meeting customer defined requirements (Ramesh, 2016). Quality Assurance and Quality Control are two interlaced aspects of quality management.

Quality assurance is a process-based proactive approach to guarantee the quality of the product. Its primary objective is to prevent the presence of defects in deliverables in the planning and design phase to ensure the modeling is accurate from start. QA helps to understand the product’s requirements and expectations from the beginning of the project and to develop a plan to meet these requirements. Rigorous planning and guidelines are therefore necessary to meet these objectives (Usmani, 2012).

Quality control is a product-based reactive approach, which helps to correct defects in deliverables. The primary objective of the quality control process is to verify the compliance of the product with the requirements. This process requires finding any defects in the product, correcting any that are found, and validating the deliverable (Usmani, 2012).

Quality assurance and control rely on each other; the quality control process receives input from the quality assurance process, and its feedbacks helps update the quality assurance process. The updated process helps the quality control people to ensure the defect does not recur (Usmani, 2012).

Specifically, in the construction industry, quality management aims to improve efficiency, and ensure contract compliance and cost effectiveness of design, engineering, construction (Rumane, 2019). Just as for the physical building, quality management principles also apply for the BIM model. QA and QC approaches for BIM models guarantee the quality of the model throughout the project lifecycle and ensure that the information is adequate for downstream use during the O&M phase.

The National BIM Guide (National Institute of Building Sciences, 2017) identifies procedures to be defined and documented within the BIM Execution Plan (BEP), such as a QA approach for monitoring the modeling process and a QC approach to test the compliance of the final deliverables with quality standards (Motamedi et al., 2018). However, current BEPs do not feature comprehensive QC/QA processes (Motamedi et al., 2018). A continuous QA mechanism set up by the owner would guarantee the quality of the model throughout the project lifecycle.

### 1.4.2 BIM Models Quality Issues

The quality of data and its availability is crucial in making it possible for the FM database to provide information with the required level of detail. However, although BIM models are successfully used in the design and construction phase, most models created for these phases contain significant quality issues (Zadeh et al., 2015).

Ramesh (2016) summarized various quality dimensions and investigated how they apply to facility information. However, he did not explore how these dimensions apply to BIM models, nor what kind of information is expected in an FM-BIM. Additionally, Zadeh et al., (2017) identified similar types of BIM data quality issues (e.g. incompleteness, inaccuracy, incompatibility, incoordination, incomprehensibility) and categorized them according to

different model perspectives (i.e. objects, attributes, relations, locations) and relevant facility management perspectives (i.e. assets, MEP systems, spaces). Both Ramesh and Zadeh's quality attributes are presented in
Table 1.2. Nonetheless, there is a need for further work in converting these overall assessments into specific checklist items that can be verifiable in a model. Moreover, they only scarcely used commercial tools to assess the models according to the identified quality dimensions, most of the assessment was manual.

Table 1.2 Facility information quality attributes
Adapted from Ramesh (2016) and Zadeh et al. (2017)

| **Attribute** | **Definition** | **Issues addressed** |
|---|---|---|
| Availability | The ability of an organization to require and obtain the facility information on a project for use by its facility team. | Lost, missing information, unnecessary information |
| Consistency | Uniformity in nomenclature and definition of information required and clear or uniform structure for each information type. | Misrepresented information, redundancy, lack of clarity, inconsistency across instances, incorrect translation of information to FM systems |
| Accessibility | The degree to which facility information is (made) available in the appropriate platforms and in the desired formats. | Inaccessible information |
| Timeliness | The documentation and validation of facility information at required milestones. | Late information or unavailable information at the time required for the task at hand. |
| Relevancy | The extent to which information is desired and helpful for majority of tasks at hand. | Irrelevant or useless information |

| Attribute | Definition | Issues addressed |
|---|---|---|
| Completeness | The availability of facility information at all levels in the facility hierarchy. The facility hierarchy typically ranges from the highest hierarchy being the facility to the lowest being the attributes that define the functioning capacity of an asset. | Incomplete information, missing information |
| Accuracy | The degree of closeness to the truth of all classes and hierarchy of facilities information at the time of handover. | Erroneous data, misrepresented data |
| Well-formedness | Refers to the information format and structure and their compliance with standards | Incompatible format |

### 1.4.3 Planning Quality Assurance

Ramesh (2016) proposed a QA and QC planning procedure (Figure 1.5). The procedure allows owner organizations, along with project teams, to systematically identify areas of concern when documenting and delivering facilities information, and to eventually define ways to manage them. This procedure consists of: (1) identifying facility information users; (2) understanding user needs; (3) translating the needs to quality attributes; (4) establishing process controls; and (5) defining product controls. The procedure identifies the goals of owner organizations, lists their concerns, and helps to develop a strategy for quality management, enabling the exchange of usable information. However, Ramesh's procedure for QA remains generic and does not revolve around the use of a BIM model. It mainly focuses on information to deliver and the identification of related stakeholders. Likewise, the procedure remains limited in terms of quality control, as it only mentions the need to define quality attributes and responsibilities. He does not provide a thorough checklist of specific quality items to verify in the models, nor a method and tools to apply such checklist.

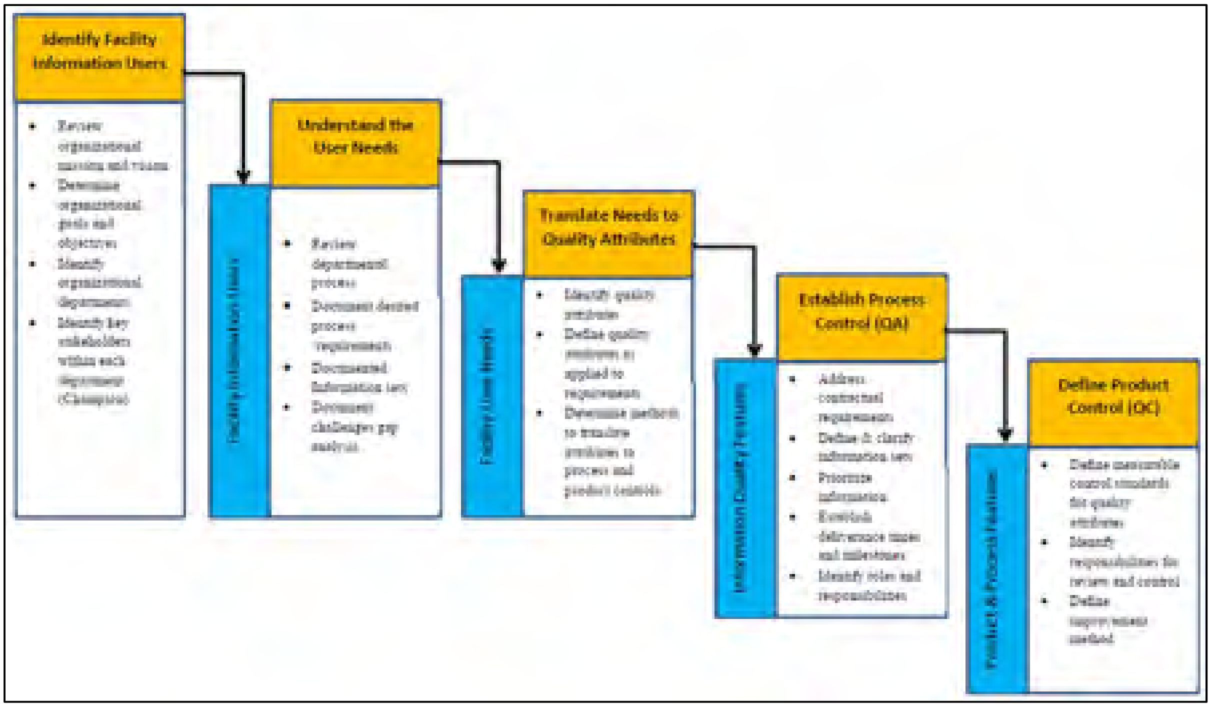


Figure 1.5 Procedure for planning the quality assurance for facility information handover
Taken from Ramesh (2016)

### 1.4.4 Executing Quality Control

To leverage the use of the BIM model during O&M, owners should increase quality control during design and construction to ensure that the BIM used for FM complies with their requirements (Motamedi et al., 2018). The designers' work is reported at project meetings and a report is prepared for project-specific official checkpoints, describing the priority issues that require attention. At these checkpoints, QC include several steps, such as a self-check, carried-out by the designer, internal check, by the project manager, and a client assessment (Kulusjärvi, 2012). Several types of checks at the checkpoints are proposed by Ramesh (2016):

1) *visual checks* to ensure there are no unintended model components and the design intent has been followed,
2) *interference checks* to detect problems in the model where two building components are clashing,
3) *standard checks* to ensure that the model meets the standards selected by the team, and

4) *element validation* to ensure that the dataset has no undefined or incorrectly defined elements.

In addition, gradual QC and a continuous monitoring of the requirements solicitation status is desired. This gradual QC should be performed by both the appointing party and the BIM project team. The *standard checks* are the most relevant checks among this list for FM purpose and examples of such were proposed by Motamedi et al. (2018) in a QC checklist that yet needs to be evaluated in real projects.

### 1.4.5 Quality Control Checklists and Automated Tools

The goal of the model preparation process is to provide operators with a lightweight federated model that complies with a standard format and is enriched with FM data. To achieve this, Zadeh et al. (2017) proposed QC checklists. Various checklists also exist in BEPs and modeling guidelines, however, they are not specifically design for data quality assessment for Facility Management. Overall, these checklists are not exhaustive and remain very generic. Motamedi et al. (2018) proposed a more detailed checklist, based on actual model elements rather than quality attributes, that includes both quality control and model clean-up items. Yet, this checklist can be further extended and remains to be verified and validated in industrial projects.

Furthermore, manually reviewing thousands of components with multiple parameters can be labor-intensive, inefficient, and error prone. To automatically assess the model, automatic model-assessment tools are available on the market (e.g. *Revit Model Checker*, n.d.; *Revit Model Review*, n.d.; *Solibri Model Checker*, n.d.). With this type of software tool, a user can define BIM-based requirements checklists and, through implementation rules for checking the model, the user can determine whether the requirements have been met (Pishdad-Bozorgi et al., 2018). The project team can then fix any uncompliant item efficiently and also deliver the report to the client for every project milestone (Pishdad-Bozorgi et al., 2018). A scorecard and dashboard can also be used to measure the quality of the model and its compliance with requirements (GSA, 2011). However, the applicability of these tools for FM purposes must be evaluated since these tools are not adequate if a comprehensive list of checks based on the user's requirements does not exist. Additionally, none of these tools can adequately perform all the required types of QC. Moreover, appropriate processes should be designed to employ the tools for QC/QA.

Example of commercial tools to assess the quality of a BIM model include Revit Model Checker (*Revit Model Checker*, n.d.) and Model Review (*Revit Model Review*, n.d.), which are free tools embedded in Revit to perform simple rules, such as the existence or the filling of a parameter. Additional rules for controlling the model integrity are present and they are capable of producing reports. Additionally, Solibri (*Solibri Model Checker*, n.d.) is more suited for program checks or verifying the compliance with design rules, such as clearance and accessibility. Another tool is BIM Assure (*BIM Assure*, 2019), which is an online solution that enables non-BIM user to create and execute rules that can be applied to very specific items. Finally, Dynamo (*Dynamo*, n.d.) is a visual programming environment embedded in Revit, which offers vast opportunities for controlling the quality of a model.

## 1.5 Interoperability

### 1.5.1 Definition and Importance of Interoperability

Facilities information usage is hindered by frequently ad-hoc information exchanges for operations and gathering information from documents handed over after construction is expensive and time consuming. As the formats in which facility information is created (i.e. BIM files) often do not comply with FMS, operators lose a significant amount of time mining for information (Ramesh, 2016). Therefore, standard data representation is necessary to perform a seamless transfer between the model and the FM platforms (Kensek, 2015). Moreover, the lifespan of a facility far exceeds the typical duration of proprietary formats, which eventually become outdated.

Hence, interoperability between the authoring software and the FM software is crucial to avoid any information loss at project handover (Vega Völk, 2017). Interoperable software reduce the amount of time required to exchange information and also minimizes the risk of data transfer errors often caused by manual information exchange methods (National Institute of Building Sciences, 2017).

Interoperable format work in pair with open standards, which are crucial to public procurers, as they provide a way to state data requirements in a format and a data model that any member of the supply chain can deliver (EUBIM Task Group, 2017). Besides, interoperability and open formats are crucial for owners and operators as the software applications used during the operation are very different from design and construction. Besides, the operation phase spanning for decades, technologies change and evolve during the life of a built facility.

### 1.5.2 Industry Foundation Classes (IFC)

An example of an open standard is IFC (buildingSMART, 2013), an open and object-based file format that encodes both geometry and data about BIM objects. This neutral format was created to mitigate the possibility of any information loss between multiple software solutions, provide a consistent data representation of an asset and avoid the dependence on product or vendor specific file formats (Vega Völk, 2017). Initiatives such as the IFC enable interoperability between software to share design, as built and maintenance data during the entire lifecycle of an asset (Jawadekar, 2012).

IFC is gaining acceptance world-wide with some government organizations mandating its use, but it is not yet generally required. Revit models are usually the final deliverables in North America, and spreadsheets or custom plug-ins are used to transfer data to FM systems (Kensek, 2015).

Despite its capabilities for addressing the interoperability gap between platforms, IFC is still a perfectible format. It is often deemed to be too rigid to be implemented during all life cycle stages of the facility. Another problem with IFC export as a means for information transfer to FM is the large file sizes and populated information that is not totally relevant or useful for FM (Parsanezhad et al., 2014). Additionally, although the treatment of geometry is satisfactory, IFC still faces weakness in the transfer of attributes and some relationships features are missing (e.g. difference between architectural and HVAC spaces). Finally, not all software-specific objects definitions are covered by IFC, thus the data transfer through IFC between two software may result in loss of data.

### 1.5.3 Construction Operations Building information exchange (COBie)

A Model View Definition (MVD) of IFC specifically created for FM data transfer is COBie, a non-proprietary data structure that enables the creation and transfer of asset information. The COBie approach envisions capturing information incrementally throughout the project lifecycle (East et al., 2017). It is used as a data handover tool for transferring the data taken from the BIM models. It enables the creators of the data, particularly for equipment, during design, construction, and commissioning to populate a spreadsheet with the desired facility information. This spreadsheet can then be directly imported into many FM databases to populate facility data. This information delivery method is growing in popularity as a required deliverable for many owners (PSU, 2013).

Despite its growing popularity, COBie is only a platform for data capture and transfer and does not include specific data requirements for each asset type. Additionally, even though COBie can be used to populate FM databases, the data exchange is unidirectional, which means it cannot synchronize between the model and the database. Moreover, a lack of incentives for manufacturers to provide their product information in a COBie-compatible format often leads to not delivering this information (Parsanezhad et al., 2014). Finally, BEPs are generally imprecise regarding data requirements, delivery schedule, and the data quality of COBie deliverables.

## 1.6 Chapter Summary and Research Gaps

### 1.6.1 Facility Management and BIM for Operations

The literature emphasized the high financial impact of the O&M phase during the lifecycle, which signifies the importance of establishing efficient management strategies, including a data management strategy. It indicated various issues in the quality of facility information, such as missing or excessive available information, and lack of expertise of designers and constructors in facility management. Additionally, a major cause of the lack of quality of facility information, which impedes the efficient management of assets throughout the lifecycle, was reported to originate from the use of static documentation. Therefore, the literature acknowledged the rising potential of BIM for use during the O&M phase, as it offers promising opportunities to deliver facility information. Finally, while the literature proposed a method for creating a dedicated FM-BIM model, this method lacks a clear focus on assuring and verifying the quality of the FM-BIM.

### 1.6.2 Requirements Identification and Compliance Monitoring

The review of the literature showed a lack of focus on standards that can help to identify data quality requirements and data quality management procedures. This shortcoming can result in a weak adoption of BIM quality management in contracts and thus makes it difficult for the project team to deliver compliant models. Hence, this research investigates the industry needs through various resources—such as standards, best practice guidelines and contracts—to establish the data quality requirements for FM purposes.

### 1.6.3 BIM Data Quality Assurance and Quality Control

The literature highlighted a lack of comprehensive checklists and procedures to assess the data quality of the BIM model for FM. The limited usage of automated methods to identify and correct quality issues was also noticed in the literature. Therefore, this research proposes a comprehensive list of required information that must be present in the model for the operations of the facility, and information that must be purged from the design and construction models. Automated checking and purging methods to ensure the quality and lightness of the models to be delivered are also proposed.

Moreover, the literature suggested a lack of comprehensive processes to implement the data quality assurance and the data quality control, specifically for using the models during the operations. Therefore, process flows to be used by owners and constructors regarding the requirements for FM are proposed in this research.

### 1.6.4 Interoperability

The literature highlighted the necessity of interoperability and open standards for seamless information exchanges. IFC is an example of such data exchange format. COBie is introduced as a promising subset of IFC, and the literature showed its capabilities in transferring asset information throughout the project. Yet, the COBie-based information exchange is unidirectional. Additionally, the data types to be included in the COBie file needs to be complemented by specific data requirements for each asset type.

# CHAPTER 2

# RESEARCH METHODOLOGY AND PROPOSED SOLUTION

The proposed solution builds on the work performed in the previous studies and aims to address their identified gaps (Section 1.4). The Design Science Research methodology (Dresch et al., 2015) was employed to develop artifacts that alleviate the afore mentioned gaps. The FM-BIM preparation and assessment processes by Motamedi et al. (2018) (explained in Subsection 1.2.3) are expanded to form a more thorough quality management framework that includes QA and QC activities. This framework proposes a link between commonly used BIM documentation in the industry (such as various types of IRs explained in Subsection 1.3.2), relevant project stakeholders' roles and responsibilities, and a sequence of actions to perform to ensure the smooth delivery of a useable FM-BIM model. The proposed framework is presented in Section 2.2.

Moreover, the quality issues identified by Ramesh (2016) and Zadeh et al. (2017) (explained in Subsection 1.4.2) are leveraged to propose a thorough quality control checklist for the FM-BIM. This checklist is based on the work of Motamedi et al. (2018) mentioned in Subsection 1.4.5, which is extended to include more quality items. This new quality control checklist forms the central piece of the proposed framework and is presented in Section 2.3.

Finally, the quality control process flow proposed by Motamedi et al. (2018) (explained in Subsection 1.4.4) is extended to illustrate the role of both the appointed and the appointing parties (UK BIM Alliance, 2019a). The proposed method also includes the use of automated tools for assessing the models, a key aspect that was not thoroughly explored in the current literature. The improved process flow is presented in Section 2.4.

## 2.1 Research methodology: Design Science Research

Design science research aims to study, research, and investigate the artificial and its behavior from an academic and organizational standpoint. Design science research is a rigorous process of designing artifacts to solve problems, to evaluate their results and to communicate the outcomes of the proposition. Based on the understanding of the problem, the designed artifacts enable the transformation of situations by changing their conditions to better or desirable states (Dresch et al., 2015).

Design Science contributions can be positioned along two dimensions: application domain maturity and solution maturity. Application domain maturity is about the maturity of the practice for which the contribution is intended, whereas solution maturity is about the maturity of artifacts that could be used as a starting point for finding solutions. The application domain and the solution maturity form four types of contributions (Johanesson & Perjons, 2014):

- *Invention* (New Solutions for New Problems): this type of contribution is a radical innovation that addresses an unexplored problem context and offers a novel and unexpected solution. Such a contribution can enable new practices and create the basis for new research fields.
- *Improvement* (New Solutions for Known Problems): this type of contribution addresses a known problem and offers a new solution or a substantial enhancement to an existing one. The present research fall in this category as the quality problems of BIM models for the O&M phase is commonly accepted in the literature.
- *Exaptation* (Known Solutions Extended to New Problems): this type of contribution adapts an existing solution to a problem for which it was not originally intended.
- *Routine Design* (Known Solutions for Known Problems): this type of contribution is an incremental innovation that addresses a well-known problem through minor modifications to an existing solution.

### 2.1.1 Research steps

A proposed framework for Design Science Research (Johanesson & Perjons, 2014) includes five main activities that range from problem investigation and requirements definition, through artifact design and development, and finally, to demonstration and evaluation (Figure 2.1).

**Explicate Problem (1)**

- Investigating and analysing a precisely formulated problem of general interest. Underlying causes to the problem and its solving approach in similar researchs may be analysed.

**Define Requirements (2)**

- Outlining a solution to the explicated problem in the form of an artifact and elicits clearly defined requirements, both in their functionality and their structure.

**Design and Develop Artifacts (3)**

- Creating an original artifact that specifically addresses the explicated problem and fulfils the defined requirements.

**Demonstrate Artifacts (4)**

- Using the developed artifact in a clearly justified real-life case, proving the applicability of the artifact in solving an instance of the problem.

**Evaluate and Communicate Artifacts (5)**

- Determining how well the artifact fulfils the requirements to alleviate the explicated problem. The way the artifact is evaluated also requires precise description.

Figure 2.1 Five-steps framework from conducting Design Science Research
Adapted from Johanesson & Perjons, 2014

These five main activities were mapped to the research steps undertaken in this project:

1) The explicate problem step included the identification of the research problem, i.e. the need to improve the BIM models delivered at the handover stage so that they become usable during the O&M phase of a facility. A thorough literature review based on industrial and academic publications, which was presented in Chapter 1, enabled to comprehensively explore the extend of the problem and understand how the solutions proposed in similar research projects can be improved to address the problem.
2) The literature review and the analysis of additional resources such as industrial reports and standards, owner organizations guidelines and project contracts provided the opportunity to investigate and document the requirements for the proposed artifacts (i.e. quality

management framework for the delivery of high-quality FM-BIM models, quality control checklist and procedures, automated quality control tools), which aim to alleviate the problem. The requirements identified in the literature review and the other publications, presented in Chapter 2, led to the design of the artifacts.

3) The proposed solution (i.e. the artifacts) was further developed and implemented using automated quality control tools and programming environment, which are explained in Chapter 3.
4) The applicability of the artifacts was demonstrated in two case studies of real projects, in which the designed artifacts were assessed. The results of the evaluation of the artifacts enabled to improve them in an iterative process. The case studies are presented in Chapter 4.
5) The case studies enabled to validate the capacity of the artifacts to alleviate the explicated problem, as they enabled the partner organizations to improve their current practices in requiring, delivering, and assessing high-quality BIM models. Ultimately, the results diffused in the industry and the research community will contribute to creating more usable BIM models for FM, increase the quality of facility operations and improve the quality of life of the occupants. The findings are elaborated in Chapter 5.

### 2.1.2 Data collection methods and validation approach

Various data collection methods were employed to define the artifacts requirements identified in the literature review. Previous research publications were used as a basis for determining the content of the proposed checklist (e.g. Motamedi et al., 2018; Zadeh et al., 2017). The first iteration of requirements determination was completed by analyzing available publications from advanced organizations, such as industrial reports, best practice guidelines, owner and international standards. The next iteration of requirements determination was performed when analyzing the capabilities of the assessed commercial tools, as some of them included relevant built-in checks. Finally, the last iteration occurred during the case studies, in which the owners, consultants, and specific project requirements provided new content to be included in the checklist.

The case study method was chosen as a validation approach as it provides the opportunity to assess the designed artifacts in a real-world setting and ensure they are suited to address the research problem in the field (Johanesson & Perjons, 2014). The projects selected for the case studies were chosen due to their potential for assessing the applicability of the designed artifacts. Additionally, the case studies were chosen because of their different contexts in terms of delivery methods, project type (academic and healthcare), partner organization (owner and general contractor), and lifecycle stages (handover and construction). Selecting two projects for the case study enabled to have multiple sources of evidence and ensured the designed artifacts were suited for different types of projects.

## 2.2 Proposed Framework for FM-BIM Quality Management

### 2.2.1 Documents and requirements relationships

In order to efficiently communicate and leverage the various types of IR (as defined in ISO 19650), the industry commonly uses a collection of documents (whose relationships are presented in Figure 2.2). The main purpose of Figure 2.2 is to identify how BIM requirements documentation that are currently used in the industry can be part of information requirements categories formalized in industry standards, and as a result, facilitate the transition of the industry towards the adoption of such standards.

As such, nomenclatures and standards and asset attribute matrices fall into the AIR (purple box) as these documents clearly list Information Requirements that are not project specific. In most cases, they are created to correspond to the needs of operation systems. Additionally, other documents that identify the required object types to be included in the model and the project specifications, which are a collection of project specific IR, are contained in the PIR (green box).

The best practices for the BIM modeling and quality control checklist proposed in this research form the modeling standard (grey box) with which to verify whether the information meets the standard defined in the AIR and PIR. Information management and delivery matrices are part of the EIR (red box), since they dictate the method and timetable to populate and share the information required. All these documents shall be referenced in the BMP / BEP as their content has a contractual value and ensures the liability of all parties in their scope of work.

Finally, the efficient use of the abovementioned documents enables the creation of a high-quality BIM model, confirmed by auditing reports, that are included in the PIM (blue box). The facility information in the model can be exported using COBie or other data transfer methods to populate the AIM. It is recommended that the information (e.g. documents, models, procedures etc.) is organized in a CDE, which facilitates communication and ensures reliable access.

This proposal focused on file-based model exchanges; however, it can be easily expanded to a database approach, in which case, the need for removing information becomes unnecessary. A rigorous structure of information in the database makes it possible to define MVD for various usages, thus reducing the need for purging unnecessary information.

### 2.2.2 Stakeholders' roles and responsibilities

Various stakeholders are involved in the delivery of a BIM project. Facility *Operators* are in charge of ensuring that the facility operates smoothly. To achieve this, they should provide FM requirements at project onset, such as required attributes or operating information (part of the AIR in Figure 2.2). The *Client* (or *Owner* or *Consultant*) is identified as the appointing party in ISO 19650. They bridge the gap between the operators and the delivery team and are also involved in identifying the BIM requirements, such as modeling guidelines, or in creating project specifications (green and grey boxes in Figure 2.2).

Additionally, the BIM project team is usually led by a *BIM Manager* (or lead appointed party in ISO) who supervises the seamless delivery of the information. As such, he is also involved in creating the procedures to deliver the information and ensuring their correctness (included in the EIR in Figure 2.2). Other members of the BIM project team include the *BIM Coordinators* (or appointed party in ISO), that are mostly in charge of verifying the quality of the model and the information it contains, according to the guidelines and requirements prepared by the other parties. The model is produced as PIM and, alongside the quality reports, is delivered as AIM to the client (blue boxes in Figure 2.2).

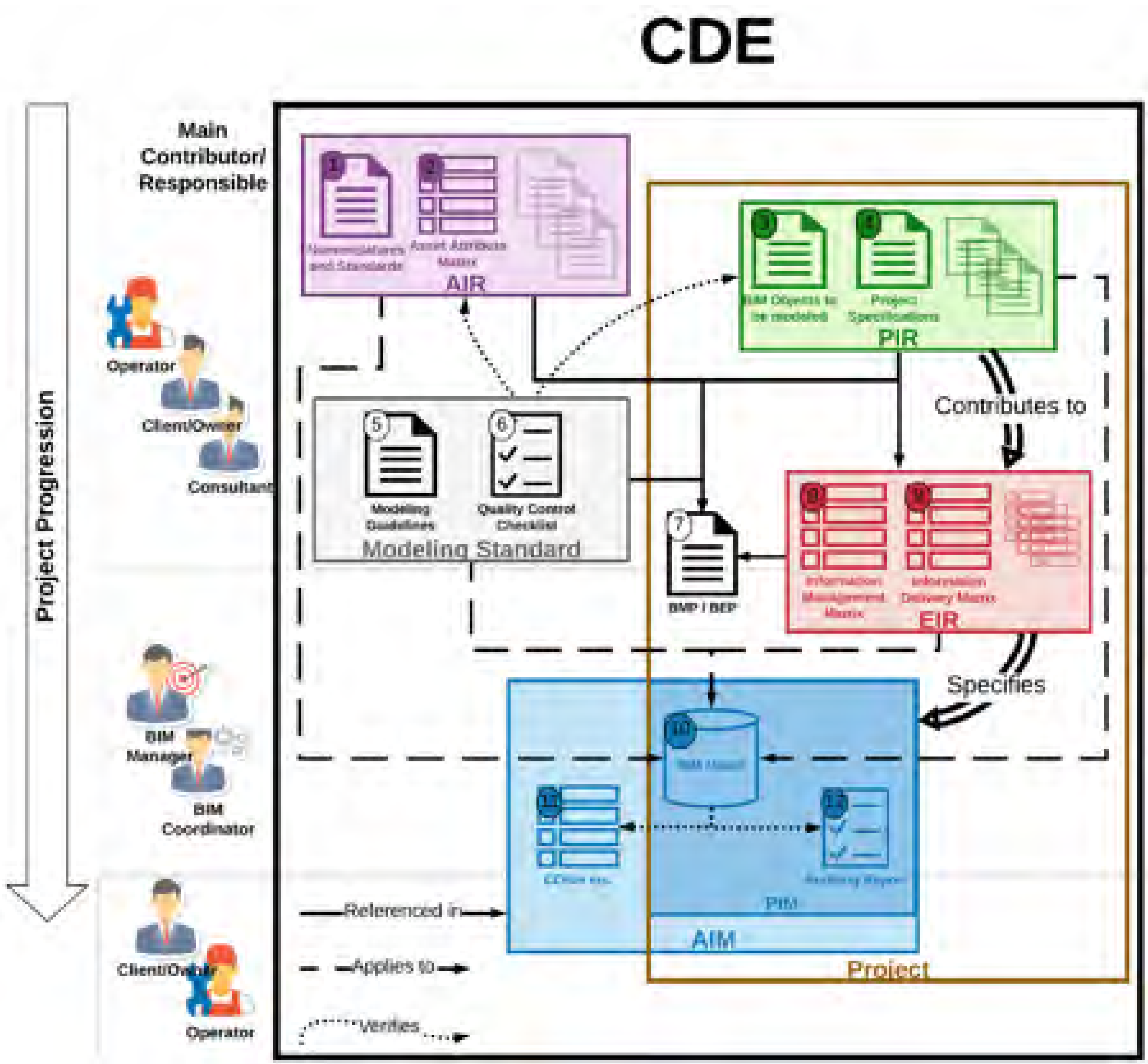


Figure 2.2 Link between different types of IR, corresponding documentation, and involved parties

### 2.2.3 Quality Management Process Flow

Figure 2.3 demonstrates the proposed quality management process flowchart with their correspondence to the IR and the typical BIM documentation related to data quality. An extended Figure that includes relationships between IR is presented in ANNEX I. The sequence of various activities is categorized by stakeholders. The Figure also includes arrows pointing to the numeric identifier of documents presented in Figure 2.2, which are used as inputs or outputs to each process activity.

The process flow in the left-hand side describes the quality assurance activities as a proactive process occurring before and during the modeling activities. First, the *Client* or a *Consultant* uses the requirements documentation (i.e. AIR and PIR) to produce a quality control checklist (A). In parallel, the *BIM Manager* develops information management (B) and delivery matrices (E, part of the EIR), and makes sure the resources (i.e. people, software, etc.) are available and capable of performing modeling activities (C). Testing procedures are defined (D) and are used with the checklist to monitor the modeling progress (F). Reviews of the modeling process and testing procedures may be required (G). Finally, the *BIM Coordinator* updates the content of the EIR to communicate the evolution of the model and raise potential issues (H).

As for quality control, it occurs during the development of the FM model. The *BIM Coordinator* starts by setting-up the automatic tools required to perform quality control (I) and monitors the model information (e.g. version, location, phase, etc.) (J). The quality control checklists are executed by the *BIM Modeler* on the BIM models (K) and the resulting reports are delivered with the PIM. Then, the *BIM coordinator* reviews the reports and seeks solutions with the other members of the modeling team (L). Once the quality issues are fixed in the model by the *BIM Modelers* (M), the *Client* performs quality control at defined milestones and reports the corrections to be applied by the modeler (N). Finally, the *Operator* verifies the usability of the model information by importing them in the FM platform (O).

Both axes end with continual improvement, which is the third aspect of the quality management trilogy (Nelson, 2017). Although the illustrated framework focuses on file-based deliverables, the aforementioned concepts remain relevant in a database-oriented approach. Evidently, the framework should be adapted for database-oriented approach (such as open BIM databases), for example by modifying some items in the checklist, and the execution of customized queries to perform quality control. Finally, requirements management platforms are currently being adopted in the industry. They make it possible to formalize information requirements for modeling. If such platforms are integrated with the BIM authoring software, the QA and QC processes can be facilitated, as they offer guidelines for the designers and automatic control of the content of the model.

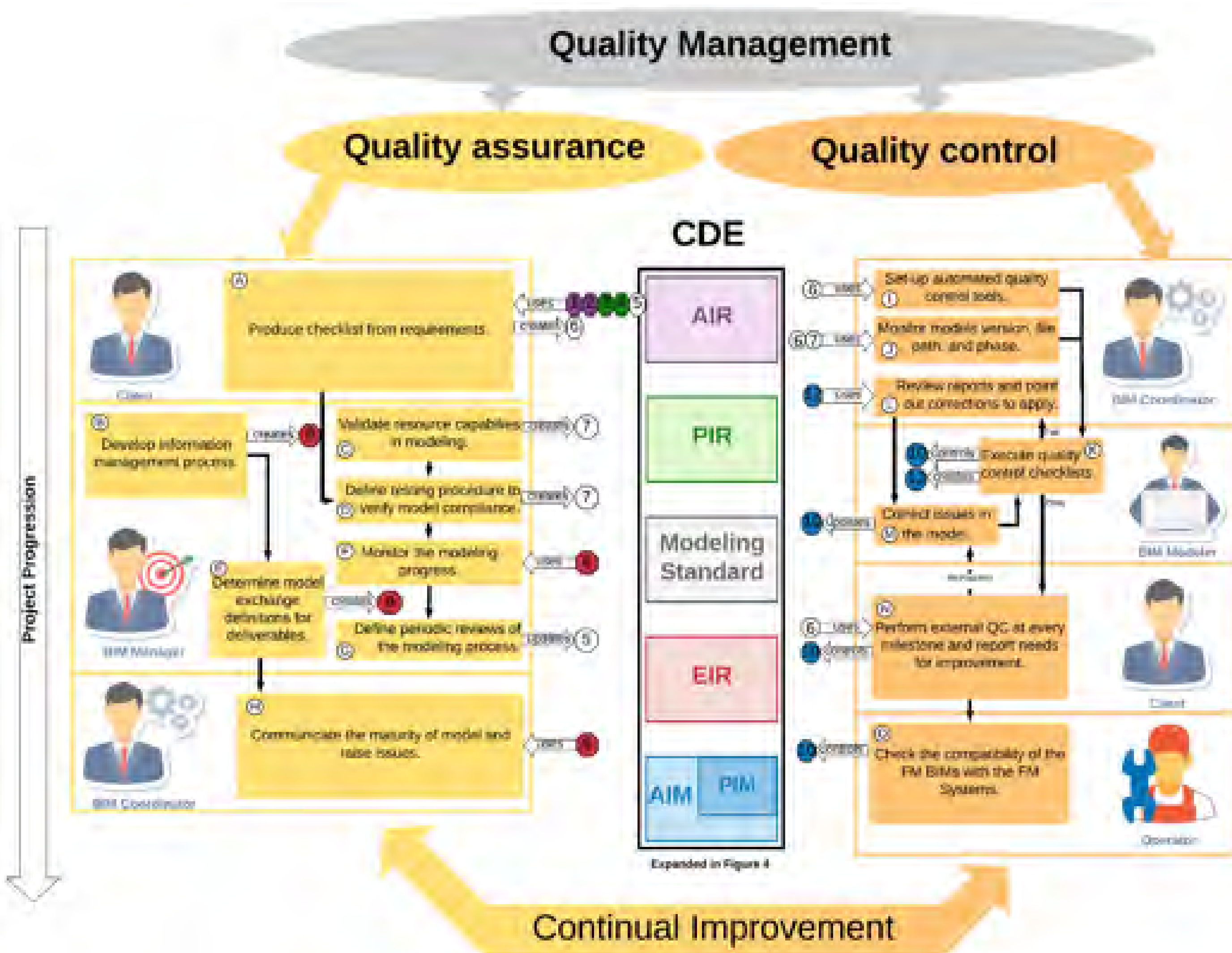


Figure 2.3 Proposed quality management framework

## 2.3 Proposed Checklist for Model Quality Control and Clean Up

Alongside the specific data required by the owner, which may vary from one project to another, the overall quality of an FM-BIM (e.g. data format, assets relationships, room definition) must be evaluated. It is proposed to develop a Quality Control Checklist that complements the owner's specific needs (i.e. naming conventions, attributes required, classification system employed). The proposed checklist specifically focuses on the overall quality of an FM-BIM (e.g. data format, assets relationships, room definition) targeting for its use during the operation phase. Since this model derives from an as-build model, a preliminary preparation step is needed to ensure that all the required data are included in the model following a comprehensive checklist. Additionally, since the as-built model contains unnecessary information for the purpose of O&M (e.g. assembly modeling, analysis and design calculations, on-site logistics), these items needs to be removed to create a more lightweight model.

To develop a comprehensive checklist, and iterative process was adopted. First. a set of requirements for a BIM model suitable for O&M use was identified by investigating both previous academic publications (e.g. Motamedi et al., 2018; Zadeh et al., 2017) and various owner documentations, such as guidelines, standards, best practices, and the BIM Execution Plans of several organizations. Although these owner documents remain succinct in terms of FM-BIM preparation, some still provide generic guidelines for model preparation. These requirements were later complemented by exploring built-in capabilities of commercial tools and finally by interacting with owners, consultants, and operators and analyzing specific project requirements during the case studies (Section 4.2).

The terminology used for categorizing each items of the checklist (listed in Table 2.1) is adapted from the work of Zadeh et al. (2017) and modified to match IFC terminology. The items in the checklist are categorized based on quality dimensions and are presented in a table for each dimension (Table 2.2 to Table 2.7). Further categorization is developed by FM product categories (e.g. element, space, system, facility as a whole) and by aspects (i.e. objects, attributes, location, relations, and integrity). The proposed checklist mentions both the required information and unnecessary information that needs to be removed. Most items of the checklist are generic for all BIM models – regardless of the authoring software – based on IFC terminology. The items with an asterisk (*) are related to a specific authoring tool (i.e. Autodesk Revit) used in the implementation of the proposed method and the case study. Some checklist items refer to various types of IR (e.g. required element properties) specific to each project or owner, and are indicated by (IR).

Table 2.1 Definitions of related terms

| **Dimension** | **Metrics to measure the value of information provided to the user.** | **Product** | **BIM objects selected for evaluation** | **Aspect** | **Characteristic selected for the evaluation of product in each quality dimension** |
|---|---|---|---|---|---|
| Completeness | All necessary information is present per the requirements. | Elements | Individual item of a building | Objects | Individual or collection of similar BIM objects relevant for FM specific task. |
| Accuracy | All required information correctly represents the relevant objects per the requirements. | Spatial Elements | Area separated from other areas by physical or functional boundaries | Attributes | Object specifications. |
| Consistency | All included information can be traced back to reality without contradiction in representation. | System | Set of MEPF assets semantically connected and working together to fulfil a specific FM task. | Relations | Relationships between assets to form a system. |
| Compliance | All included information complies with standards or regulations. | Annotations | Elements providing graphical additional information. | Location | Relationships between elements and spatial elements. |
| Clarity | All required information is provided to the user in a straightforward manner. | Drawings | Support for visualizing the information. | Integrity | Digital and functional representation of collection of assets to form a whole facility. |
| Relevancy | All included information is desired and helpful for intended usage. | Facility | Built property for the execution of specific activities. | | |

Table 2.2 FM-BIM Quality Control Checklist – Completeness

| Product | Persp. | Item Definition |
|---|---|---|
| Elements | Objects | All required elements must be included in the model. (IR) |
| | | All assets must have the correct LOD. (IR) |
| | Attributes | All required element properties must be available in the model. (IR) |
| Spatial Elements | Objects | There should not be infant spaces (e.g. on roofs, external stairs, parking, shafts). |
| | | Zones are defined in addition to spaces for grouping by function purpose. |
| | Attributes | Spaces should have finishes in addition to materials. |
| | | Every Space should be assigned to at least one Zone. |
| System | Relations | Systems must be defined and have all their individual components assigned to them. |
| Facility | Integrity | Delivered models should be complete including: plans, schedules, diagrams, and data from all disciplines. (IR) |

Table 2.3 FM-BIM Quality Control Checklist – Accuracy

| Product | Persp. | Item Definition |
|---|---|---|
| Elements | Objects | Floors should be properly defined and should not exist as ceilings. |
| | | Ceilings should not be cut by a space. |
| | Attributes | All elements properties must reflect as-built conditions. |
| | Location | Elements should have a relation to the space where they are located. |
| Spatial Elements | Objects | Spaces should be in a properly enclosed/bounded region. |
| | | Space volume should go from current level up to the slab. |
| | Attributes | All space properties must reflect as-built conditions. |
| System | Relations | No disconnection should exist in the systems. |
| Facility | Integrity | The model should be geolocated using shared coordinates. |

Table 2.4 FM-BIM Quality Control Checklist – Consistency

| Product | Persp. | Item Definition |
|---|---|---|
| Elements | Objects | There should not be duplicate elements. |
| | Attributes | There should not be duplicate properties. |
| | Location | Elements should have a relationship with the space they are accessed from. |
| Spatial Elements | Objects | There should not be multiple spaces in the same enclosed region. |
| | Attributes | Unique name and numbering should be used for spaces. |
| System | Relations | Unique name and numbering should be used for systems definition. |
| | | The architecture, structural and MEP models should match and align. |

| | | |
|---|---|---|
| Facility | Integrity | Links should be pinned in place. (*) |
| | | Links should use overlay method. (*) |
| | | Models files are organized in a standard and consistent directory structure. (IR) |

Table 2.5 FM-BIM Quality Control Checklist – Compliance

| **Product** | **Persp.** | **Item Definition** |
|---|---|---|
| Elements | Objects | Element names should conform to a standard. (IR) |
| | Attributes | Elements should be classified following a standard classification scheme. (IR) |
| | | Consistent units should be used for the properties of elements. (IR) |
| Spatial Elements | Objects | All spaces should be hosted to the level in which they contribute to the building square footage. |
| | | Floors and levels naming should be consistent and conform to a standard. (IR) |
| | | Spaces names should be consistent and conform to a standard. (IR) |
| | Attributes | Spaces should be classified following a standard classification scheme. (IR) |
| | | The area calculation method should comply with a guideline. (IR) |
| System | Relations | System names should be consistent and conform to a standard. (IR) |
| Facility | Integrity | Model file names should conform to a standard. (IR) |
| Drawings | Objects | Model view and sheets names should be consistent and conform to a standard. (IR) |
| Annotations | Objects | All annotations should be consistent and conform to a standard. (IR) |

Table 2.6 FM-BIM Quality Control Checklist – Clarity

| **Product** | **Persp.** | **Item Definition** |
|---|---|---|
| Elements | Objects | There should not be any hidden objects, filter, or annotative element in any view. |
| | | Each object should be modeled in the proper phase. (*) |
| | | Elements should be placed only in their associated models. |
| | Attributes | Values of property set should only include URLs when there is no alternative. |
| | | Elements properties name and values must be comprehensible. |
| Spatial Elements | Objects | Spaces should be visible and tagged in all plan views. (*) |
| | Attributes | Spaces properties name and values must be comprehensible. |
| System | Relations | System views of the included components and their relations must exist in the model. |
| Facility | Integrity | FM-BIM model files should be delivered standalone, preferably integrated. If the size does not allow, various discipline models should be properly linked. |
| | | Details about the compatible version of the viewing and editing applications and IFC standard should be provided per model. |
| | | Reference nesting should be avoided. (*) |
| | | Whenever possible, all links must have relative file paths. |

Table 2.7 FM-BIM Quality Control Checklist – Relevancy

| Product | Persp. | Item Definition |
|---|---|---|
| Elements | Objects | All unnecessary generic models should be removed. Generic models should be generally avoided. (*) |
| | | All unnecessary in place families should be removed. In place families should be generally avoided. (*) |
| | | All unused objects should be purged and removed. (*) |
| | | All unnecessary mass elements should be removed. Mass elements should be generally avoided. (*) |
| | | All detailed components should be removed. (*) |
| | | All groups used to model the building must be ungrouped. (*) |
| | Attributes | There should not be duplicate identification values for elements (e.g. mark, tag). |
| Spatial Elements | Objects | Non-building story levels and floors should be removed. |
| | | All unnecessary area space schemes should be removed, specifically related to structure, installation, assembly, or construction. (*) |
| | | All unnecessary color schemes should be removed, specifically related to structure, installation, assembly, or construction. (*) |
| | | There should not be multiple levels at the same elevation. |
| | Attributes | Identification values for spaces (e.g. name, number) should be unique. |
| Facility | Integrity | Scope Boxes should be removed from the model. (*) |
| | | Design Options should be removed from the model. (*) |
| | | Worksets should be discarded. (*) |
| | | Keep only the default browser organization ("all") for views, sheets and schedules. (*) |
| | | All non-transmittal linked-in files (CAD/Revit/SketchUp) should be removed from the model. |
| | | The models must be purged multiple times before it is shared. (*) |
| | | Warning count should be reduced to zero. (*) |
| Annotations | Objects | All unnecessary annotation should be deleted, specifically related to structure, installation, assembly, or construction. |
| | | Revisions information should be purged from the model. |
| | | All non-required line styles should be removed, specifically related to structure, installation, assembly, or construction. |
| | | All non-required legends should be removed, specifically related to structure, installation, assembly, or construction. |
| Drawings | Objects | All unnecessary schedules should be removed, specifically related to structure, installation, assembly, or construction. (IR) |
| | | All unnecessary sheets should be removed. (IR) |
| | | All unnecessary view templates should be removed, specifically related to structure, installation, assembly, or construction. |
| | | All views not on any sheet should be removed (e.g. plan, section, elevation, detail, test, work in progress and drafting views). |
| | | All unnecessary images should be removed. |

Finally, once the model containing all the necessary information (owner's requirements) attains a sufficient level of quality and all superfluous information has been removed, it becomes an FM-BIM and can be exported in an interoperable format, such as IFC. The model's data is then transferred to CMMS or CAFM platforms, where it will evolve in an *As-Maintained* model throughout the operations phase.

## 2.4 Proposed Quality Control Process Flow

Figure 2.4 shows the proposed process flow for FM-BIM model preparation from the *As-Built* model. The assessment of the models occurs at two levels: (1) the modeler carries out self-checks according to the modeling guidelines using a combination of automated quality control tools (pink axis); (2) at specified milestones—to be determined in the BEP—the appointing party executes a control of the models using the same combination of automated tools (yellow boxes). The last milestone verification also includes a purging step. At each milestone, the generated report automatically populates a dashboard (brown rectangle) to monitor the quality status and to determine any necessary improvements. It is recommended that the quality control tools only be utilized once the quality of the models is reasonably good, to avoid long computing times in the generation of heavy reports.

For owner organizations that are experienced in the delivery of BIM projects and have skilled BIM specialists, the QC tools can be developed internally and shared across multiple projects and with the appointed parties. Alternatively, the owner organization can appoint a dedicated consultant or mandate the creation of these tools to the appointed parties. Likewise, the creation of the dashboard and its population can be performed by the owner organization or mandated to partners. It is recommended that the dashboard and the tools are shared among the appointing and appointed parties, to better evaluate and monitor the quality of the deliverables. In Figure 2.4, the dashboard is populated by the appointing party.

After a number of iterations, the *As-Built* model passes approval to become the FM-BIM and is exported to an interoperable format, such as IFC, and delivered to the appointing party. The export of the model to IFC and its interoperability are outside the scope of this study and require further work to resolve the potential loss of information, which can occur during export. Additionally, a COBie file or a native BIM format can be delivered if requested by the owner, especially if the CMMS employed by the operators supports COBie or BIM file import.

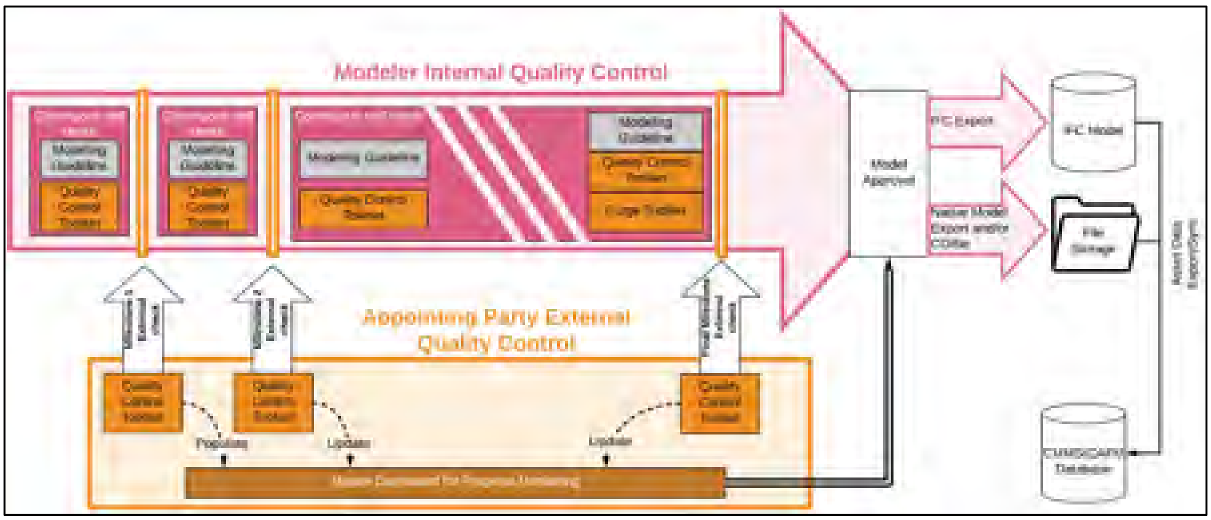


Figure 2.4 Overall workflow view of FM-BIM preparation showing checks performed at milestones

The QM process should be included in contractual documents, such as the BMP / BEP, to make sure the stakeholders deliver high quality BIM data according to the owner's needs. By sharing the checklist and tools that will be used for quality assessment with the project team, the efficiency of the quality control is increased. It also makes it possible for modelers to use the tools for self checks, which eventually decreases efforts in quality control and corrections.

## 2.5 Chapter Summary

The proposed solution elaborated in this chapter expanded the work of previous researcher by addressing issues identified, such as the use of overly generic quality control checklists, the lack of precise process flow for QA and QC, and the limited usage of automatic tools. Hence, a quality management framework was developed to ensure the delivery of high-quality FM-BIM. It included formalizing the relationships between commonly used documentation in the industry, information requirements defined in ISO standards, and corresponding project stakeholders. Additionally, the proposed framework included the process flow for various QA and QC activities to be performed by project stakeholders, and the documentation used in the process. Additionally, the framework contained a thorough QC checklist to assess the content of the models in terms of required information, modeling best practices, and superfluous information. Finally, a workflow was developed to indicate the sequence of checks performed at project milestones.

# CHAPTER 3

# DEVELOPING AND IMPLEMENTING QM TOOLS

This chapter reports on how the proposed methodology, elaborated in the previous Chapter, is used to develop and implement various tools for use in the industry. For that, a comparison of the feature of existing commercial tools is performed to identify their applicability in implementing the items of the proposed checklist (Section 2.2). The chapter reports how a collection of tools can partially correspond to the QC/QC processes. The efforts for customizing the current tools is also explained in this chapter. Additionally, the developed visual programming scripts, which correspond to some of the checklist items that could not be covered by the commercial tools is elaborated. Finally, the creation and use of a quality management dashboard to monitor the quality status of the models is elaborated.

## 3.1 Software Used

In order to apply the proposed QC checklist, several commercial model checking tools were assessed, such as Revit schedules (Version 2018), Revit Model Review (RMR, Version 2018), Revit Model Checker (RMC, Version 7.1), Solibri Model Checker (SMC, Version 9.9), and BIM Assure (Version 1.3). Although most of these tools are embedded in Revit, it is possible to import an IFC file generated in other authoring tools into Revit and then use the control tool.

The tools were assessed with regards to the proposed quality control checklist (Section 2.3) by mapping the items of the checklists to the features of the tools. The result of the feature review, based on the current version of the tools, is presented in ANNEX II and shows that a combination of tools is required because no single tool can adequately support all the required checks. Although some items of the checklist can be verified using multiple tools, some items cannot be checked by any of the available tools. Hence, the development of special tools is required using programing environments such as Dynamo.

## 3.2 Customization of tools

Revit Model Checker is a tool in which a large portion of the quality control checklist items can be programed. Model Checker allows parametric verification using scripts (e.g. verify that all Rooms have finishes). Hence, scripts for various checks has been developed in this research. Table 3.1 shows an example of the developed model-checker script. In the software used during the case studies, i.e., Autodesk Revit, building volumes include *Rooms* (used by architects) and *Spaces* (used by engineers). Both *Rooms* and *Spaces* are exported to IFCSpace. For consistency and coordination purposes, it is important that the name and number of *Rooms* and *Spaces* match. Therefore, the model-checker script (Table 3.1) that reports the spaces where their names and numbers do not match the names and numbers of their corresponding room, is developed.

Table 3.1 Example of check code using Model Checker

| Check Name | Check Code |
|---|---|
| Space matches room | (Category OST_MEPSpaces Included Code:True<br>AND Type or Instance Is Element Type = Code:False<br>AND Parameter SPACE_ASSOC_ROOM_NAME Does Not Match Parameter Code: ROOM_NAME)<br>OR (CATEGORY OST_MEPSpaces Included Code:True<br>AND Type or Instance Is Element Type = Code:False<br>AND Parameter SPACE_ASSOC_ROOM_NUMBER Does Not Match Parameter Code: ROOM_NUMBER) |

It is possible that a Revit *Room* spans multiple Revit *Spaces*, for instance in a large atrium where the heating and cooling conditions vary inside the volume. In this case, the script in Table 3.1 can be adapted using the query “does not include” instead of “does not match” (e.g. Spaces 101-A and 101-B matches Room 101).

In addition, Revit Model Review is used for specific checklist items (e.g. any enclosed volume should have a defined space, Figure 3.1a). For some of these checks, the software includes a feature to automatically address the reported errors, such as creating *Revit Rooms* in volumes where none are defined. Solibri Model Checker was also evaluated to assess its capabilities for verifying items related to the proposed FM-BIM checklist. It focuses more on the evaluation of design, such as clearances and code compliance (Figure 3.1b), which makes it a powerful tool to use in the design phase. Hence, this tool is not employed for FM-BIM QC.

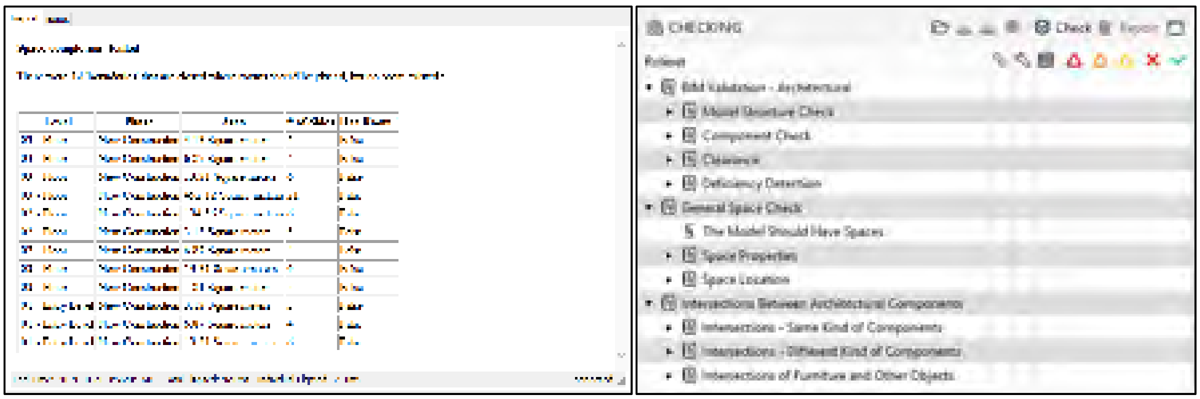


Figure 3.1 (a) Example of check report using Model Review and (b) Example of design and constructability rules in Solibri

Finally, BIM Assure is especially powerful for checks related to specific elements and parameters with a lot more granularity than the other tools. This makes it very convenient to assess the compliance of the model with AIR by providing an automated verification of the asset attribute matrix and ensuring that each object has the correct attributes.

### 3.3 Development of Software Tools for Specific Quality Control Items

In this research, Dynamo is used to implement most of the cleanup checks in a semi-automated way. Most codes list all the elements corresponding to an item of the checklist and allow the user to remove the unnecessary elements by filtering through a keyword or chain of characters (e.g. all view templates that contain “struct”). The process requires human input to identify the keywords or take the final decision on the deletion of data. This method is efficient for viewing a list of potentially unnecessary similar items and removing them simultaneously. Some other items of the checklist do not require human input, for instance Figure 3.2 presents a script for removing all superfluous browser organizations.

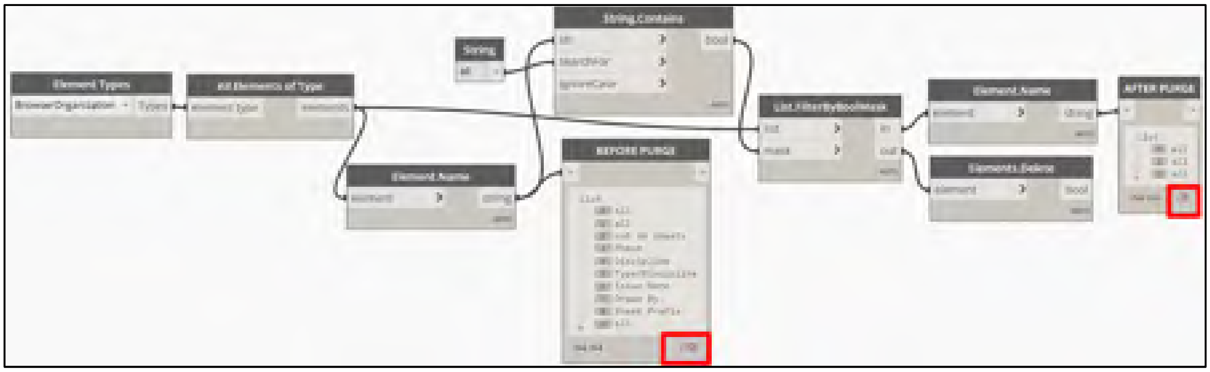

Figure 3.2 Example of a Dynamo script to remove unnecessary browser organizations

An important item in the checklist is to ensure that the spatial elements have correct height definitions, as this identifies the location association of existing elements and contributes to the soundness of architectural and engineering analysis and simulation.

Revit *Rooms* are floor-to-ceiling volumes whose properties are designed for architectural use (e.g. volumetric calculations or finishes). Revit *Spaces* are floor-to-slab volumes whose properties are organized for engineers (e.g. heating and cooling analysis). The location association of architectural components, such as furniture, doors, windows, specialty equipment is based on *Rooms* and the location association of MEP equipment, such as boilers, outlets, sprinklers, pumps, and any asset that can be found between the ceiling and the slab is based on *Spaces*.

Dynamo was utilized to provide a custom 3D visualization of the *Rooms* and *Spaces* to enable visual inspection and detection of height incompliance issues. The script in Figure 3.3 can be used for both *Rooms* and *Spaces*. The code first generates a 3D geometry for the *Rooms* or *Spaces* and displays it in the Dynamo viewer. It makes it possible to visually detect clashing *Rooms* or *Spaces*, or gaps in their definition. For instance, the rectangle in Figure 3.3 highlights a large gap in the definition of two volumes, while the oval indicates two clashing rooms, as the slight gap of the slab is not visible. The code tests whether each *Room* or *Space* intersect with one another and counts the overlapping spaces. Finally, it fills the "Comments" parameter of the *Rooms/Spaces* that are overlapping with one another.

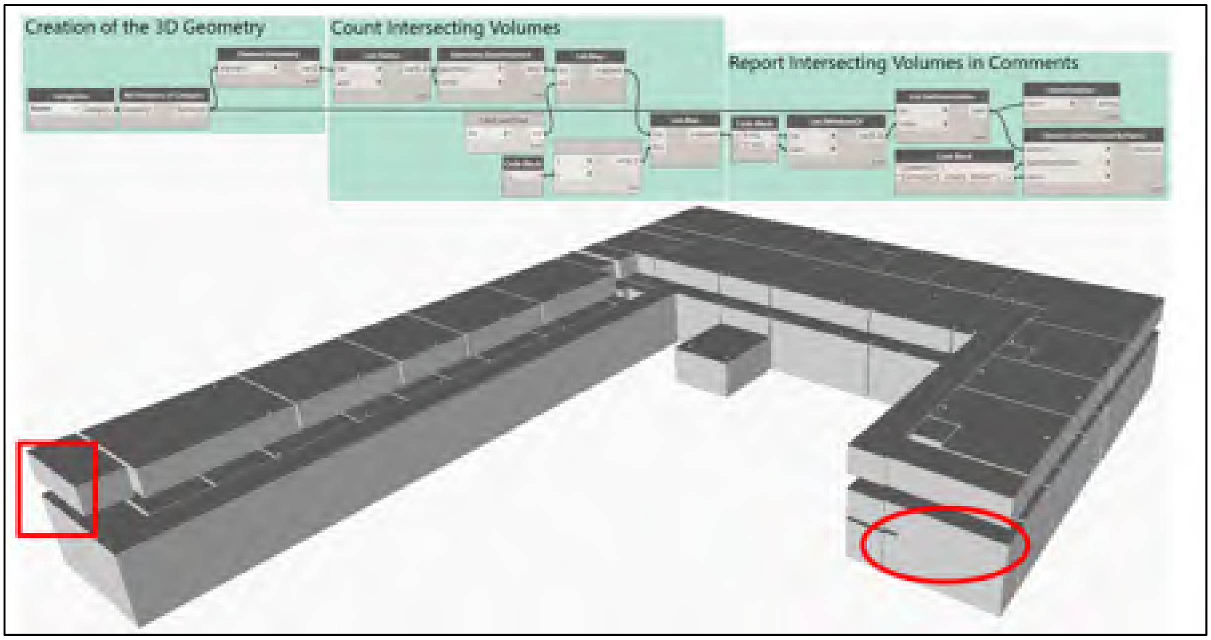


Figure 3.3 Dynamo script for Room/Space visual inspection

To provide an example of an issue resolution within the model, in addition to a visual assessment, a Dynamo script is developed to automatically adjust the height of *Rooms* and *Spaces* (Figure 3.4). First, the room bounding parameter needs to be unchecked to enable the adjustment of the height offset above the ceilings in the linked models where *Spaces* are used (i.e. MEP models) (row A). Then, the height value of the *Spaces* is adjusted to align with the slab above the current floor in order to encompass equipment located above the ceiling (row C). Finally, *Room* height is adjusted to match the ceiling height if there is one in the *Room*, to enable correct room volume calculations. Since the ceiling height varies from one *Room* to another, the script detects the first ceiling or slab above the *Room's* floor and matches its height to the *Room's* (row B).

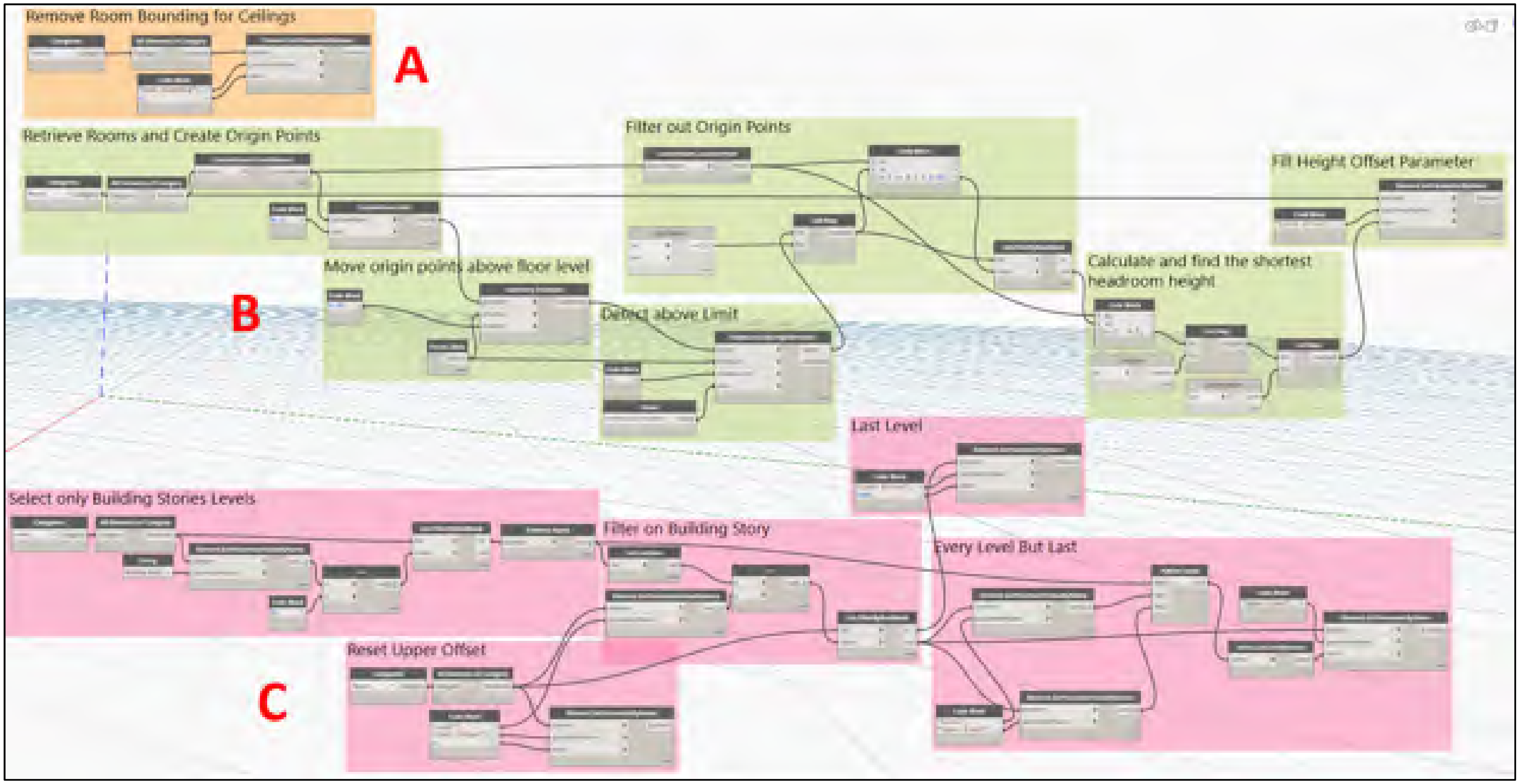


Figure 3.4 Dynamo script for automatic adjustment of Room/Space heights

### 3.4 Development of a QM Dashboard

In this study, a management dashboard (Figure 3.5) was created to keep track of the improvement of the model's quality. This dashboard is populated by the results of the assessments of the Model Checker and it displays statistics related to both quality control and purgeable items. The results of the Dynamo code could also be exported to Excel to provide additional indicators for checklist items that are not covered by Model Checker. Overall, the dashboard makes it possible to quickly visualize the model's quality status and helps to identify areas of improvement in the model.


Figure 3.5 Extract of the dashboard developed to visualize required improvements in a FM-BIM

### 3.5 Chapter Summary

This chapter discussed the capabilities of various commercial tools with regards to the evaluation of the quality of BIM models based on our developed checklist. The results of the assessment showed that no single tool is capable to accommodate all the items of the checklist and a collection of tools is required to be employed. Additionally, the tools needed to be programmed and customized to be able to correspond to items of the proposed checklist. The chapter provided examples of the scripts developed for specific quality items of the checklist (e.g., the height adjustments for *Rooms* and *Spaces*, or checks related to the clean-up of the model). Finally, a dashboard populated with the results of the checks carried-out in the tools is discussed, which enables monitoring the quality improvement of the model.

# CHAPTER 4

# CASE STUDIES: BIM QUALITY MANAGEMENT

The proposed QM method and developed tools were validated using two case studies. The completeness and relevancy of the checklists, the usability of the tools and applicability of the process were analyzed, and stakeholder feedback was gathered for future improvements.

The first case study took place during the handover phase of a large university building project and sought to verify the efficiency of the developed QC tools as well as validate the checklist. In this case study, the partner organization was the client (i.e., the University). The second case study occurred at the beginning of the construction phase of a medical center project and sought to verify and validate the applicability of the developed tools for a particular format of deliverables (i.e. COBie process). In this case, the partner organization was the general contractor. Both case studies made it possible to evaluate the process of quality management and the applicability of the tools.

## 4.1 University Campus Expansion Project

### 4.1.1 Project Presentation

École de Technologie Supérieure (ÉTS), based in Montreal (QC), is transitioning towards the creation of an integrated digital built environment for its campus. To do so, the University is exploring and implementing construction 4.0 processes and technologies in their facility operations. Thus, an ÉTS research chair specialized in the digitalization of the construction industry was mandated by the University to provide guidance during this transition. The first stage of this transition started with a pilot project of a new building (Pavilion D, shown in Figures 4.1) and the first step was the preparation and delivery of an adequate FM-BIM model. Although the delivery of BIM models was requested to the General Contractor, the models (architecture (ARC), electrical (ELE), structure (STR), mechanical (MEP) and fire protection

(FP)) were intended solely for 3D coordination purpose. As a result, they do not include the necessary information for operations management and do not follow modeling best practices.

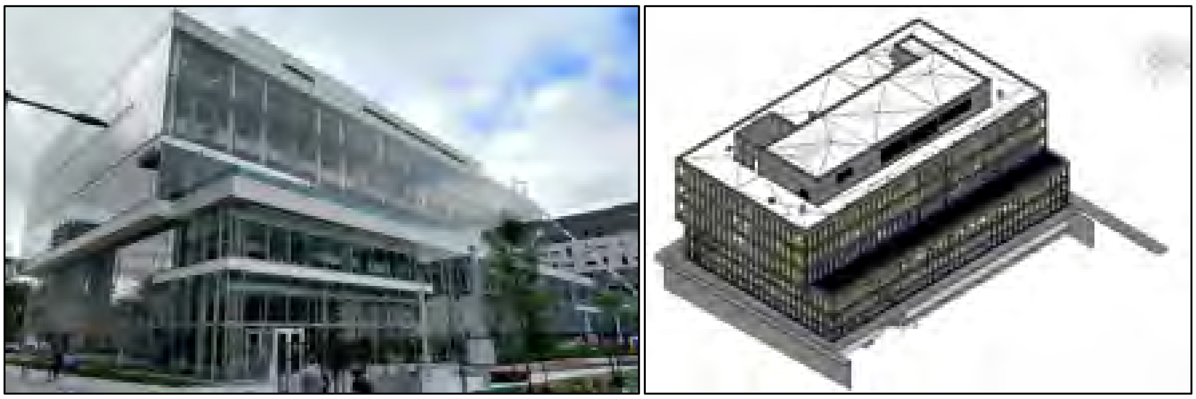

Figure 4.1 Exterior view (a) and BIM model (b) of ETS Pavilion D
(courtesy of MSDL Architecture)

In this case study, the proposed method for quality assessment of the FM-BIM models is applied to the deliverables provided by the General Contractor to improve their usability for operations. The quality of the existing models is assessed to determine the amount of efforts required to improve them. To achieve this, first, the pertinence of the checklist items was verified by consulting the facility management team and their BIM consultant.

Additionally, the efficiency of the Quality Assessment tools was analyzed and compared to the manual QC process. The checklist items, related to modeling best practice, were applied to the existing models. The Information Requirements and the information delivery needs for operations were identified in a separate research project that aimed at improving contractual documents for the campus development projects. These requirements will be used as a reference for many items of the proposed quality control checklist (e.g. classification system, naming conventions, required asset properties).

### 4.1.2 Implementation of the Quality Management Process

Although most documents related to Information Requirements are not available at the institution, the sequence of quality activities presented in the proposed quality management process (Section 2.2.3, Figure 2.3) can still be implemented. Regarding the quality assurance aspect of the Figure, the checklist used to evaluate the models already contains many modeling best practices. For future projects, it will be expanded to include the items that rely on Information Requirements (e.g. naming conventions, required properties) once these have been defined with the operators and the owner. In this project, the model improvements and the progress review were performed internally by a research team that has modeling capabilities. Regarding the quality control aspect, the processes leverages the developed tools (CHAPTER 3) to detect and correct the issues in the models, which is more thoroughly explained in the next Section (4.1.3). Ultimately, the content of the improved model will be transferred to the FM platforms used by the university.

### 4.1.3 Assessing the Efficiency of Developed Tools

The checklist items corresponding to modeling best practice were applied to the models, and the developed tools (described in CHAPTER 3) were employed to verify their efficiency. Table 4.1 shows an example of a subset of the checklist that was applied to the models. The detail of the assessment per model and some additional checks are provided in ANNEX III. The items with an asterisk (*) correspond to Revit specific checks.

Two types of assessments were conducted:

1) the time required to evaluate the models: the checklist items were assessed using a manual process (e.g. creation of a schedule, visual exploration of the model). The time required to identify the quality issues is compared to that of using automated tools (i.e. developed scripts in Revit Model Checker). The results (Table 4.1) clearly highlight the amount of time saved to evaluate the models when using an automated tool. Some of the time savings originate from the ability of Revit Model Checker to execute the checklist on the five

models simultaneously, as opposed to the manual process that requires opening each file and assessing them individually,

2) the accuracy of the assessment: the number of errors detected when using a manual process is compared to that of an automated tool. This demonstrates that the scripts developed in Revit Model Checker are able to detect non-compliant items that would otherwise be inaccessible for the user when visually exploring the model (e.g. Detail Components or Groups) or when listing objects in Revit schedules.

Two research aids (Ms. Lamia Belharet and Ms. Nouha Boufares), who are Revit users, helped to perform the two types of assessment. The use of external resources to perform the assessments enabled providing an unbiased data collection to carry-out verification and analysis.

Table 4.1 Comparison between time required and number of errors detected in manual and automated process (for a subset of the checklist)

| **Item Definition** | **Time** | | **# of identified issues** | |
|---|---|---|---|---|
| | Man. | Aut. | Man. | Aut. |
| The model should be geolocated | 03:30 | 00:15 | 0 | 0 |
| The models must match and align | 03:05 | 00:10 | 2 | 2 |
| Links should be pinned in place (*) | 14:38 | 00:30 | 5 | 44 |
| Ceiling must not be room-bounded (*) | 04:45 | 00:06 | 6 | 234 |
| Spaces must be placed | 03:31 | 00:03 | 25 | 28 |
| Spaces must be in enclosed regions and must not overlap | 02:00 | 00:03 | 0 | 2 |
| Elements should be placed in their associated models | 23:27 | 00:28 | 11731 | 16520 |
| Elements should have a relation with the space they are located in | 18:00 | 00:14 | 17960 | 18136 |

| Item Definition | Time | | # of identified issues | |
|---|---|---|---|---|
| | Man. | Aut. | Man. | Aut. |
| There should not be any hidden objects, filter, or annotative element in any view | 39:13 | 01:12 | 434 | 860 |
| Generic Models must be avoided (*) | 06:06 | 00:22 | 1700 | 1705 |
| Mass must be avoided (*) | 04:37 | 00:19 | 6 | 12 |
| Detail components must be avoided (*) | 04:19 | 00:16 | 21962 | 22017 |
| Groups must be dissociated (*) | 20:15 | 00:16 | 67 | 2985 |
| Views that are not on any sheet must be purged | 05:12 | 00:16 | 210 | 209 |
| Total | 01:44:38 | 04:30 | 54108 | 62754 |

The Table compares the time spent and the number of detected errors for the assessment of the models. The Table can be further expanded by comparing the time required to fix the detected issues manually and automatically. The developed tools to automatically fix the detected issues were also employed.  For instance, the developed script to automatically set the height of Revit *Rooms* and *Spaces* (Section 3.3) took around 10 minutes, as opposed to 40 minutes when the correction is performed manually. Furthermore, contrary to a manual process where the effort required to correct the model increase with the size of the model (i.e. the more rooms in the building, the longer it takes to manually fix them), the execution time remains relatively constant. Developing tools to automatically fix the issues in the model, and the assessment of the tools' efficiency and accuracy, is beyond the scope of this research.

Additionally, the changes in the file size of the model can be assessed. It is expected that the size of the files increases as the missing operation and maintenance data (e.g. new parameters, classification value) are added to the file, and decreases as the unnecessary data for operation is removed. This analysis will be performed in a separate research project.

### 4.1.4 Addressing missing requirements

The results of the evaluation of the models, partially listed in Table 4.1, clearly demonstrate the need to improve their quality in order to be used for facility operations. Once the Information Requirements are determined, the naming conventions, classifications systems, and correct LOD must be implemented in the models.

In addition, relevant parameters for the use during the O&M need to be added and filled in the models. For a trained Revit modeler, the duration for creating one parameter was measured at in average 1min10 in each model, using the dialog box shown in Figure 4.2 (10 parameters were successively created to obtain an average). Advanced owner organizations, such as Veterans Affairs (US Department of Veterans Affairs, 2017), require around 150 different parameters to be created in the delivered models. Therefore, the creation of the parameters would require around 3h per model. Alternatively, it is possible to create the parameters required by the operators only in the first model and share them across subsequent models and projects. Using the *Shared Parameter* functionality of Revit makes it possible to drastically reduce the time required to create these parameters and also ensure their consistency between models and projects.

However, the task of finding the right values for the required properties is very daunting, as the operators will need to dig in the project documentation (e.g. shop drawings, specifications, warranty manuals, etc.) to find these values. Instead, the process of creating the required parameters and filling their values must be performed by the designers (for design properties, e.g. voltage or warranty duration) and the builder (for construction properties, e.g. serial number or installation date). It is thus very important that required properties, as a part of the AIR, are requested early in the project lifecycle.

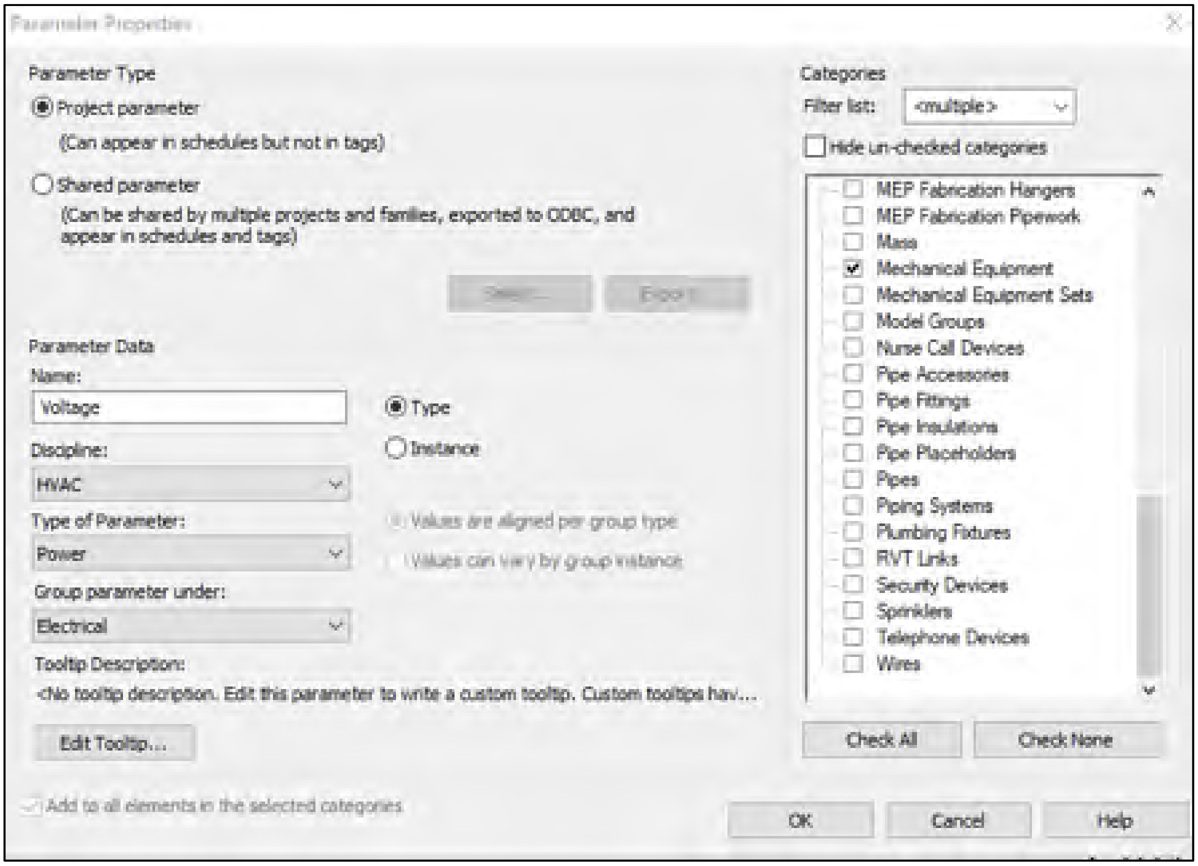


Figure 4.2 Creation of a new parameter in Revit

### 4.1.5 Upcoming opportunities

The proposed checklist and the developed tools were validated by the consultants appointed by the university. Both the checklist and the tools, along with the knowledge gained by identifying the operators' needs, will greatly benefit the university in its digitalization efforts.

Yet, further work is required in additional projects to bring the models to a suitable level of quality in an efficient way. These additional tasks include a thorough, rigorous, and systemic definition of the requirements of the facility operators, and the development of more tools to automatically correct the models according to the proposed checklist.

To maximize the potential of these new methods, it is crucial that the commitment of the FM department of the university be sustained and that contractual requirements be developed to secure the delivery of usable models. This can be achieved by integrating the checklist in the contract, alongside the proposed process.

## 4.2 Care Center Project

### 4.2.1 Project presentation

The second case study was performed in a Design-Build project of a care-center (Figure 4.3) mandated by Alberta Health Service (AHS), the owner, and Alberta Infrastructure (AI), the client. AI assisted AHS in defining their requirements for the BIM deliverables. The research team worked with the BIM delivery team of Pomerleau, the Design-Builder of the project, based in Quebec and one of the pioneers in BIM implementation in Canada. Pomerleau was in charge of managing the production of as-built BIM content and the delivery of operation data in the form of a customized COBie database. The research team's involvement in the project was to assist the Design-Builder in evaluating and improving the quality of the deliverables.

The following steps were undertaken in the case study:

1) identification of current issues in the BEP and existing deliverables (section 4.2.3);
2) addition of new requirements and application of proposed procedures (section 4.2.4) and tools (section 4.2.5);
3) improvement of the deliverables (section 4.2.6).

Figure 4.3 Photo realistic rendering of the BIM model of Willowsquare Continuing Care (courtesy of S2 Architecture)

### 4.2.2 FM-Platform and COBie Mandate

AHS centrally operates its installations with eFacilities, a custom made CMMS that derives from Oracle Unifier (Figure 4.4). AHS maintenance practices for their 1500 facilities rely heavily on reactive maintenance (two third of their 3.3 million work orders during the past five years). Moreover, transferring the project data into their FM platform requires them to hire dedicated staff. Since the data input in the FM platform is a manual process, only 15% of the operations data was transferred in the platform after two years in one of AHS previous projects. As a result, AHS decided to mandate COBie delivery for their new construction project to reduce the extended efforts for data transfer at project handover.

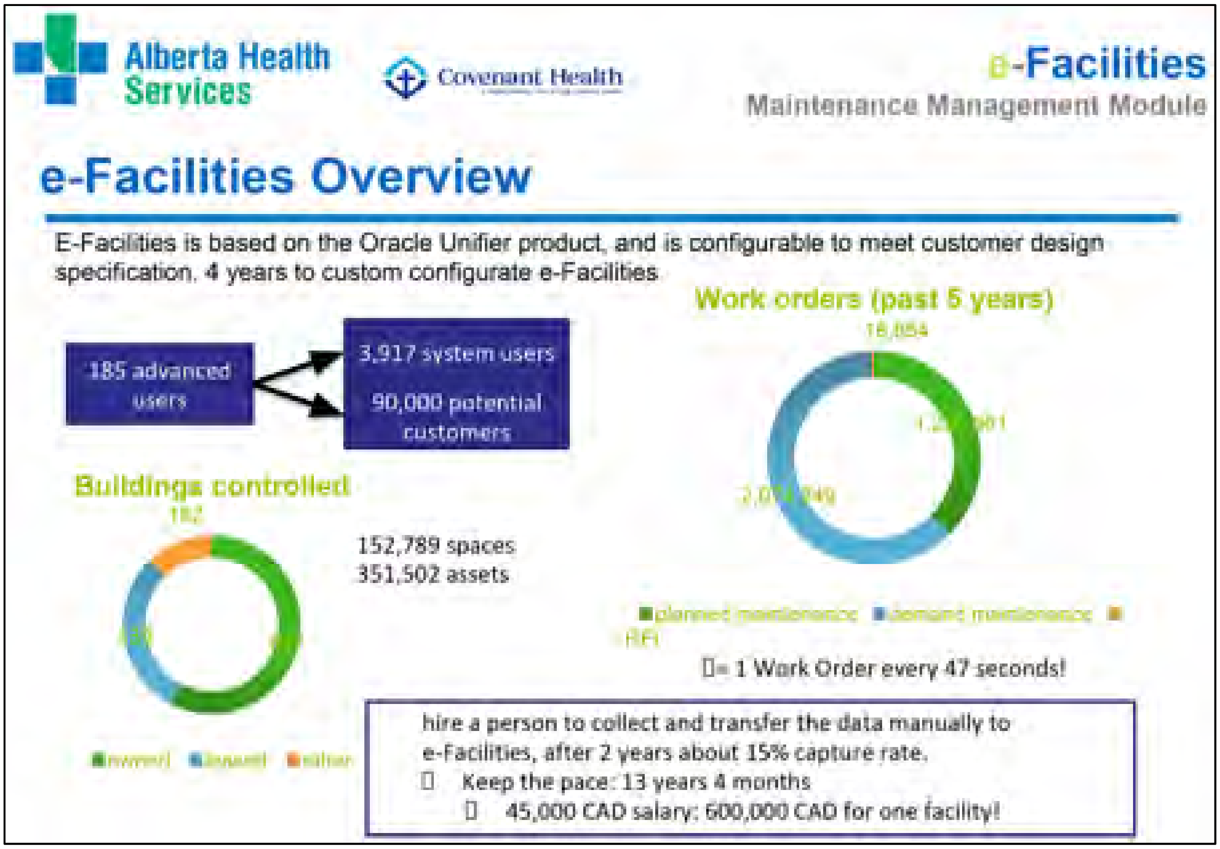


Figure 4.4 Striking Figures regarding maintenance and data transfer for eFacilities (courtesy of AHS)

AHS mapped the required attribute fields of assets in eFacilities with COBie parameters and included them as Information Requirements in the initial contract, alongside the COBie rules defined in the NIBS standard (detailed in Section 4.2.4) for quality control. In the initial contract, only the design-related sheets of standard COBie worksheets (i.e. Contacts, Facility, Floor, Space, Type, Component, System) were requested. For each of these sheets, a list of required COBie parameters was communicated in the BEP.

### 4.2.3 Identified Issues

The research team joined the project at the beginning of the construction phase and analyzed contractual documents and the BEP, specifically for the quality aspects. The following is an excerpt from the BEP regarding QC:

*"BIM Model Quality Control*

*A quality check is mandatory during the multi-disciplinary coordination review.*

*The following procedure is an example of an additional quality control that must be done a month before the official release of the BIM models:*

- *Revise randomly the documented information*
- *If the rate of mistakes is less than 3%, document the warning reasons and bring the modifications to the rest of the model*
- *If the error rate is between 3 and 5%, revise randomly an additional 15% of documented information*
  - *If the error rate is more than 3% after reviewing 25% of the document, the project team must update and resubmit the documents, so to not delay the progression of the work*
  - *If the rate is less than 3% after reviewing 25% of the document, identify the reasons for the errors and make the changes to the rest of the model*
- *If the rate is over 5%, the project team must update and resubmit the documents, so to not delay the progression of the work "*

The QC procedure mandated in the BEP is based on a random and partial assessment of information, instead of systematically assessing the provided information. Additionally, making decisions based on a percentage of mistakes can only be achieved with a rigorous process of defining what are the possible errors (quality dimensions) and reporting these errors (using a quality control checklist). Hence, it was necessary to include a thorough quality control checklist in the BEP, alongside mandating the use of automatic tools to perform the quality control and adding the procedure that guides the use of such tools. Further analysis of the BEP highlighted that, aside of the required COBie fields, no documentation was in place with regards to information requirements, such as asset attribute matrix or LOD/LOI Tables. Moreover, modeling standard and asset attributes outside of the COBie scope were not defined. Likewise, no naming conventions were mentioned, and no classification system was selected at this time.

At the beginning of the construction phase, four existing design models relevant for FM and COBie export (i.e. Architectural (ARC), Electrical (ELE), Mechanical (MEC), and Fire

Protection (FP)) were provided. The software used was Autodesk Revit with specific add-ins used to generate COBie deliverables (i.e. Classification Manager and COBie Extension). The COBie process had already started and some data entry and configuration occurred prior to the analysis of the quality of the content.

Example A (Figure 4.5) is an extract of the COBie.Type built-in Revit schedule in the existing ARC model at the beginning of the construction phase. It shows missing values for most of the Category and Description fields. Manufacturer, Model Number and Warranty Information were seldom populated (red box in Figure 18). Additionally, the naming of objects was not consistent, thus limiting the understanding of what the object is (yellow box in Figure 18). Finally, some items are placed in the ARC model, whereas they should be in other models (e.g. plumbing drain in MEP or light fixtures in ELE).

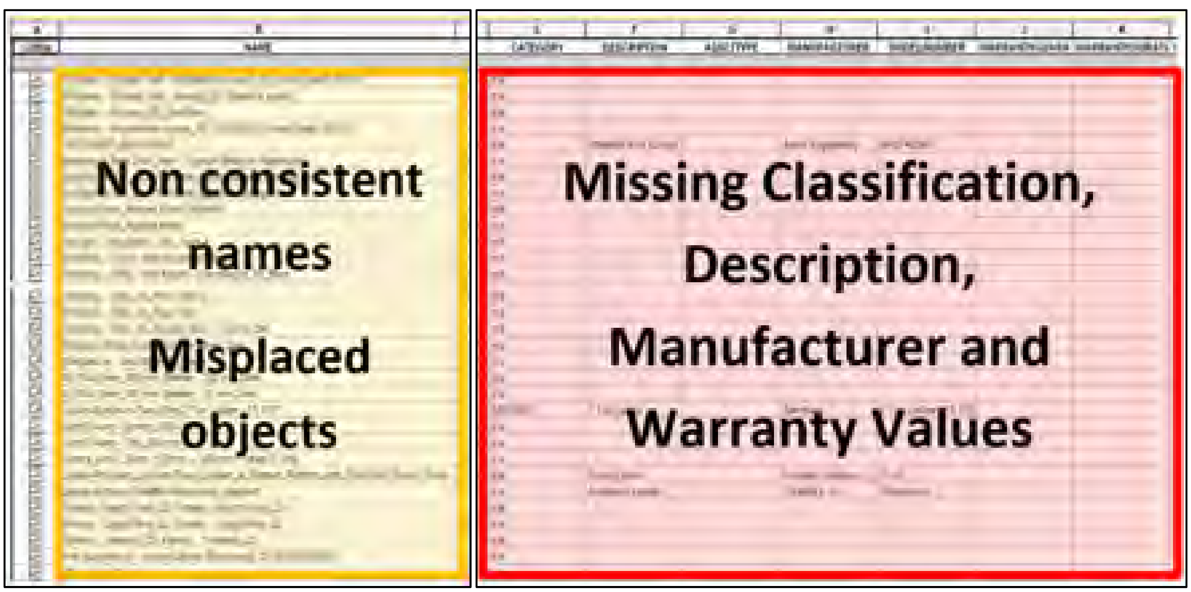


Figure 4.5 Quality issues for COBie.Type schedule in ARC model

Example B (MEP model) shows missing values for classification and description. Additionally, despite the fact that the COBie best practice (East et al., 2017) recommends human-readable names, some system names were both incomprehensible (e.g. the abbreviation “CNDWR” in Figure 4.6), redundant (e.g. the duplicate use of the abbreviated code “CNDWR-

CNDWR" in Figure 19), and inconsistent naming in terms of using abbreviated codes ("Chilled Water Return_CWR" vs. "CNDWR-CNDWR").

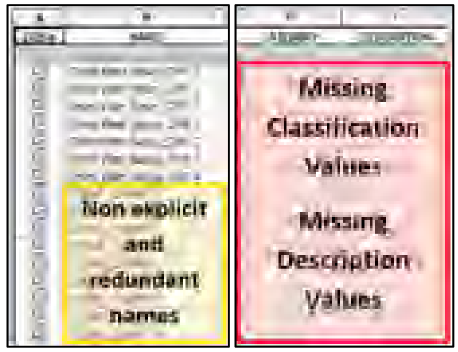


Figure 4.6 Quality issues for COBie.System schedule in MEC model

Finally, the COBie.Component schedule in the MEC model shows many components with no Space definition. The same issues of the lack of consistency (e.g. Air Conditioning use the prefix "AC" but Condensing Units use the full text "Condensing Unit" in Figure 4.7), incomprehensible names (e.g. "AC PFKY-P12NHMU 1TON"), and redundancies (e.g. Component names are doubled such as "Condensing Unit PUMY – P60NKMU1_Condensing Unit PUMY – P60NKMU1") were also found in this schedule. Finally, although the Serial Number and the Installation Date were missing in the schedules, these properties would be populated at the end of the construction phase with the information provided by the site team.

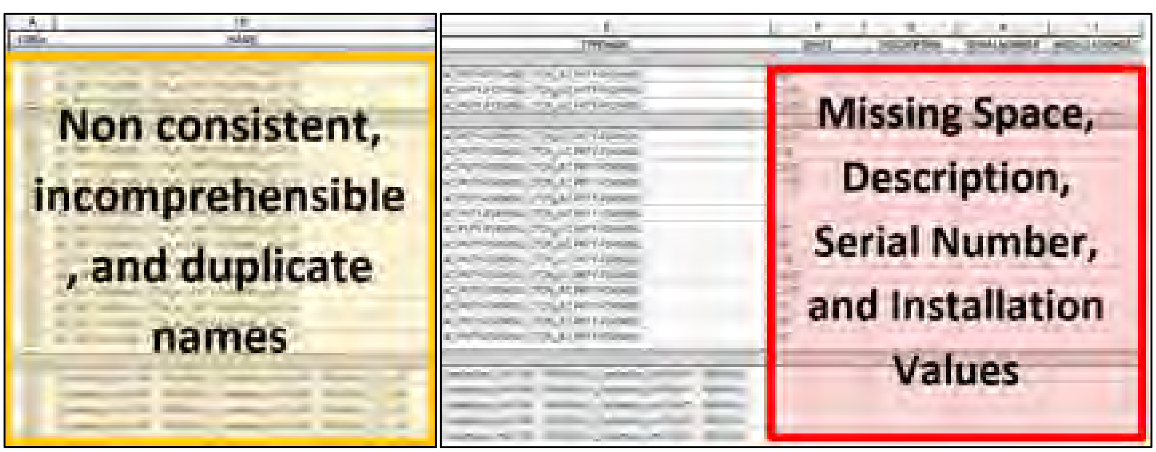


Figure 4.7 Quality issues for COBie.Component schedule in MEC model

The overall analysis of the existing design models showed major quality issues. Most of the required COBie properties to be populated by the architects and the engineers (e.g. classification, description, manufacturer, warranty information, etc.) were not added to the model, due to the lack of explicit contractual requirements. Since the designers drastically reduced their involvement in the project after the design phase, addressing all the quality-related issues and adding the missing data had to be done by the General Contractor. Additional quality problems included lack of consistency in the naming of objects and their placement in wrong models. This is explained by the project's lack of thorough and precise definition of requirements.

Another notable problem was that the definition of the Revit *Rooms* and *Spaces* in the models led to major issues in the localization of assets. Some infant volumes were in the models with no *Rooms* or *Spaces* defined. In the engineer models, Revit *Spaces* were either not created, or had their height stopped at the ceiling. Revit *Spaces* were also missing on the site or on the roof. These inadequately defined *Spaces* prevented the localisation of all equipment around the building, on its roof, and between the ceilings and the slabs.

Finally, the built-in COBie schedules in Revit did not display the COBie parameters that were mapped with native Revit parameters (e.g. COBie.Space.Description were mapped with the Revit "*Room Name*" parameter). Thus, some values that had been populated in non-COBie fields were not displayed in these schedules. In addition, the schedules only gave a general view of the quality status of the deliverables, they lack a systemic and quantifiable assessment of the information. Thus, the built-in COBie schedules were not sufficient to thoroughly evaluate the quality of the information. To make sure these values are correctly filled and comply with the requirements, automatic quality control tools such as those presented in the proposed method were necessary.

### 4.2.4 Application of the Proposed Methods

Regarding the proposed quality management framework (Figure 2.3), in this case study, the IR documentation related to the project was poorly defined. Although the use of COBie made it possible to define the AIR in a standard format and enabled an efficient population of the AIM, the other documents in the Modeling Standards (e.g. modeling best practices) and EIR (e.g. LOD definition, model delivery matrix, etc.) were poorly defined.

Therefore, after having evaluated the content of the contractual documentation and the overall quality of the existing models, the researchers proposed clarifications in the definition of the requirements (e.g. the choice of classification system, guidelines related to naming conventions, or additional asset attributes) to mitigate most of the aforementioned issues. Consequently, the owner selected the Uniformat classification system for both the COBie Types and Systems. Finally, recommendations were provided as to the naming of objects. Although these decisions were made late in the project (construction advancement around 50%), they addressed multiple gaps in definition of the requirements and made it possible to improve the quality of the information.

Moreover, the use of the quality control checklist, the developed QC tools, and the QC procedures were recommended for the remainder of the project. However, since the proposed method (Figure 2.3) was not possible to be fully implemented, due to the contractual constraints and the timeframe when the intervention took place, some of the quality assurance process steps (such as validation of resource capabilities, definition of model exchanges and communication of model quality status) were not employed.

The QC process (orange axis in Figure 2.3) was employed and deemed efficient. Once the new requirements definition was in place, the checklist was adapted to suit the specific project delivery method (i.e. delivering the required O&M data in the COBie format). Then, the research team implemented the proposed automatic QC tools to improve the quality of the models and make them compliant to the COBie standards and the owner requirements.

Following the framework, identified issues were communicated to the corresponding designers when the client performed an external verification of the deliverables. Finally, the compatibility of the data with the FM platform was ensured by the operators through data transfer activities.

In this project, the proposed FM-BIM preparation process (Figure 2.4) was also applied to the model. The implemented QC tools (Sections 3.2 and 3.3) and the proposed dashboard (Section 3.4) were adapted for the specific requirements of the project (i.e. delivering the data in COBie format). The tools and the dashboard were supported by continuous self-checks performed by the appointed party (i.e. the Design-Builder) to monitor the progress of the quality assessment.

In this project, the proposed method was not adopted at the client's side. This is because changing established processes at a large governmental organization requires time and several approval processes. Consequently, the automatic QC tools and dashboard were not employed by the client at regular milestones, instead, the responsibility to perform quality control was entirely left to the general contractor. At the end of the project, the client only transferred the delivered COBie file to the owner, who manually assessed its content and provided comments. Finally, the models were delivered in IFC format and the FM database was populated by importing the COBie file.

### 4.2.5 Adapting the Proposed QC Tools and Processes for COBie Deliverables

The proposed method for quality management (Figure 2.3) was modified for this project to correspond to COBie data exchange requirements, which is presented in Figure 4.8. The terminology and the concepts presented in Figure 2.2 can be adapted to be used regardless of the project delivery mode. The procedure includes a detailed identification of data requirements by the client and the owner (e.g. assets and parameters to be included, classification standard and naming conventions). Once the requirements definition is completed, the project manager (Design-Builder in this case), together with the designers, can set up the models of various disciplines accordingly by creating the parameters and choosing the appropriate classification system. The task of populating the model with the required COBie data is to be carried out by the corresponding designer (modeling process box). Quality control is then performed by the project manager, using COBie schedules embedded in Revit and the Model Checker. Once the model is complete, the COBie file can be generated and assessed using QC Reporter (quality control box). Finally, the COBie file and the quality reports are shared with the client for evaluation. If the file complies to the requirements, it can be imported in the custom FM platform of the client, otherwise it loops back to the model update and quality control steps.

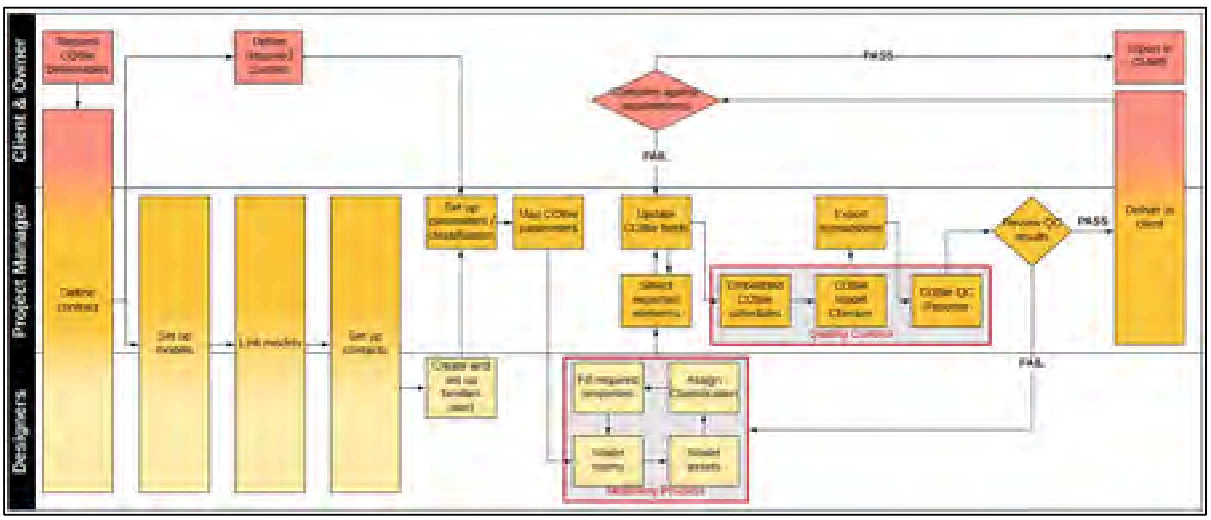


Figure 4.8 Proposed workflow to deliver a high-quality COBie

For the purpose of assessing the quality of deliverables, the BEP required the COBie information to comply with a collection of rules developed by the NIBS (National Institute of Building Sciences, 2015a) and are applied to all parameters in each COBie sheet (Table 4.2). Common rules require for instance that the parameter not be null (a value needs to be filled), the parameter not to be empty (a value or n/a need to be filled) or the maintaining of cross-referencing between sheets. Most NIBS rules correspond to various items of the proposed checklist (e.g *NotNull* is similar to several items of the "Completeness" section of the checklist, whereas *Unique* is similar to several items of the "Consistency" section). Additionally, the rules include items that are specific to the COBie deliverables (e.g. *CrossReference* or *AtLeastOneRow*).

Table 4.2 NIBS rules applicable on COBie parameters for the project

| COBie Rule Name | COBie Rule Definition |
|---|---|
| NotNull | Must have a text value that is not n/a or empty |
| NotEmpty | Must have a text value (n/a is acceptable) |
| Unique | Must be unique within the scope of the worksheet |
| CrossReference | Must match a referenced Name column in another worksheet |
| OneAndOnlyOneFacilityFound | Only one facility is allowed |
| ValidNumber | Must represent a valid number – n/a is not acceptable |
| ValidNumberOrNA | If text is provided it must represent valid number or n/a |
| AtLeastOneRowPresent | Worksheet must have at least one row |
| ZeroOrGreaterOrNA | If text is provided it must represent a valid number greater than zero or n/a |

To evaluate the compliance of the model's data with the COBie rules, two tools were customized, COBie QC Reporter and Revit Model Checker. COBie QC Reporter, a java-based program initially mandated by the client, is used to assess the content of COBie files. However, the tool is complicated to work with and is not capable of verifying all the required data values for the project. In order to assess the remaining data values and provide a more robust workflow, the research team developed new rulesets using Revit Model Checker. Although there is an existing template in Model Checker for COBie assessment, its analysis showed that it does not include all the required rules and fails to detect many existing errors. Thus, a new set of checks was programmed in Model Checker. The BEP was updated to mention the use of Model Checker in addition to QC Reporter.

Table 4.3 shows a comparison of the number of NIBS COBie rules assessed by each tool. The detailed list of the rules defined by the NIBS are found in ANNEX IV. The numbers in each column in Table 6 indicate the number of rules for each COBie sheet that can be assessed by each tool (total of 156 rules) and the results demonstrate that none of these tools is capable of assessing all the rules and they need to be used in parallel.

Table 4.3 Comparison of number of rules assessed by each COBie control tool

| COBie Sheet Name | Only Model Checker | Only QC Reporter | Shared between tools |
|---|---|---|---|
| Contact | 0 | 20 | 0 |
| Facility | 5 | 2 | 14 |
| Floor | 1 | 1 | 10 |
| Space | 1 | 1 | 15 |
| Zone | 1 | 3 | 7 |
| Type | 4 | 7 | 32 |
| Component | 0 | 6 | 14 |
| System | 1 | 3 | 8 |

Once the two tools have been customized to include all the required COBie rules, they were used to quantify the quality issues discovered in Section 4.2.3 and highlight the areas of improvements. First, the Model Checker codes are executed in the models, then the data is exported in an Excel format and the QC Reporter is used to assess the remaining rules (e.g., contact rules, such as *Contact.Email.Unique* or sheet cross-referencing, such as *Component.TypeName.CrossReference*). Table 4.4 shows an extract of the errors listed in the report showing the assessment of the COBie data available at the beginning of the construction phase using Model Checker and QC Reporter. The rows with an asterisk (*) present the rules that were later fixed using our proposed tools (see Subsection 4.2.6).

Table 4.4 Number of major errors in original COBie file according to Model Checker and QC Reporter

| COBie Rules | | Errors | # of elements |
|---|---|---|---|
| Space | Name.Unique (*) | 4 | 451 |
| | Category.NotNull (*) | 451 | |
| | Category.Format (OmniClass 13) (*) | 451 | |
| Type | AComponentForEachType | 111 | 607 |
| | Name.Unique (*) | 3 | |
| | Category.NotNull (*) | 160 | |
| | Category.Format (Uniformat 2) (*) | 500 | |
| | Description.NotNull | 481 | |
| | AssetType.NotNull | 607 | |
| | Manufacturer.NotNull | 488 | |
| | Manufacturer.CrossReference (Contact) | 607 | |
| | ModelNumber.NotNull | 494 | |
| | WarrantyGuarantorParts.NotNull | 607 | |
| | WarrantyGuarantorParts.CrossReference (Contact) | 607 | |
| | WarrantyGuarantorLabor.NotNull | 607 | |
| | WarrantyGuarantorLabor.CrossReference (Contact) | 607 | |
| | WarrantyDurationUnit.NotNull | 607 | |
| | DurationUnit.NotNull | 607 | |
| Component | Space.NotNull (*) | 12168 | 16678 |
| | Space.CrossReference (*) | 12790 | |
| | Description.NotNull | 16678 | |
| | SerialNumber.NotNull | 16678 | |
| | InstallationDate.NotNull | 16678 | |
| | WarrantyStartDate.NotNull | 16678 | |
| Syste | PrimaryKey.Unique (Name, Category, ComponentNames) (*) | 3049 | 75435 |

| COBie Rules | | Errors | # of elements |
|---|---|---|---|
| | Category.NotNull (*) | 75435 | |
| | Category.Format (Uniformat 2) (*) | 75435 | |
| | ComponentNames.CrossReference (*) | 64907 | |

Additionally, some non-COBie related checks proposed in this research were run to improve the quality of the model. For example, the developed Dynamo scripts (Section 3.3) to assess and automatically fix the height compliance of rooms and spaces were applied. This ensures that each COBie component was correctly included in a *Room* (in the architecture model) or *Space* (in the engineer's models). Without this script, multiple hours would have been necessary to manually correct the settings of Revit Rooms and Spaces. Other Model Checker codes were run to detect the elements present in the wrong model (e.g. mechanical equipment in the architectural model), detect the errors in the geolocation of the models, and ensure that generic elements are replaced by specific object categories (e.g. mechanical equipment, light fixtures).

### 4.2.6 Evaluation of results

Once the various checks were applied and the changes were made to the models, QC assessment was performed by the general contractor. It showed a drastic reduction in the number of errors in the resulting COBie file. The issues that were addressed by employing the proposed checks and automatic tools – with an asterisk (*) in Table 4.4 - include items such as the localisation of assets, their categories, and the cross-referencing between the sheets. The number of errors for these items was reduced to zero. Therefore, the use of implemented QC tools and the application of the proposed procedures made it possible to notably increase the quality of the deliverables.

However, several missing data (e.g. model number, manufacturer, warranty data) cannot be automatically fixed and needs to be added by the designers and contractors, instead of the QC agent. Other missing data (e.g. serial number and installation date) could not be filled until it is retrieved from the site team at the time of handover.

To better visualize the progress made in the evaluation of the quality of the deliverables, the adapted dashboard was populated with the results of the assessment of the deliverables. Figure 4.9 shows the dashboard with data populated towards the end of construction, after the intervention. It displays the number of errors for each COBie rule compared to the number of elements, similar to the content shown in Table 4.4 (e.g. there are 60 uncompliant Components regarding the *Component.Space.NotNull* rule, out of 1943 Components). The number of elements slightly differs from the ones in Table 4.4, as new elements were added to the COBie export since the initial evaluation was performed. The blue bars show the target (i.e. the number of elements that should have their properties filled) and the orange bars show the current state. The total score is calculated by dividing the number of compliant elements by the total number of elements exported in the COBie file (COBie elements in Figure 4.9).

Two versions of this dashboard were created: one was designed to evaluate all the standard COBie data (whether mandatory or optional) and one was specifically designed to display only the project requirements (mandatory data only). The use of the project-specific dashboard clearly demonstrated the efficiency of the developed tools, as the compliance score notably increased between the files produced before the intervention and after the corrections were applied. The remaining missing or wrong fields required to reach 100% compliance were mainly due to missing data that should have been provided by the designers.

The proposed checklist was validated by the General Contractor as it demonstrated its relevancy to improve the quality of the deliverables. Both the client and the General Contractor were satisfied with the set of tools developed and benefitted from the improved deliverables the tools helped to achieve. The checklist, tools and procedures will improve the digital delivery practices of the General Contractor and offer a competitive advantage in the FM-BIM market.


Figure 4.9 Extract of the dashboard developed to visualize required improvements in a COBie set

# CHAPTER 5

# DISCUSSION

Two case studies with different time of intervention in different project settings were performed. In both case studies, similar issues of low-quality models were observed. It was mainly due to a lack of clear information requirements and guidelines for modeling, and to a lack of quality management in place such as QC processes. The proposed framework was then applied to assess how the new method and tools can improve the processes. In the first case study, the tools were verified and their time saving potential was assessed. In the second case study, the process and tools were implemented, and their efficiency was assessed for specific AIR (which was COBie). However, since the framework was mostly evaluated in isolated parts – for specific project phases, setting, partners, due to time and contractual constraints – further work is required to evaluate the whole framework throughout all phases of the projects and with every stakeholder.

The main observations drawn during the case studies were the importance of working with the owners to develop well-defined IRs and modeling best practices and to include in the contract. It was observed that failure to do so resulted in deliverables lacking relevant information and the need to make major corrections to the models to render them useful for the O&M phase of the facility. By including various types of IRs in contractual documentations, the various stakeholders can clearly identify the information they need to deliver and their liability.

The applicability of the checklist was validated when it came to provide high-quality deliverables that complied to project requirements and that are usable for FM purposes. Besides, the observations made during the case studies provided feedback and enabled to finetune the definition of the artifacts' requirements started during the literature review (i.e. new items in the checklist). The observations were the results of the involvement of the researcher in multiple project meetings, interaction with the project teams, and thorough analysis of project specific requirements to identify additional needs for the artifacts.

Furthermore, even though the proposed method focuses mainly on quality control of FM-BIM models, to achieve a good quality model, it is important that QC be performed during the design and construction phases. There are two main reasons for this: 1) having an existing *As-Built* model of good quality reduces the effort required to use it during the O&M after converting it to FM-BIM, 2) most of the participants involved in the creation and updates of the model (i.e. architects and engineers) are less likely to be actively involved towards the end of the construction phase and at the time of handover. For these reasons, it is crucial to start including operations data during the design and construction phases and to identify the liable party that is to deliver each information (e.g. using responsibility matrix) and ensure it is provided before the stakeholder leaves the project. These data provision roles and responsibilities must also be clearly indicated in the contractual documentation.

The process of assessing the quality of the deliverables and highlighting the required improvements is highly time-consuming when it is performed at the end of the project. This process is currently generally done manually by the owner or the operators, who must absorb the costs of finding missing data and improving delivered information. In the case studies, the developed automated tools that verified the quality items of the checklist made it possible to achieve crucial time- and cost-savings for the owner. The owner can mandate the continuous use of automated QC tools and quality reports by the project delivery team, instead of employing resources to evaluate the content of the deliverable, address the incompliances, and perform the transfer of information to the FM platform. To complement the continuous QC of the delivery team, the owner can use the same automated tools at defined milestones to track the progress made in the preparation of the models.

The case studies showed that no one tool is currently able to adequately verify the whole content of the quality checklist. Therefore, a combination of tools is required to cover all items of the checklist. Even though many quality items in the checklist are not project specific, some require customization from one project to another. For instance, the required asset parameters are different between two owners or projects, thus these tools must be customizable. Additionally, for certain items, development of new tools might be required. The efficiency and accuracy of the automated tools was validated when compared to a manual process of quality control.

Finally, it is important that the definition of requirements and the implementation of QC tools be part of a global quality procedure that is accepted by all parties involved in the project. The BEPs in place for both case studies did not include an adequate procedure for quality management of the deliverables. The proposed procedure was compared to the ones currently in place during the projects and made it possible to identify its influence on the quality of deliverables. It can guide the appointing and the appointed parties by defining the necessary quality assurance actions to be undertaken, as well as identifying the role of each stakeholder, with regards to the quality of the delivered FM-BIMs. The procedure was further detailed to include multiple quality control milestones, the tools to be used, and the reports to deliver to the client. It is as important to mention these procedures in the contracts as it is to define the requirements, to ensure a smooth delivery of the FM-BIM.

# CONCLUSION AND FUTURE WORK

This research investigated methods to improve the quality of BIM models for O&M by proposing a QM framework, which aims to improve quality assurance and quality control for FM-BIM. The framework proposed leveraging BIM documentation and various types of IR to clearly determine the sequence of tasks stakeholders must perform with regards to the delivery of an optimal FM-BIM. The framework included an FM-BIM checklist of items that must be included in and superfluous items that must be purged. The checklist included both generic items and items specific to certain BIM authoring software (i.e. Revit). The checklist was accompanied by a detailed process flow, which included the use of QC tools. To achieve this, various commercial tools were assessed and customized, and additional scripts were developed to complement these tools.

The proposed method was assessed using case studies of two real projects having different contexts and requirements. In the first case study, the research team joined the project at the handover stage and assessed the method in terms of applicability of the framework and the efficiency of the QC tools. In the second case study, the research team joined the project during the construction phase and assessed the applicability of the framework and its adaptability to specific project delivery methods (i.e. COBie). The QC tools were adapted so as to be used with this delivery method.

The applicability of the method was validated as it helped to define requirements for the owners, provide guidelines regarding quality assurance and quality control of the deliverable, and perform automatic QC of the information. The case studies confirmed various aspects of quality management for FM-BIM, such as: (1) the need for owners to define thorough and precise information and quality requirements and include them in the project contracts, (2) the importance of performing QC tasks and adding operation data to the models during the design and construction phase to reduce effort at the time of handover, (3) the challenges for the owner to manually perform quality control of all delivered information after the project, (4) the inadequacy of existing tools to perform all the quality items using a single commercial tool, and (5) the need to have a robust and contractual procedure that involves all parties in planning the quality and evaluating the content of the deliverables.

The results of this research contribute to creating more useable BIM models for FM due to their improved quality and their compliance with owners needs, which will eventually increase the quality of operation and achieve major cost reductions. Ultimately, the effective management of buildings will also help to increase the comfort and quality of life of their occupants.

Although the developed tools addressed multiple items of the checklist, there are still quality control items for which assessment is not automated. The use of programming environments can be extended to include these remaining items. Additionally, Artificial Intelligence and Machine Learning can be leveraged to provide automation in the quality control and improvement of BIM models, for instance by providing instant feedbacks or guidelines to the modeler during modeling activities, or automatically adding missing data.

Additionally, while it is proposed that various content be added to the contractual documentation (e.g. quality management procedures, extensive IRs, modeling guidelines), further work is required to thoroughly investigate the required changes in contract templates to enable seamless digital delivery of facility information and bridge the gap between Project Management and Asset Management.

Even though the study applied the proposed framework to two different project lifecycle stages, to further evaluate the framework, it can be applied to other types of projects and lifecycle stages. Ideally, the proposed framework should be applied on the whole project lifecycle with all parties involved to study the implications at each stage and for each team. The checklist can also be further extended by gathering additional requirements. Further work is needed to evaluate the process flow in other project realization modes. Also, the issues of transferring native models to the IFC format, performing the quality control directly on the IFC file, and the import and control of data in the FM platforms were not investigated in this study.

A method needs to be determined to ensure that no data is lost during the transfer from authoring software to IFC to the FM platform. However, the methods are dependant on the proprietary development software platforms and the evolution of the IFC Standard. The advent of OpenBIM platforms and BIM servers are opportunities to be explored to address this gap.

**ANNEX I**

**QUALITY MANAGEMENT PROCESS**

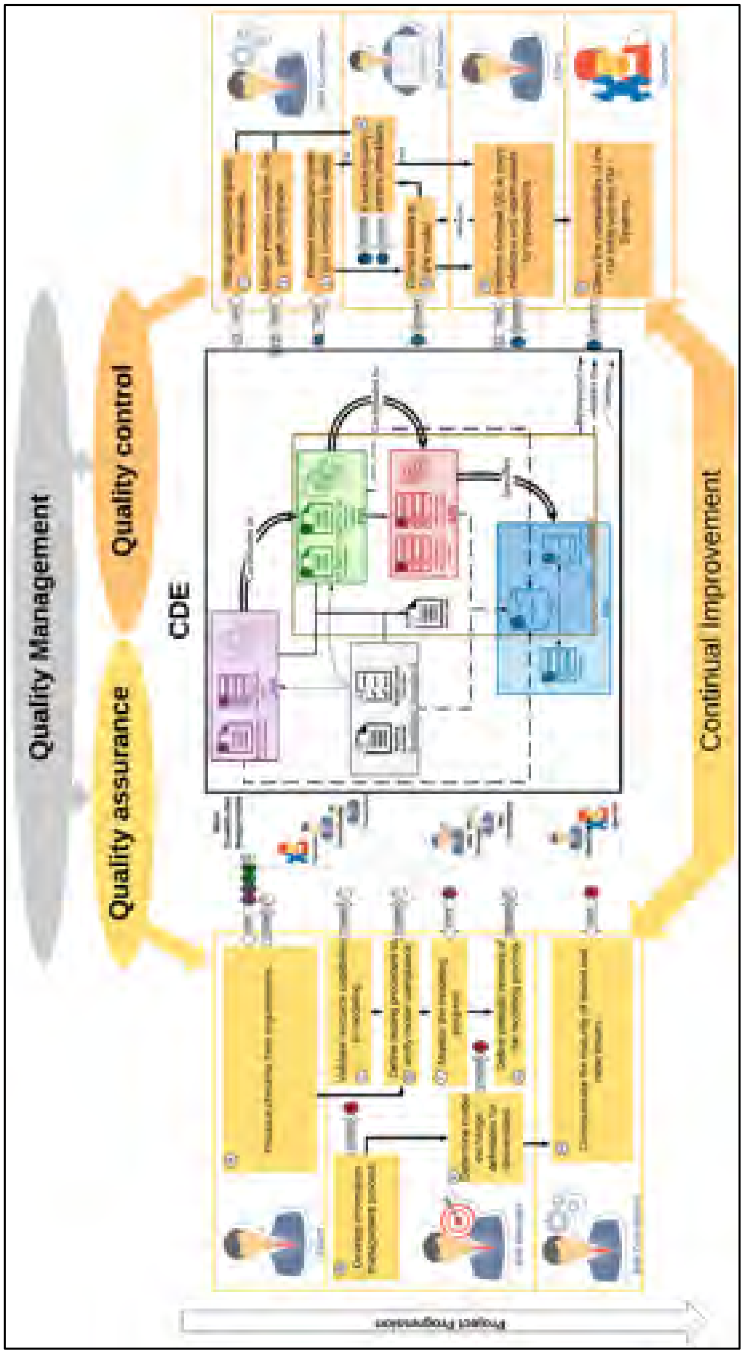


Figure-A I-1 Quality management framework including links with requirements documentation

# ANNEX II

## EXTENSIVE FEATURES COMPARISON BETWEEN VARIOUS COMMERCIAL QUALITY CONTROL TOOLS

Table-A II-1 Comparison of various commercial tools capabilities for applying the proposed checklist

| | Item Definition | Schedule | RMC | RMR | SMC |
|---|---|---|---|---|---|
| Completeness | All required elements must be included in the model. (IR) | | | | |
| | All assets must have the correct LOD. (IR) | | | | |
| | All required element properties must be available in the model. (IR) | ✓ | ✓ | ✓ | ✓ |
| | There should not be infant spaces (e.g. on roofs, external stairs, parking, shafts). | | | ✓ | ✓ |
| | Zones are defined in addition to spaces for grouping by function purpose. | | ✓ | ✓ | |
| | Spaces should have finishes in addition to materials. | ✓ | ✓ | ✓ | |
| | Every Space should be assigned to at least one Zone. | | ✓ | ✓ | ✓ |
| | Systems must be defined and have all their individual components assigned to them. | | ✓ | | |
| | Delivered models should be complete including: plans, schedules, diagrams, and data from all disciplines. (IR) | | | | |
| Accuracy | Floors should be properly defined and should not exist as ceilings. | | | | ✓ |
| | Ceilings should not be cut by a space. | | | | |
| | All elements properties must reflect as-built conditions. | | | | |
| | Elements should have a relation to the space where they are located. | ✓ | ✓ | ✓ | ✓ |
| | Spaces should be in a properly enclosed/bounded region. | ✓ | ✓ | ✓ | ✓ |
| | Space volume should go from current level up to the slab. | ✓ | ✓ | | |
| | All space properties must reflect as-built conditions. | | | | |
| | No disconnection should exist in the systems. | | ✓ | | ✓ |
| | The model should be geolocated. | | ✓ | | |
| Consistency | There should not be duplicate elements. | | ✓ | ✓ | ✓ |
| | There should not be duplicate properties. | ✓ | | | |
| | Elements should have a relationship with the space they are accessed from. | | | | |
| | There should not be multiple spaces in the same enclosed region. | ✓ | ✓ | ✓ | ✓ |
| | Unique name and numbering should be used for spaces. | ✓ | ✓ | | ✓ |
| | Unique name and numbering should be used for systems definition. | ✓ | ✓ | | |
| | The architecture, structural and MEP models should match and align. | | ✓ | | |
| | Links should be pinned in place. (*) | | ✓ | | |

| | Item Definition | Schedule | RMC | RMR | SMC |
|---|---|---|---|---|---|
| | Links should use overlay method. (*) | | ✓ | | |
| | Models files are organized in a standard and consistent directory structure. (IR) | | | | |
| Compliance | Element names should conform to a standard. (IR) | ✓ | ✓ | ✓ | |
| | Elements should be classified following a standard classification scheme. (IR) | ✓ | ✓ | | |
| | Consistent units should be used for the properties of elements. (IR) | | | ✓ | |
| | All spaces should be hosted to the level in which they contribute to the building square footage. | ✓ | | | |
| | Floors and levels naming should be consistent and conform to a standard. (IR) | ✓ | ✓ | ✓ | ✓ |
| | Spaces names should be consistent and conform to a standard. (IR) | ✓ | ✓ | | ✓ |
| | Spaces should be classified following a standard classification scheme. (IR) | ✓ | ✓ | | ✓ |
| | The area calculation method should comply with a guideline. (IR) | | | | |
| | System names should be consistent and conform to a standard. (IR) | ✓ | ✓ | | |
| | Model file names should conform to a standard. (IR) | | ✓ | ✓ | |
| | Model view and sheets names should be consistent and conform to a standard. (IR) | ✓ | ✓ | ✓ | |
| | All annotations should be consistent and conform to a standard. (IR) | | | | |
| Clarity | There should not be any hidden objects, filter, or annotative element in any view. | | ✓ | ✓ | |
| | Each object should be modeled in the proper phase. (*) | | ✓ | | |
| | Elements should be placed only in their associated models. | | ✓ | | ✓ |
| | Values of property set should only include URLs when there is no alternative. | | | | |
| | Elements properties name and values must be comprehensible. | ✓ | | | |
| | Spaces should be visible and tagged in all plan views. (*) | | | | |
| | Spaces properties name and values must be comprehensible. | ✓ | | | |
| | System views of the included components and their relations must exist in the model. | | | | ✓ |
| | FM-BIM model files should be delivered standalone, preferably integrated. If the size does not allow, various discipline models should be properly linked. | | | | |
| | Details about the compatible version of the viewing and editing applications and IFC standard should be provided per model. | | | | |
| | Reference nesting should be avoided. (*) | | | | |
| | Whenever possible, all links must have relative file paths. | | | | |
| Relevancy | All unnecessary generic models should be removed. Generic models should be generally avoided. (*) | ✓ | ✓ | | |
| | All unnecessary in place families should be removed. In place families should be generally avoided. (*) | | ✓ | | |
| | All unused objects should be purged and removed. (*) | ✓ | ✓ | | |
| | All unnecessary mass elements should be removed. Mass elements should be generally avoided. (*) | ✓ | ✓ | | |
| | All detailed components should be removed. (*) | | ✓ | | |
| | All groups used to model the building must be ungrouped. (*) | | ✓ | | |
| | There should not be duplicate identification values for elements (e.g. mark, tag). | | | | |
| | Non-building story levels and floors should be removed. | ✓ | ✓ | ✓ | |

| | Item Definition | Schedule | RMC | RMR | SMC |
|---|---|---|---|---|---|
| | All unnecessary area space schemes should be removed, specifically related to structure, installation, assembly, or construction. (*) | | ✓ | | |
| | All unnecessary color schemes should be removed, specifically related to structure, installation, assembly, or construction. (*) | | | | |
| | There should not be multiple levels at the same elevation. | ✓ | ✓ | | |
| | Identification values for spaces (e.g. name, number) should be unique. | ✓ | ✓ | | |
| | Scope Boxes should be removed from the model. (*) | | ✓ | | |
| | Design Options should be removed from the model. (*) | | ✓ | | |
| | Worksets should be discarded. (*) | | ✓ | | |
| | Keep only the default browser organization (“all”) for views, sheets and schedules. (*) | | ✓ | | |
| | All non-transmittal linked-in files (CAD/Revit/SketchUp) should be removed from the model. | | ✓ | | |
| | The models must be purged multiple times before it is shared. (*) | | ✓ | | |
| | Warning count should be reduced to zero. (*) | | ✓ | | |
| | All unnecessary annotation should be deleted, specifically related to structure, installation, assembly, or construction. | | | | |
| | Revisions information should be purged from the model. | | | | |
| | All non-required line styles should be removed, specifically related to structure, installation, assembly, or construction. | | ✓ | | |
| | All non-required legends should be removed, specifically related to structure, installation, assembly, or construction. | ✓ | ✓ | | |
| | All unnecessary schedules should be removed, specifically related to structure, installation, assembly, or construction. (IR) | ✓ | ✓ | | |
| | All unnecessary sheets should be removed. (IR) | ✓ | ✓ | | |
| | All unnecessary view templates should be removed, specifically related to structure, installation, assembly, or construction. | ✓ | ✓ | | |
| | All views not on any sheet should be removed (e.g. plan, section, elevation, detail, test, work in progress and drafting views). | ✓ | ✓ | | |
| | All unnecessary images should be removed. | | ✓ | | |

## ANNEX III

## COMPARISON BETWEEN TIME REQUIRED AND NUMBER OF ERRORS

Table-A III-1 Extended comparison between time required in manual and automated process (in min:sec)

| Item Definition | Manual | | | | | | Automated | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ARC | STR | MEP | ELE | PI | Tot. | ARC | STR | MEP | ELE | PI | Tot. |
| The model should be geolocated (*) | 00:30 | 00:30 | 01:15 | 00:30 | 00:45 | 03:30 | 00:03 | 00:03 | 00:03 | 00:03 | 00:03 | 00:15 |
| The models must match and align | 01:10 | 01:10 | 00:15 | 00:15 | 00:15 | 03:05 | 00:02 | 00:02 | 00:02 | 00:02 | 00:02 | 00:10 |
| Links should have relative paths | 00:10 | 00:06 | 00:10 | 00:10 | 00:10 | 00:46 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Nonessential links must be discarded | 00:11 | 00:19 | 00:10 | 00:10 | 00:10 | 01:00 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Links should be pinned in place (*) | 01:00 | 04:33 | 03:50 | 02:00 | 03:15 | 14:38 | 00:06 | 00:06 | 00:05 | 00:05 | 00:05 | 00:27 |
| Non-building stories must be removed | 01:14 | 01:12 | 01:05 | 01:00 | 01:00 | 05:31 | 00:02 | 00:02 | 00:05 | 00:05 | 00:05 | 00:19 |
| There should not be multiple levels at the same elevation | 02:00 | 00:45 | 00:30 | 01:00 | 00:15 | 04:30 | 00:02 | 00:02 | 00:05 | 00:05 | 00:05 | 00:19 |
| Floor and level naming convention should conform to a standard | 00:56 | 00:40 | 00:30 | 01:00 | 00:30 | 03:36 | 00:03 | 00:03 | 00:05 | 00:05 | 00:05 | 00:21 |
| Floors must not be defined as ceilings | 05:05 | 05:55 | n/a | n/a | n/a | 11:00 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Ceilings must not be room bounded (*) | 03:22 | 01:22 | n/a | n/a | n/a | 04:44 | 00:03 | 00:03 | n/a | n/a | n/a | 00:06 |
| Spaces must be placed | 03:31 | n/a | n/a | n/a | n/a | 03:31 | 00:03 | n/a | n/a | n/a | n/a | 00:03 |
| Spaces must be in enclosed regions and must no overlap | 02:00 | n/a | n/a | n/a | n/a | 02:00 | 00:03 | n/a | n/a | n/a | n/a | 00:03 |
| Spaces should be placed at the level where they correspond to the building square footage | 02:30 | n/a | n/a | n/a | n/a | 02:30 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Spaces must have finishes | 03:00 | n/a | n/a | n/a | n/a | 03:00 | 00:03 | n/a | n/a | n/a | n/a | 00:03 |
| Revit rooms should be defined as floor-to-slab volumes (*) | 03:00 | n/a | n/a | n/a | n/a | 03:00 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Revit spaces should be defined as slab-to-slab volumes (*) | n/a | n/a | 02:00 | 02:00 | 02:00 | 06:00 | 00:05 | n/a | 00:05 | 00:05 | 00:05 | 00:20 |
| Unique numbering should be used for the spaces | 03:00 | n/a | n/a | n/a | n/a | 03:00 | 00:05 | n/a | n/a | n/a | n/a | 00:05 |
| names and numbering of spaces should correspond to a standard | 04:15 | n/a | n/a | n/a | n/a | 04:15 | n/a | n/a | n/a | n/a | n/a | 00:00 |

| Item Definition | Manual | | | | | | Automated | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ARC | STR | MEP | ELE | PI | Tot. | ARC | STR | MEP | ELE | PI | Tot. |
| Spaces should be classified following a standard classification scheme | 02:00 | n/a | n/a | n/a | n/a | 02:00 | 00:05 | n/a | n/a | n/a | n/a | 00:05 |
| Spaces should be visible and tagged in the plan view | 03:28 | 04:51 | 04:30 | 04:30 | 03:00 | 20:19 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Elements should be placed in their associated model | 02:44 | 04:43 | 05:30 | 07:20 | 03:10 | 23:27 | 00:05 | 00:05 | 00:05 | 00:08s | 00:05 | 00:20 |
| Elements should have a relationship with the space they are located in | 02:00 | n/a | 01:30 | 01:30 | 01:30 | 06:30 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Elements names should conform to a standard | 02:00 | 02:00 | 02:00 | 02:00 | 02:00 | 10:00 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Elements should be classified following a standard classification scheme | 10:37 | 04:19 | 30:00 | 30:00 | 30:00 | 01:44:56 | 00:05 | n/a | 00:05 | 00:05 | 00:05 | 00:20 |
| Systems names and numbering should be unique | n/a | n/a | 03:10 | 05:50 | 02:40 | 11:40 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Systems names should conform to a standard | n/a | n/a | 02:50 | 06:00 | 02:00 | 10:50 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| There should be no element filtered, hidden or annotated in the views | 17:22 | 15:51 | 02:00 | 02:00 | 02:00 | 39:13 | 00:40 | 00:10 | 00:05 | 00:12 | 00:05 | 01:12 |
| Sheets and views names should conform to a standard | 02:00 | 02:00 | 05:50 | 03:00 | 02:00 | 14:50 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Generic models should be avoided (*) | 01:36 | 01:30 | 01:00 | 01:00 | 01:00 | 06:06 | 00:04 | 00:03 | 00:05 | 00:05 | 00:05 | 00:22 |
| Mass should be avoided (*) | 01:00 | 00:37 | 01:00 | 01:00 | 01:00 | 04:37 | 00:04 | 00:03 | 00:05 | 00:02 | 00:05 | 00:19 |
| Detail components should be avoided (*) | 04:11 | 03:35 | 01:30 | 01:30 | 01:30 | 12:16 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |
| Groups should be dissociated (*) | 02:15 | 05:30 | 04:30 | 03:30 | 04:30 | 20:15 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |
| Unnecessary color scheme should be deleted (*) | 01:00 | 00:56 | 02:30 | 01:30 | 01:30 | 07:26 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |
| Scope boxes should be deleted (*) | 01:50 | 01:00 | 02:30 | 01:00 | 02:30 | 08:50 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |
| Design options should be deleted (*) | 00:21 | 00:15 | 00:30 | 00:30 | 00:30 | 02:06 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |
| Worksets should be discarded (*) | 00:45 | 00:21 | 02:00 | 02:00 | 02:00 | 07:06 | 00:04 | 00:03 | 0:03 | 00:03 | 00:03 | 00:16 |
| Only one browser organization should be kept ("all") (*) | 00:15 | 00:20 | 01:00 | 01:00 | 01:00 | 03:35 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |
| Revisions must be unissued (*) | 00:35 | 00:45 | 00:15 | 00:15 | 00:15 | 02:05 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Unnecessary view templates should be deleted | 03:33 | 02:52 | 02:00 | 02:00 | 02:00 | 12:25 | n/a | n/a | n/a | n/a | n/a | 00:00 |
| Views not on any sheet should be deleted | 01:12 | 01:00 | 01:00 | 01:00 | 01:00 | 05:12 | 00:04 | 00:03 | 00:03 | 00:03 | 00:03 | 00:16 |

Table-A III-2 Extended comparison between number of errors detected in manual and automated process

| Item Definition | Manual | | | | | | Automated | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ARC | STR | MEP | ELE | PI | Total | ARC | STR | MEP | ELE | PI | Total |
| The model should be geolocated (*) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| The models must match and align | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 2 |
| Links should have relative paths | 0 | 0 | 2 | 0 | 0 | 2 | n/a | n/a | n/a | n/a | n/a | n/a |
| Non essential links must be discarded | 0 | 0 | 0 | 0 | 0 | 0 | n/a | n/a | n/a | n/a | n/a | n/a |
| Links should be pinned in place (*) | 1 | 1 | 1 | 1 | 1 | 5 | 6 | 3 | 17 | 12 | 6 | 44 |
| Non-building stories must be removed | 7 | 4 | 6 | 5 | 4 | 26 | 0 | 0 | 0 | 0 | 0 | 0 |
| There should not be multiple levels at the same elevation | 9 | 0 | 1 | 1 | 1 | 12 | 4 | 0 | 0 | 0 | 0 | 4 |
| Floor and level naming convention should conform to a standard | 5 | 0 | 4 | 4 | 0 | 13 | 22 | 11 | 12 | 12 | 12 | 69 |
| Floors must not be defined as ceilings | 28 | 0 | n/a | n/a | n/a | 28 | n/a | n/a | n/a | n/a | n/a | n/a |
| Ceilings must not be room bounded (*) | 6 | n/a | n/a | n/a | n/a | 6 | 234 | n/a | n/a | n/a | n/a | 243 |
| Spaces must be placed | 25 | n/a | n/a | n/a | n/a | 25 | 28 | n/a | n/a | n/a | n/a | 28 |
| Spaces must be in enclosed regions and must no overlap | 0 | n/a | n/a | n/a | n/a | 0 | 2 | n/a | n/a | n/a | n/a | 2 |
| Spaces should be placed at the level where they correspond to the building square footage | 0 | n/a | n/a | n/a | n/a | 0 | n/a | n/a | n/a | n/a | n/a | n/a |
| Spaces must have finishes | 1088 | n/a | n/a | n/a | n/a | 1088 | 302 | n/a | n/a | n/a | n/a | 302 |
| Revit rooms should be defined as floor-to-slab volumes (*) | 0 | n/a | n/a | n/a | n/a | 0 | n/a | n/a | n/a | n/a | n/a | n/a |
| Revit spaces should be defined as slab-to-slab volumes (*) | n/a | n/a | 296 | 296 | 296 | 888 | n/a | n/a | 0 | 0 | 0 | 0 |
| Unique numbering should be used for the spaces | 0 | n/a | n/a | n/a | n/a | 0 | 23 | n/a | n/a | n/a | n/a | 23 |
| names and numbering of spaces should correspond to a standard | 25 | n/a | n/a | n/a | n/a | 25 | n/a | n/a | n/a | n/a | n/a | n/a |
| Spaces should be classified following a standard classification scheme | 296 | n/a | n/a | n/a | n/a | 296 | 302 | n/a | n/a | n/a | n/a | 302 |
| Spaces should be visible and tagged in the plan view | 0 | 296 | 296 | 296 | 296 | 1184 | n/a | n/a | n/a | n/a | n/a | n/a |
| Elements should be placed in their associated model | 0 | 172 | 0 | 11316 | 243 | 11731 | 16017 | 462 | 14 | 14 | 13 | 16520 |
| Elements should have a relationship with the space they are located in | 7197 | n/a | 13004 | 53994 | 15974 | 90169 | n/a | n/a | n/a | n/a | n/a | n/a |
| Elements names should conform to a standard | 19271 | 56 | 13004 | 53994 | 15974 | 102299 | n/a | n/a | n/a | n/a | n/a | n/a |

| Item Definition | Manual | | | | | | Automated | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ARC | STR | MEP | ELE | PI | Total | ARC | STR | MEP | ELE | PI | Total |
| Elements should be classified following a standard classification scheme | 19089 | 1202 | 13004 | 53994 | 15974 | 103263 | 2173 | n/a | 31 | 2507 | 1986 | 4524 |
| Systems names and numbering should be unique | n/a | n/a | 0 | 1302 | 293 | 1595 | n/a | n/a | n/a | n/a | n/a | n/a |
| Systems names should conform to a standard | n/a | n/a | 0 | 4 | 308 | 312 | n/a | n/a | n/a | n/a | n/a | n/a |
| There should be no element filtered, hidden or annotated in the views | 286 | 142 | 4 | 1 | 1 | 434 | 404 | 274 | 75 | 103 | 4 | 860 |
| Sheets and views names should conform to a standard | 12 | 358 | 36 | 82 | 76 | 564 | n/a | n/a | n/a | n/a | n/a | n/a |
| Generic models should be avoided (*) | 1566 | 122 | 0 | 11 | 1 | 1700 | 1569 | 122 | 0 | 13 | 1 | 1705 |
| Mass should be avoided (*) | 6 | 0 | 0 | 0 | 0 | 6 | 12 | 0 | 0 | 0 | 0 | 12 |
| Detail components should be avoided (*) | 0 | 3 | 0 | 1 | 0 | 4 | 12962 | 8192 | 0 | 863 | 0 | 22017 |
| Groups should be dissociated (*) | 20 | 47 | 0 | 0 | 0 | 67 | 843 | 2142 | 0 | 0 | 0 | 2985 |
| Unnecessary color scheme should be deleted (*) | 5 | 4 | 16 | 16 | 16 | 57 | n/a | n/a | n/a | n/a | n/a | n/a |
| Scope boxes should be deleted (*) | 0 | 0 | 4 | 3 | 0 | 7 | 2 | 5 | 13 | 21 | 13 | 54 |
| Design options should be deleted (*) | 0 | 0 | 0 | 0 | 0 | 0 | 22 | 0 | 27 | 160 | 83 | 292 |
| Worksets should be discarded (*) | 19 | 16 | 13 | 17 | 17 | 82 | 19 | 16 | 30 | 122 | 42 | 229 |
| Only one browser organization should be kept ("all") (*) | 9 | 9 | 8 | 8 | 8 | 42 | 9 | 8 | 8 | 8 | 8 | 41 |
| Revisions must be unissued (*) | 1 | 30 | 1 | 0 | 0 | 32 | n/a | n/a | n/a | n/a | n/a | n/a |
| Unnecessary view templates should be deleted | 313 | 271 | 35 | 80 | 76 | 775 | n/a | n/a | n/a | n/a | n/a | n/a |
| Views not on any sheet should be deleted | 11 | 8 | 35 | 80 | 76 | 210 | 12 | 7 | 35 | 79 | 76 | 209 |

# ANNEX IV

# NIBS COBIE RULES

National BIM Standard - United States®

- NotNull
- NotEmpty
- Unique
- CrossReference
- OneAndOnlyOneFacilityFound
- ValidNumber
- ValidNumberOrNA
- AtLeastOneRowPresent
- ZeroOrGreaterOrNA

In accordance with the COBie Guide publication, the criteria for evaluation of the content of a COBie deliverable is that the information provided in a COBie file match the information that would be found in the equivalent drawing or document set.

#### 4.2.8.1.2 Quality control test rule definition

The following general rules are applied for Quality Control testing of submitted COBie files:

**NotNull** - Must have a text value that is not n/a or empty

**NotEmpty** - Must have a text value (n/a is acceptable)

**Unique** - Must be unique within the scope of the worksheet

**CrossReference** - Must match a referenced Name column in another worksheet

**OneAndOnlyOneFacilityFound** - Only one facility is allowed

**ValidNumber** - Must represent a valid number - n/a is not acceptable

**ValidNumberOrNA** - If text is provided it must represent valid number or 'n/a'

**AtLeastOneRowPresent** - Worksheet must have at least one row

**ZeroOrGreaterOrNA** - If text is provided it must represent a valid number greater than zero or n/a

The following sections describe the full application of these rules to a given COBie file that is tested. This description is organized in a specific format to assist the reader of this standard to understand and evaluate these rules. First the rules are based on the COBie SpreadsheetML representation of COBie data. The first of the rules in each set applies to number of rows in a given COBie entity. Following rules in each set apply to specific fields within that worksheet. These tests are applied regardless of the format of the COBie test file tested (IFC, ifcXML, SpreadsheetML, COBieLite).

#### 4.2.8.1.3 Quality control test rule application

Rules applied to COBie.Contacts:

- Contact.AtLeastOneRowPresent
- Contact.Email.Unique
- Contact.Email.NotNull
- Contact.Email.Format
- Contact.CreatedBy.CrossReference
- Contact.CreatedBy.NotNull
- Contact.CreatedOn.NotNull
- Contact.ExternalSystem.NotEmpty

- Contact.ExternalObject.NotEmpty
- Contact.ExternalIdentifier.NotEmpty
- Contact.Category.NotNull
- Contact.Company.NotNull
- Contact.Phone.NotNull
- Contact.Department.NotEmpty
- Contact.OrganizationCode.NotEmpty
- Contact.GivenName.NotEmpty
- Contact.FamilyName.NotEmpty
- Contact.Street.NotEmpty
- Contact.PostalBox.NotEmpty
- Contact.Town.NotEmpty
- Contact.StateRegion.NotEmpty
- Contact.PostalCode.NotEmpty
- Contact.Country.NotEmpty

Rules applied to COBie.Facility:

- Facility.OneAndOnlyOneFacilityFound
- Facility.Name.NotNull
- Facility.Name.Unique
- Facility.CreatedBy.CrossReference (ToContact)
- Facility.CreatedBy.NotNull
- Facility.CreatedOn.NotNull
- Facility.CreatedOn.Valid (Valid Email Address)
- Facility.Category.NotNull
- Facility.Description.NotEmpty
- Facility.ProjectName.NotNull
- Facility.SiteName.NotNull
- Facility.LinearUnits.NotNull
- Facility.AreaUnits.NotNull
- Facility.VolumeUnits.NotNull
- Facility.Currency.NotNull
- Facility.AreaMeasurement.NotNull
- Facility.ExternalSystem.NotEmpty
- Facility.ExternalProjectObject.NotEmpty
- Facility.ExternalProjectIdentifier.NotEmpty
- Facility.ExternalSiteObject.NotEmpty
- Facility.ExternalSiteIdentifier.NotEmpty
- Facility.ExternalFacilityObject.NotEmpty
- Facility.ExternalFacilityIdentifier.NotEmpt

Rules applied to COBie.Floor:

- Floor.AtLeastOneRowPresent
- Floor.Name.NotNotNull
- Floor.Name.Unique
- Floor.CreatedBy.CrossReference (ToContact)
- Floor.CreatedBy.NotNull
- Floor.CreatedOn.Valid (Valid Email Address)
- Floor.CreatedOn.NotNull
- Floor.ExternalSystem.NotEmpty
- Floor.ExternalObject.NotEmpty
- Floor.ExtIdentifier.NotEmpty
- Floor.Category.NotNull

- Floor.Elevation.ValidNumberOrNA

Floor.Height.ZeroOrGreaterOrNARules applied to COBie.Space:

- Space.AtLeastOneRowPresent
- Space.CreatedBy.CrossReference (ToContact)
- Space.CreatedBy.NotNull
- Space.CreatedOn.NotNull
- Space.CreatedOn.Valid (Valid Email Address)
- Space.ExternalSystem.NotEmpty
- Space.ExternalObject.NotEmpty
- Space.ExtIdentifier.NotEmpty
- Space.Category.NotNull
- Space.Name.NotNull
- Space.PrimaryKey.Unique.Warning (Name)
- Space.PrimaryKey.Unique.Error (Name, FloorName)
- Space.FloorName.NotNull, FloorName.CrossReference
- Space.Description.NotNull
- Space.RoomTag.NotEmpty
- Space.UsableHeight.ZeroOrGreaterOrNA
- Space.GrossArea.ZeroOrGreaterOrNA

Space.NetArea.ZeroOrGreaterOrNARules applied to COBie.Zone:

- Zone.CreatedBy.CrossReference (ToContact)
- Zone.CreatedBy.NotNull
- Zone.CreatedOn.NotNull
- Zone.CreatedOn.Valid (Valid Email Address)
- Zone.Category.NotNull
- Zone.Description.NotEmpty
- Zone.ExternalSystem.NotEmpty
- Zone.ExternalObject.NotEmpty
- Zone.ExtIdentifier.NotEmpty
- Zone.Name.NotNull
- Zone.PrimaryKey.Unique (Name, Category, SpaceNames)
- Zone.SpaceNames.NotNull, SpaceNames.CrossReference

Rules applied to COBie.Type:

- Type.AtLeastOneRowPresent
- Type.Name.NotNotNull
- Type.Name.Unique
- Type.CreatedBy.CrossReference (ToContact)
- Type.CreatedBy.NotNull
- Type.CreatedOn.NotNull
- Type.CreatedOn.Valid (Valid Email Address)
- Type.Category.NotNull
- Type.ExternalSystem.NotEmpty
- Type.ExternalObject.NotEmpty
- Type.ExtIdentifier.NotEmpty
- Type.Type.Component.AComponentFo rEachType
- Type.AssetType.NotNull
- Type.Manufacturer.NotNull
- Type.Manufacturer.CrossReference (Contact Sheet)
- Type.ModelNumber.NotNull
- Type.WarrantyGuarantorParts.NotNull
- Type.WarrantyGuarantorParts.CrossR eference (Contact Sheet)
- Type.WarrantyDurationParts.validNum berZeroOrGreaterOrNA
- Type.WarrantyGuarantorLabor.NotNull
- Type.WarrantyGuarantorLabor.CrossR eference (Contact Sheet)
- Type.WarrantyDurationLabor.ZeroOrGr eaterOrNA
- Type.WarrantyDurationUnit.NotNull
- Type.ReplacementCost.ZeroOrGreater OrNA
- Type.ExpectedLife.ZeroOrGreaterOrN A
- Type.DurationUnit.NotNull
- Type.WarrantyDescription.NotEmpty
- Type.NominalLength.ZeroOrGreaterOr NA
- Type.NominalWidth.ZeroOrGreaterOrN A
- Type.NominalHeight.ZeroOrGreater
- Type.ModelReference.NotEmpty
- Type.Shape.NotEmpty
- Type.Size.NotEmpty
- Type.Color.NotEmpty
- Type.Finish.NotEmpty
- Type.Grade.NotEmpty
- Type.Material.NotEmpty
- Type.Constituents.NotEmpty
- Type.Features.NotEmpty
- Type.AccessibilityPerformance.NotEm pty
- Type.CodePerformance.NotEmpty
- Type.SustainabilityPerformance.Not Empty

Rules applied to COBie.Component:

- Component.AtLeastOneRowPresent
- Component.CreatedBy.CrossReferenc e (ToContact)
- Component.CreatedBy.NotNull
- Component.CreatedOn.NotNull
- Component.CreatedOn.Valid (Valid Email Address)
- Component.ExternalSystem.NotEmpty
- Component.ExternalObject.NotEmpty
- Component.ExtIdentifier.NotEmpty
- Component.Name.NotNull
- Component.PrimaryKey.Unique.Warnin g (Name)
- Component.PrimaryKey.Unique.Error (Name, Space)
- Component.TypeName.NotNull

- Component.TypeName.CrossReference (Type Worksheet)
- Component.Space.NotNull
- Component.Space.CrossReference (Component Worksheet)
- Component.Description.NotNull
- Component.AssetIdentifier.NotEmpty
- Component.SerialNumber.NotNull
- Component.InstallationDate.NotNull
- Component.WarrantyStartDate.NotNull
- Component.TagNumber.NotEmpty
- Component.BarCode.NotEmpty

Rules applied to COBie.System:

- System.CreatedBy.CrossReference (ToContact)
- System.CreatedBy.NotNull
- System.CreatedOn.NotNull
- System.CreatedOn.Valid (Valid Email Address)
- System.Category.NotNull
- System.ExternalSystem.NotEmpty
- System.ExternalObject.NotEmpty
- System.ExtIdentifier.NotEmpty
- System.Description.NotEmpty
- System.PrimaryKey.Unique (Name, Category, ComponentNames)
- System.Name.NotNull
- System.ComponentNames.NotNull
- System.ComponentNames.CrossReference

Rules available for COBie.Assembly, if information is present:

- Assembly.CreatedBy.CrossReference (ToContact)
- Assembly.CreatedBy.NotNull
- Assembly.CreatedOn.NotNull
- Assembly.CreatedOn.Valid (Valid Email Address)
- Assembly.ExternalSystem.NotEmpty
- Assembly.ExternalObject.NotEmpty
- Assembly.ExtIdentifier.NotEmpty
- Assembly.Description.NotEmpty
- Assembly.PrimaryKey.Unique
- Assembly.Name.NotNull
- Assembly.SheetName.NotNull
- Assembly.SheetName.CrossReference
- Assembly.ParentName.NotNull
- Assembly.ParentName.Reference
- Assembly.ChildNames.NotNull
- Assembly.ChildNames.CrossReference
- Assembly.AssemblyType.NotNull

Rules available for COBie.Connection, if information is present:




Figure-A IV-1 List of COBie rules developed by NIBS for a compliant COBie export

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