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Development of quality improvement procedures and tools for facility management BIM

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ABSTRACT

Despite the potentially significant benefits that Building Information Modeling (BIM) can offer during a facility's operation and maintenance (O&M) phase, the construction industry has thus far mainly implemented BIM in the design and construction phases. This is because even though as-built BIM models are delivered at the handover stage, owners and operators rarely have the expertise to efficiently use and update them. Additionally, industry standards do not provide precise guidelines on aspects such as the ease of use, interoperability, and maintainability of FM-BIM, that could ensure their efficient and effective utilization. Moreover, given that these models are mainly developed for the design and construction phases, they usually contain design and construction details that are not useful for the building's operation and maintenance or lack information required for this phase. Thus, this paper investigates correspondences between as-built models and O&M requirements, using procedures and semi-automated tools to facilitate quality management activities for FM-BIM. To achieve this, a detailed checklist of items that are required in the BIM models at the handover stage and of the items that can be purged was created. This checklist is part of an overall quality framework that includes quality assurance and quality control tasks to deliver useable models for the operation and maintenance phase. Additionally, a procedure and a set of tools were investigated to semi-automatically apply a collection of the items of the checklist on as-built models. A process flow is presented to assist in quality management activities during the development of the models and to prepare them for handover. Finally, two case studies were conducted to verify and validate the applicability of the developed tools and proposed procedures.

1. Introduction

Building Information Modeling (BIM) consists of creating 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 vastly improve the quality of construction projects by bringing together technology, process improvements and digital information (Fallon and Palmer, 2007). 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 and Furneaux, 2013). BIM, as a methodology for the lifecycle management of buildings, helps improve collaboration between designers, engineers, constructors, and facility managers (Durdyev et al., 2021), which results in maximized efficiency, improved information exchanges, and a reduction of costs (Vega Völk, 2017).

Thus far, BIM has mainly been used in the design and construction phases (Soliman et al., 2021). However, BIM could generate major benefits during the operation and maintenance (O&M) phase by improving various processes (Motamedi et al., 2014) and acting as a repository for the detailed information of the built asset. BIM could be used during the O&M phase to populate a facility's operations database with both geometry and parameters, supporting the information technology used by owner organizations (Pishdad-Bozorgi et al., 2018).

To improve productivity and information management, many governmental and public organizations have started to mandate the use of BIM for new projects. Owners are especially interested in having complete and useful BIM models at the end of the construction project (Becerik-Gerber et al., 2012). However, although there are numerous documents, standards (such as ISO19650) and guidelines (such as BIM management plans), which define high level information requirement categories, it is still difficult for owners to, for instance, define deliverables (Thabet and Lucas, 2017) or know which information should be required (Heaton et al., 2019). This might be due to the fact that

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although owners and operators are very familiar with the types of information required for their operation and maintenance platforms (such as computerized maintenance management system (CMMS)), their knowledge of BIM data models is still limited, which makes it difficult to identify requirements related to the consistency and completeness of the models. Additionally, the gap in precisely defining information requirements at the beginning of the project and including them in contractual documents results in obstacles and difficulties for the owners in defining details of quality management process tasks, as there are no corresponding references in contractual documents to be used for defining quality control items over the model's content. As a result, the delivered models often lack many relevant types of information for the operation and maintenance of the facility and contain extraneous design and construction details (such as design alternatives, construction sequence, etc.), and as such they cannot be readily used by the operators.

To address the abovementioned problems, the main goal of this research is to develop a framework for quality management of BIM models. The framework proposes the use of procedures, checklists and semi-automated tools to help ensure that the models delivered at the end of the construction phase are readily useable for operation and maintenance applications. The results of this research will facilitate the use of BIM models as a basis to implement digital twins that will correspond to the needs of the stakeholders. Therefore, the research objectives of this study are to: (1) Investigate a checklist of data quality control items to evaluate the quality of the delivered models, (2) propose processes to prepare and deliver high-quality models for facility operation and maintenance, and (3) verify and validate the applicability of the proposed method in real projects by implementing the checklist and the developed quality control automation tools.

2. Literature review

2.1. Facility information management issues

Since O&M accounts for 85% of the life cycle costs, that is, the largest portion of asset lifecycle costs, effective management is crucial to obtain significant financial benefits (ABAB, 2018).

Facility Management (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 way to facilitate decision-making. A lack of information can result in cost overruns, inefficient building operations, and untimely resolution of client requests. Unfortunately, incomplete, inaccurate, or vaguely defined information leads to poor decisions (Parsanezhad and Dimyadi, 2014). On the other hand, an overload of information may hinder facility operators by making it difficult for them to filter the essential data needed to perform their tasks, saturate an operation's database, and decrease the efficiency of facility management altogether (Munir et al., 2020). Additionally, excessively unorganized information in nonstandard 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 the effective management of this vast quantity of information, and this is critical to the success of facility operations (Lu, 2018).

Also, designers and constructors seldom know what information is needed for the FM (Munir et al., 2020). Thus, while the owner's input and requirements should be sought out at the initial stages of the project (Masania, 2015), most owners are unable to specify requirements for information deliverables that would ensure the usefulness of the closeout information (Munir et al., 2020).

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). Implementing a BIM approach can address such shortcomings by transforming static information into computable data. Nevertheless, the adoption of BIM during the operation and maintenance phase remains limited. Durdyev et al. (2021) identified a prioritized list of barriers that are inhibiting industry-wide adoption of BIM during the facility management (FM) phase (e.g. contractual constraints, interoperability issues, high upfront cost, etc.).

2.2. BIM data usage for operation and maintenance platforms

The potential benefits of applying BIM to facility management has been discussed in a thorough literature review by Pärn et al. (2017). Moreover, the use of BIM during the O&M phase 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). At project closeout, facility information (data and geometry) can be extracted from the BIM models and transferred into FM 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 reduce efforts in data transfer, restructuring, and management (Vega Völk, 2017). Facility information provided by the BIM model can streamline the O&M activities of a facility (Vega Völk, 2017) and BIM data can be used for space management, 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 models and their information be of sufficient quality. To ensure the delivery of a high-quality BIM, owners should request that the models be adapted for FM and verify them. Yet, an analysis of owner standards and guidelines (e.g., AIQS & NIQS, 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 industry rarely uses BIM during the O&M phase as the models are not readily useable and require extensive modifications and quality improvement.

2.3. BIM information requirements

Information Requirements (IR) 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 sorted into various types, as formalized in ISO 19650 (ISO, 2018): Organization Information Requirements (OIR), which are high-level generic requirements, Asset Information Requirements (AIR), which relate to the objects and their properties, or Exchange Information Requirements (EIR), which include all the details of the production and transfer of information (BrisBIM, 2020; UK BIM Alliance, 2019a,b).

As mentioned by Cavka et al. (2017), IRs are the various types of documentations used in a project to clarify expectations to the modeling team. Examples of documentation include: the project specifications, and Asset Attributes Matrix or Modeling Guidelines. Finally, a BIM Execution Plan (BEP) commonly accompanies contractual documents to define the scope of the project, uses of BIM, roles and responsibilities, expected deliverables, etc. Although references to AIR, PIR and EIR and corresponding documentations should be included in the BEP, current BEPs seldom mention Information Requirements.

2.4. BIM data quality assurance and control

Quality management is the process of attaining and satisfying high quality output by meeting customer-defined requirements (Ramesh, 2016). Quality Assurance and Quality Control are two interconnected aspects of quality management.

Quality assurance is a process-based proactive approach used to guarantee the quality of a product. Its primary objective is to prevent the presence of defects in deliverables and help to understand the product's requirements and expectations from the beginning of the project. To meet this objective, a plan must be developed and implemented. Quality control is a product-based reactive approach that verifies the compliance of a product with the delivery requirements. The process implies several steps, such as examining the product to detect any defects, correcting any that are found, and validating the deliverable (Usmani, 2012). 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 O&M.

2.4.1. Quality of BIM models

Given the common use of BIM models in the design and construction phases, checking and evaluation processes have been developed. Some researchers (e.g., Choi et al., 2020) have explored BIM-based quality control requirements for improving the quality of architectural design. Similar work is required for models being used during the operation and maintenance phase of facilities.

For FM-BIM models, the limited availability of best practices guidelines and frequent quality issues were identified as a common barrier for BIM implementation during the O&M phase (Durdyev et al., 2021). Indeed, most BIM models created for the design and construction phases contain significant quality issues for a use after the handover phase of a project (Zadeh et al., 2015). For instance, the quality of the delivered information to be transferred to the FM database is usually low as it contains nonessential design and construction details and lacks signification information relevant for facility managers (Motamedi et al., 2018).

Ramesh (2016) summarized various quality dimensions and investigated how they apply to facility information. Additionally, Zadeh et al. (2017) identified similar types of BIM data quality attributes (i.e., completeness, accuracy, accessibility, consistency, relevancy, availability, timeliness) and categorized them according to different model perspectives (e.g., objects, attributes, relations, locations) and relevant facility management perspectives (e.g., assets, MEP systems, spaces). Nonetheless, further work is needed to convert these overall assessments into specific checklist items that could be verifiable in a model. Moreover, these studies rarely used automatic tools to assess the models according to the identified quality dimensions, that is, most of these assessments were done manually.

Ramesh (2016) proposed a QA and QC planning procedure. 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. However, Ramesh's procedure for QA remains generic and does not focus on the use of a BIM model. It mainly focuses on the information that is to be delivered 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 provides neither a thorough checklist of the specific quality items that are to be verified in the models, nor a method and tools to apply such a checklist.

2.4.2. QC checklists and automated tools

The goal of the model preparation process was 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 other checklists also exist in BEPs and modeling guidelines. However, they are not specifically designed for data quality assessment for facility management.

Several researchers have published case studies in which QC tools (such as Dynamo) were used to verify the compliance of an FM-handover BIM at project closeout (e.g. Sadeghi et al., 2020). However, even though some of the verified quality items were relevant to any project, most of the items were related to specific asset attributes required for particular projects (e.g. Thabet and Lucas, 2017). Consequently, the available quality control items in the literature are not exhaustive and remain mainly generic. Motamedi et al. (2018) proposed a list of items that must be present in the FM-BIM models and items that must be purged from the model before the handover phase. However, the developed list is not exhaustive.

Additionally, manually reviewing thousands of components with multiple parameters to verify the compliance with the checklist can be labor-intensive, inefficient, and error prone. To automatically assess the model, model-assessment tools are available on the market (e.g., Revit Model Checker, Revit Model Review, Solibri Model Checker). With this type of software tool, a user can define BIM-based requirements checklists and determine whether these have been met. However, the applicability of these tools for FM purposes must be evaluated since they need a comprehensive checklist based on the user's requirements to be effective. Moreover, appropriate processes should be designed to employ the tools for QC/QA.

2.5. Main obstacles in FM-BIM quality management

The review of the literature showed that there is a lack of standard procedures and guidelines to help identify the quality assurance and control steps, quality assessment items and automated tools for quality management of FM-BIM. These shortcomings can result in a weak adoption of BIM quality management activities in contracts, making it difficult for the project team to deliver compliant models.

The literature highlights a lack of comprehensive checklists and procedures to assess the quality of the BIM model for FM. The current checklists available in the literature are either too general to be actionable on specific model elements, or too specific so that they do not cover various important quality aspects, or are specifically focused on the design and construction phases of the lifecycle. Thus, a complete list of quality items to be checked in the FM-BIM models needs to be investigated. Furthermore, literature review showed a lack in the development of tools to automatically assess the compliance of FM-BIM models to quality requirements. Finally, the literature signifies a lack of guidelines for the quality assurance and quality control processes, including the use of automated tools by the owners at the handover phase, as well as by project stakeholders during the construction project.

3. Research methodology and proposed solution

3.1. Research methodology applied for this study

The design science research methodology was selected to conduct this study. In addition, various data collection methods were employed to define the artifacts requirements. The first iteration to determine requirements was completed by analyzing available publications, such as academic research results, industrial reports, best practices guidelines, and owner and international standards. The next iteration to determine requirements was performed by analyzing the capabilities of the assessed commercial tools, as some of these included relevant built-in checks. Finally, the last iteration was conducted 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 to assess the applicability of the designed artifacts. These two particular case studies were chosen because they had different contexts in terms of delivery methods, project type (university campus vs. healthcare facility), partner organization (owner vs. general contractor), and lifecycle stages (handover vs. construction). Both projects included FM-BIM in their scope, and provided opportunities to evaluate how the proposed solution contributed to improving the quality of information. The two projects being from different organizations and different lifecycle phases provided multiple sources of evidence and ensured the designed artifacts were suitable for different types of projects.

3.2. Proposed method for FM-BIM creation and model evolution

Various BIM models are created and used throughout a building's lifecycle (Fig. 1a). Each model is based on the models of the preceding stages. Design professionals create a geometrically accurate *As-Designed Model* for project BIM execution, digital design mock-ups, decision support, and coordination. Construction professionals change 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. Fig. 1a shows how the BIM data in models evolve during a 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 Fig. 1b illustrates the overlapping between BIM data throughout the lifecycle.

This research proposes that the FM-BIMs, which derive from the *As-Built Models*, be the source of truth for facility information at the time of handover. The FM models must include as-built geometry and should be lightweight and interoperable. *As-Built Models* also include relevant attributes for inspection, maintenance, and operation simulations – which are extracted from asset documents – as well as the relationship between elements. Indeed, to ensure the efficiency of FM models, these should only contain information valuable to FM and all unnecessary information should be purged. 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* that should contain information about the ongoing O&M of the building.

This file-based model-exchange proposal can be 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 Model View Definitions (MVDs) for various usages, thus reducing the need to purge unnecessary information.

3.3. Proposed framework for FM-BIM quality management

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 Fig. 2). Fig. 2 identifies how the BIM requirements documentation that are currently used in the industry can be part of the information requirements categories formalized in industry standards and how this can ultimately facilitate the transition towards and adoption of such standards by the industry. 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. 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 are referenced in the 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 above-mentioned 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.) be organized in a Common Data Environment (CDE), which facilitates communication and ensures reliable access.

3.3.1. Stakeholder roles and responsibilities

Various stakeholders are involved in the delivery of a BIM project. The following section explores the roles and responsibilities of each stakeholder. Facility *Operators* should provide FM requirements at the project's onset, such as required attributes or operating information (part of the AIR in Fig. 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 Fig. 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.

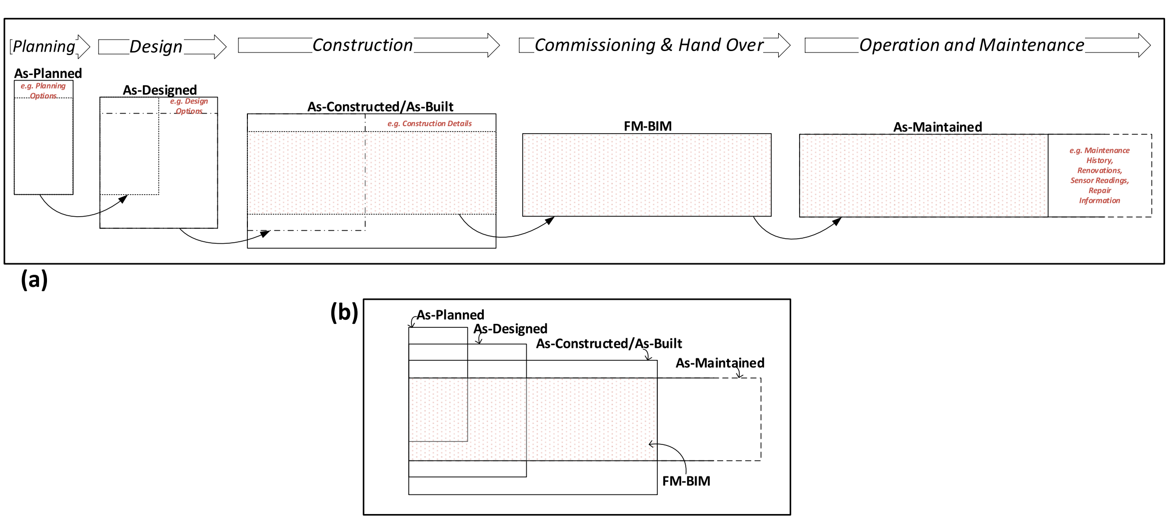

Fig. 1. (a) Evaluation of BIM deliverables (b) Schematic View of overlapping BIM data.

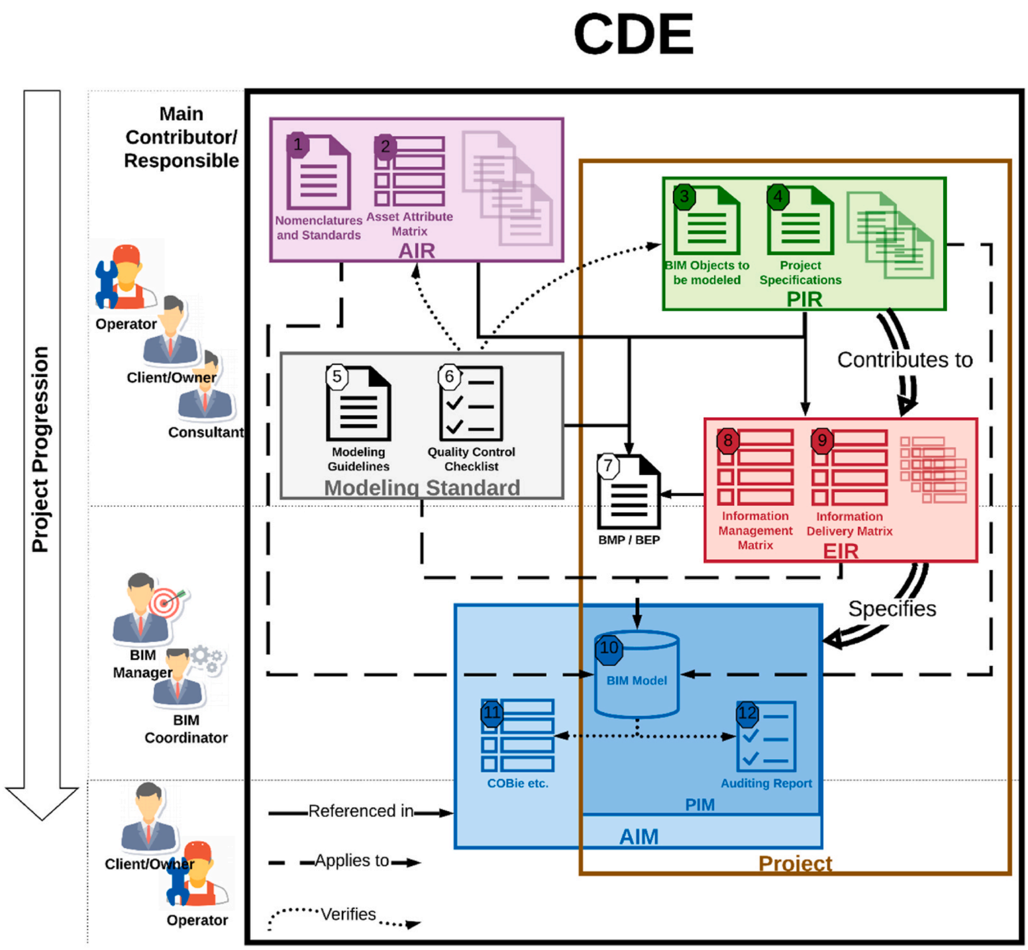

Fig. 2. Link between different types of IR, corresponding documentation, and involved parties.

The *BIM Coordinators* (or appointed party in ISO) 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 a PIM and, alongside the quality reports, is delivered as AIM to the client (blue boxes in Fig. 2).

3.3.2. Quality management process flow

Fig. 3 demonstrates the proposed quality management process flowchart with the correspondences to the IR and the typical BIM documentation related to data quality. The sequence of various activities is categorized by stakeholders. Fig. 3 also includes arrows pointing to the numeric identifier of documents (presented in Fig. 2), which are used as inputs or outputs to each process activity.

The process flow on the left-hand side describes the quality assurance activities as a proactive process occurring before and during the modeling activities. First, the *Client* or *Consultant* uses the requirements documentation (i.e., AIR and PIR) to produce a quality control checklist (A). An example of a thorough quality control checklist is provided in Section 3.4. 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 (J). Examples of such automated tools are provided in Section 4. 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 into the FM platform (O).

3.4. Proposed checklist for model quality control and cleanup

Along with 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. This paper proposes to develop a Quality Control Checklist that complements the owner's specific needs (i.e., naming conventions, required attributes, classification system employed). The proposed checklist focuses on the overall quality of an FM-BIM (e.g., data format, assets relationships, room definition), targeting its use during the operation and maintenance phase. Since this model is derived from an as-build model, a preliminary 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 information that is not necessarily useful for the purpose of O&M (e.g., assembly modeling, analysis and design calculations, and on-site logistics), these items need to be removed to ensure the model is lightweight.

To develop the checklist, an iterative process based on multiple data sources was adopted. First, a systemic literature review analyzing

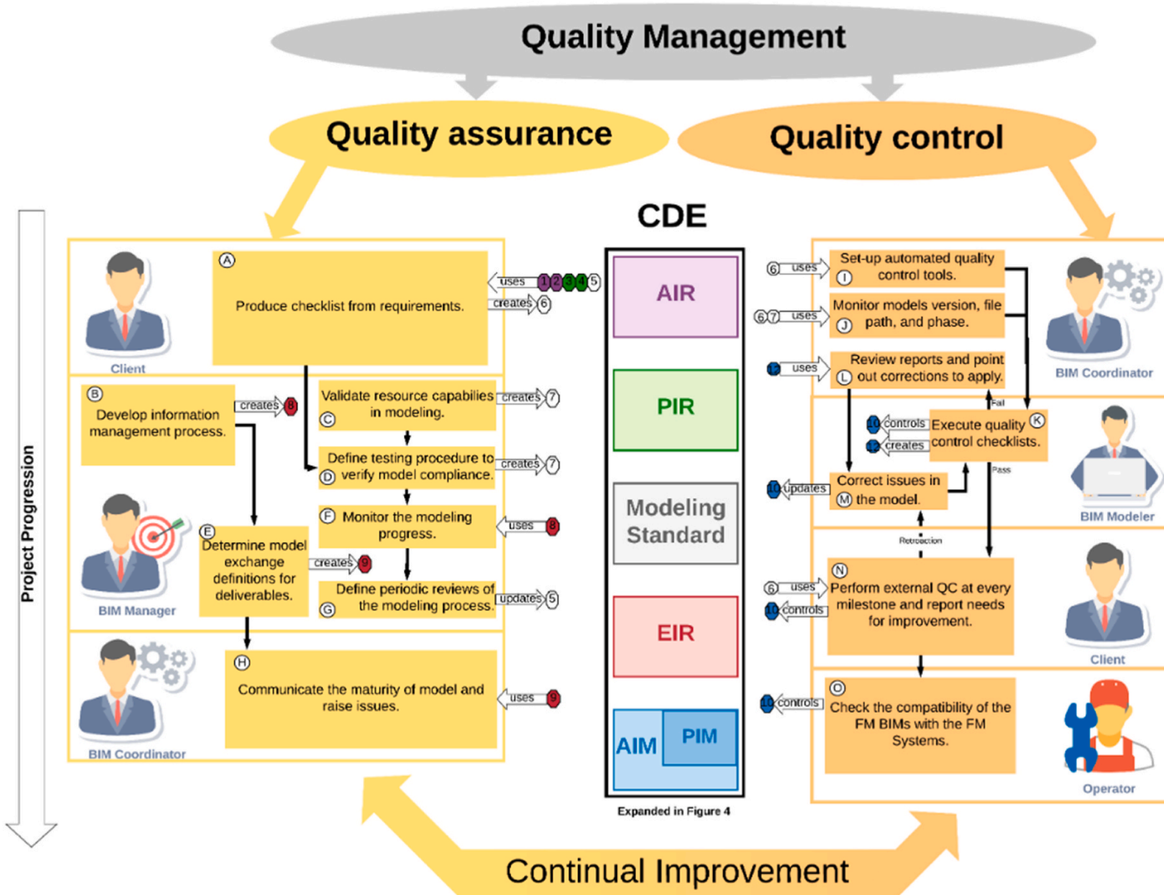

Fig. 3. Proposed quality management framework.

publications from various databases (i.e., Web of Science, Scopus, and Research Gate) was performed to find articles, using keywords, such as "Information Requirements", "BIM for Operations", "BIM for FM" and "Quality Management". The collection of references was manually filtered to focus on publications listing quality requirements for BIM models and presenting quality control processes for BIM models. Then, the collection of resources was complemented by adding standards and guidelines of major owner organizations (e.g. Smithsonian Institute, General Service Administration, Massachusetts Port Authority, Alberta Infrastructure, and Cambridge University) and of national BIM associations around the world (e.g. National Institute of Building Sciences, 2015b; NATSPEC, 2013, EUBIM, and Australian BIM Advisory Board ABAB, 2018). The standards sought in this industrial review include BIM Execution Plans, BIM Guidelines and Modeling Conventions. Although the industrial documents remain succinct in terms of FM-BIM preparation, some still provide generic guidelines for model preparation. Furthermore, the compiled list of quality requirements was later complemented by exploring the built-in tools and best practices of FM and BIM quality control commercial tools. Finally, project specific data requirements were identified through owners, consultants, and operators and by analyzing specific project documentation during the case studies.

The terminology used for categorizing each item of the checklist (listed in Table 1a) is adapted from the work of Zadeh et al. (2017). Since their proposed quality control checklist mostly included high level items based on quality attributes, it was improved to include more detailed items and to match IFC terminology. The items in the checklist are categorized based on the use of quality dimensions, FM product categories, and aspects. The proposed checklist (Table 1b) mentions both the required information and unnecessary information that needs to be removed. Most items in the checklist are generic for all BIM models – regardless of the authoring software – based on IFC terminology. Some items are shaded in grey and these relate to a specific authoring tool (i.e., Autodesk Revit) used in the implementation of the proposed method and 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 an asterisk (*). Since these requirements vary from one project or owner to another, it is unrealistic to provide a list that could be applicable for all projects. Likewise, items to be purged from the model (listed in Table 1b) vary depending on the owners' specific requirements. It should be noted that, other studies are being conducted parallel to this research to identify and categorize relevant IR for specific project settings. Finally, some items are related to MEP components (e.g., systems must be defined and have all their individual components assigned to them) while others are generic (e.g., elements should be classified following a standard classification scheme).

3.5. Proposed quality control process flow

Fig. 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 above-mentioned collection of tools is presented in Section 4. It includes Revit Model Checker (Autodesk, 2019b), Revit Model Review (Autodesk, 2019c) and Dynamo (Autodesk, 2019a). The last milestone verification also includes a purging step. At each milestone, the generated report automatically

Table 1
(a) Definitions of related terms (b) FM-BIM Quality Control and Purge Checklist.

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

Dim.	Product	Aspect	Item Definition
Completeness	Elements	Objects	All required elements must be included in the model. (*)
			All assets must have the correct LOD. (*)
		Attributes	All required elements properties must be available in the model. (*)
	Spatial Elements	Objects	There should be no infant volumes (e.g., on roofs, external stairs, parking, shafts).
			In addition to spaces, zones are defined 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. (*)
Accuracy	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.
Consistency	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.
	Facility	Integrity	The architecture, structural and MEP models should match and align.
			Links should be pinned in place.
			Links should use an overlay method.

			Models files are organized in a standard and consistent directory structure. (*)
Compliance	Elements	Objects	Element names should be in conformity with a standard. (*)
		Attributes	Elements should be classified following a standard classification scheme. (*)
			Consistent units should be used for the properties of elements. (*)
	Spatial Elements	Objects	All spaces should be hosted to the level in which they contribute to the building's square footage.
			Floors and levels naming should be consistent and standard compliant. (*)
			Spaces names should be consistent and in conformity with a standard. (*)
		Attributes	Spaces should be classified following a standard classification scheme. (*)
			The area calculation method should comply with a guideline. (*)
	System	Relations	System names should be consistent and standard compliant. (*)
	Facility	Integrity	Model file names should comply to a standard. (*)
	Drawings	Objects	Model views and sheet names should be consistent and standard compliant. (*)
	Annotations	Objects	All annotations should be consistent and standard compliant. (*)
Clarity	Elements	Objects	There should not be any hidden objects, filters, or annotative elements in any of the views.
			Each object should be modeled in the proper phase.
			Elements should be placed only in their associated models.
		Attributes	Values of property sets should only include URLs when there is no alternative.
			Elements properties names 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.
Relevancy	Elements	Objects	All unnecessary generic models should be removed. Generic models should generally be avoided.
			All unnecessary in-place families should be removed. In-place families should generally be 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 annotations should be deleted, specifically related to structure, installation, assembly, or construction.

			Revision 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. (*)
			All unnecessary sheets should be removed. (*)
			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.

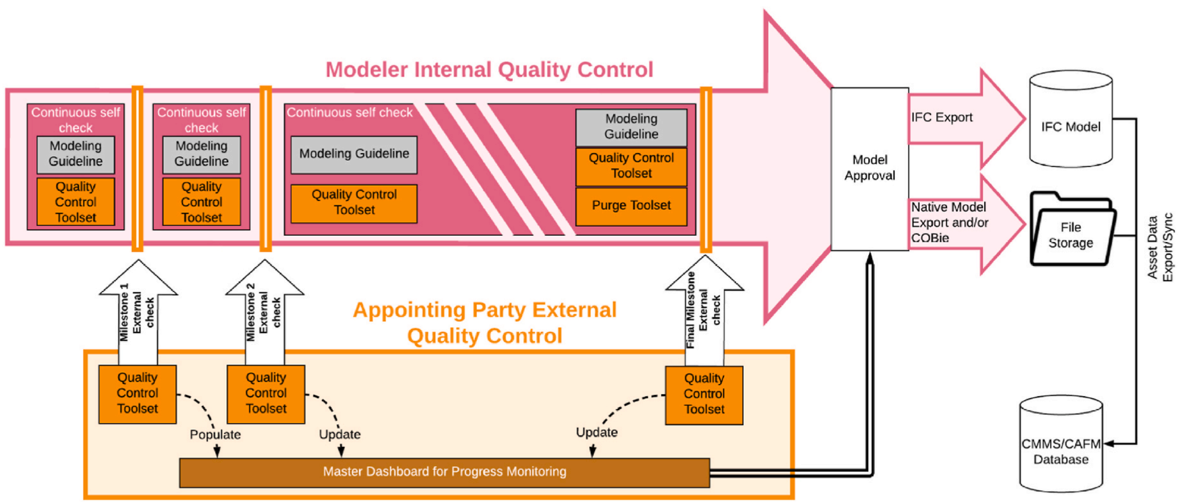

Fig. 4. Overall workflow view of FM-BIM preparation showing checks performed at milestones.

populates a dashboard (brown rectangles) to monitor the quality status and determine any necessary improvements.

After several 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.

The QM process should be included in the 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 the amount of effort required for quality control and corrections.

4. Developing and implementing QM tools

In order to apply the proposed QC checklist, several commercial model checking tools were assessed, such as Revit schedules (Version 2018), Revit Model Review Version 2018 (Autodesk, 2019c), Revit Model Checker Version 7.1 (Autodesk, 2019b), Solibri Model Checker Version 9.9 (Nemetschek, 2019), and BIM Assure (Version 1.3)

The tools were evaluated by mapping the items of the proposed checklist to the features of the tools. The result of this evaluation 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 was required using programing environments such as Dynamo.

4.1. 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. In the software used during the case studies, 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, Table 2 shows an example of the developed model-checker script that reports the spaces where the names and numbers do not match the names and numbers of their corresponding room.

Table 2
Example of check code using Model Checker.

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

In addition, Revit Model Review was used for specific checklist items (e.g., any enclosed volume should have a defined space). 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 focuses more on the evaluation of design, such as clearances and code compliance, which makes it a powerful tool to use in the design phase. Hence, this tool was not employed for the FM-BIM QC. 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 for assessing 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.

4.2. Development of software tools for specific quality control items

In this research, Dynamo was 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 make the final decision on whether to delete data. Some other items of the checklist do not require human input. For instance, Fig. 5 presents a script for removing all 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 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 automatically adjust the height of *Rooms* and *Spaces* (Fig. 6). First, the room bounding parameter is 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).

4.3. Development of a QM dashboard

In this study, a management dashboard (Fig. 7) 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 help identify areas of improvement in the model.

5. 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 the research team partnered with the client (i.e., the University). This case study sought to verify the efficiency of the developed QC tools as well as validate the checklist. The second case study started at the beginning of the construction phase of a medical center project until the handover phase. This case study aimed to assess the applicability of the proposed procedure and workflow during the construction and handover phases. The QC checklist and tools were also adapted for a particular format of deliverables (i.e., COBie process). In this case, the partner organization was the general contractor.

The two case studies made it possible to assess the applicability of the proposed solution for different project settings and for different types of requirements and deliverables.

5.1. University campus expansion project

École de Technologie Supérieure (ÉTS) is transitioning towards an integrated digital built environment for its campus. This transition requires the development of new standards and guidelines (e.g. BEP and information requirements) for BIM and Digital Delivery applied to its portfolio of assets. The first step of this transition was the preparation of a FM-BIM model for a pilot project of a new pavilion (Fig. 8). The quality management of these models will help the university in defining its standards and quality requirements, which in turn will ensure the delivery of high-quality digital models for future buildings, ultimately leading to improved operation and maintenance.

The research team worked with the facility management department of the university to analyze the BIM models delivered by the general contractor. Since the delivered BIM models were intended solely for 3D

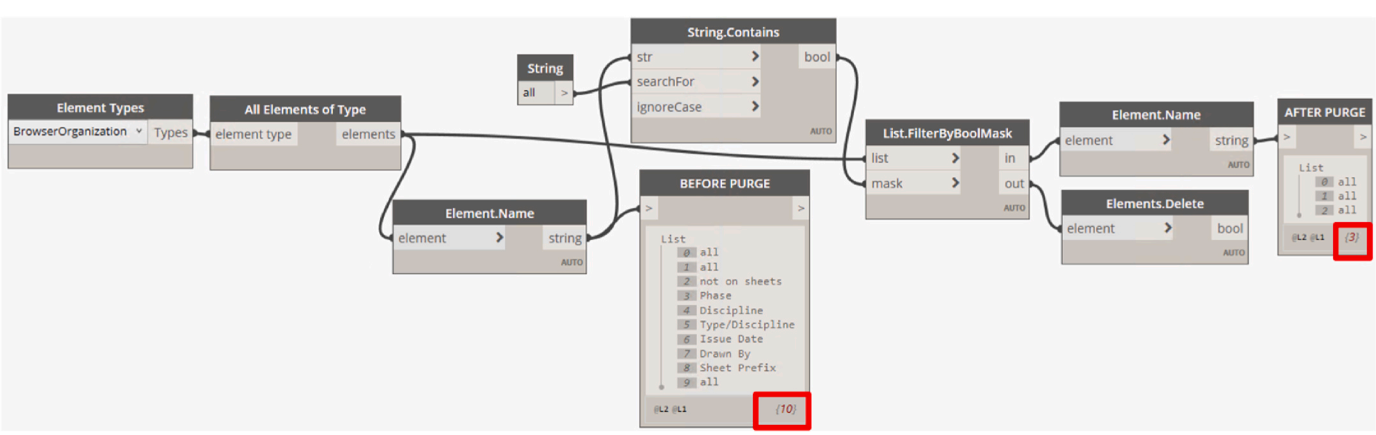

Fig. 5. Example of a Dynamo script to remove unnecessary browser organizations.

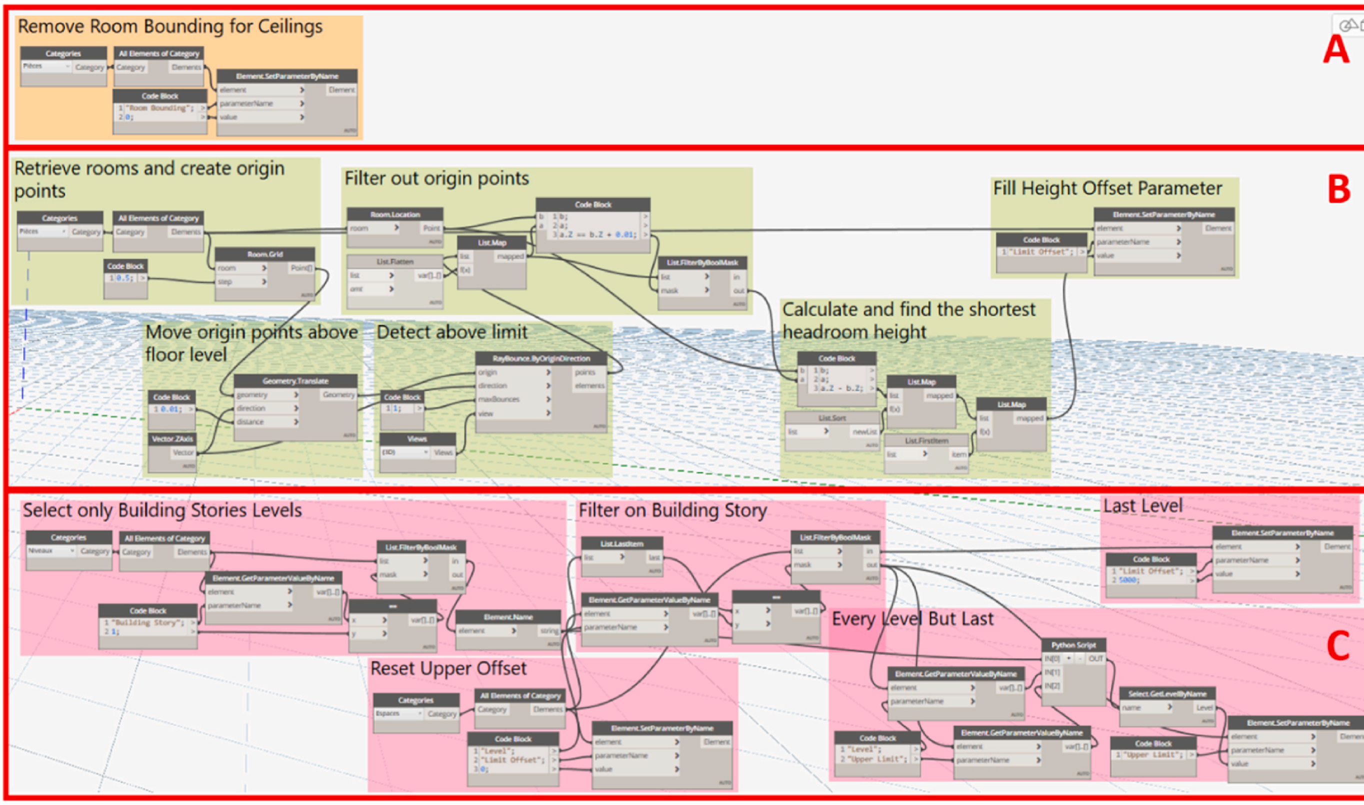

Fig. 6. Dynamo script for automatic adjustment of Room/Space heights.

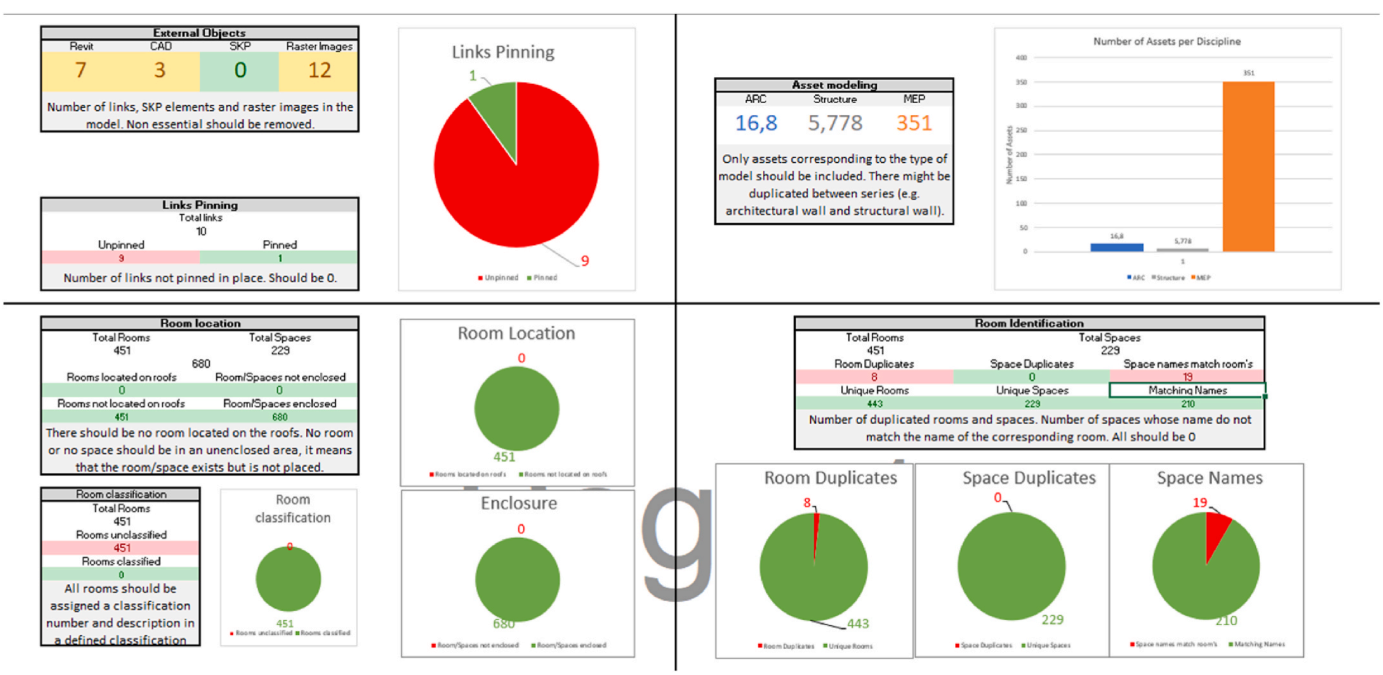

Fig. 7. Extract of the dashboard developed to visualize required improvements in a FM-BIM.

coordination purposes, they do not include the necessary information for operations management and do not follow modeling best practices. It was only decided after the handover that the models would be used for FM purposes and thus, the required improvements to make the models suitable for the O&M phase had to be performed by the research team.

In this case study, the proposed quality control checklist was applied to evaluate the quality of the existing models to determine the amount of effort required for their improvement. To achieve this, first, the pertinence of the checklist items was verified by working with 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 practices, were applied to the existing models (Table 3). Two types of assessments were conducted: (1) the time

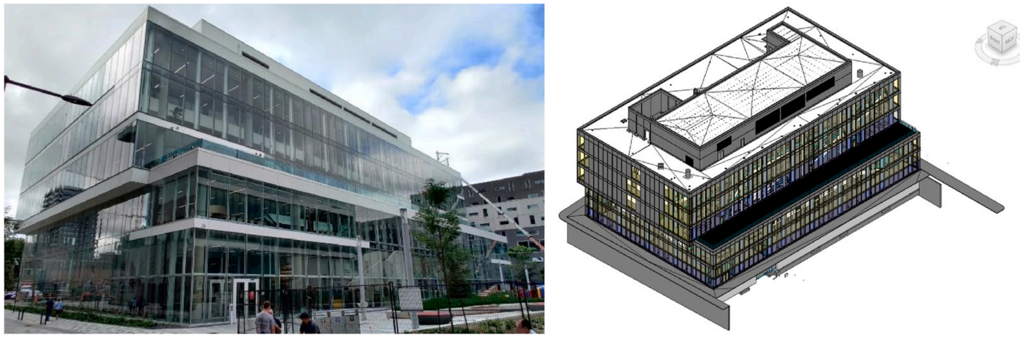

Fig. 8. Exterior view (a) and BIM model (b) of ÉTS Pavilion D (courtesy of MSDL Architecture).

Table 3
Comparison between time required and number of errors detected in manual and automated process (for a subset of the checklist).

	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 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 in	18:00	00:14	17960	18136
There should not be any hidden objects, filters, or annotative elements 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

required to evaluate the models manually vs using semi-automated tools; (2) the accuracy of the assessment. This demonstrated 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 proficient in Revit (Ms. Lamia Belharet and Ms. Nouha Boufares) helped to perform the two types of assessments. The use of external resources to perform the assessments ensured an unbiased collection of data, verification and analysis.

Tools developed to automatically fix the detected issues were also employed. For instance, the developed script to automatically set the height of Revit *Rooms* and *Spaces* took around 10 min, as opposed to 40 min when the correction was performed manually. Furthermore, contrary to a manual process where the effort required to correct the model increases with the size of the model, the execution time remained relatively constant.

5.2. Care center project

The second case study was performed in a Design-Build project of a $110 million care-center including 144 beds (Fig. 9) mandated by Alberta Health Services (AHS), the owner, and Alberta Infrastructure (AI), the client. The research team worked with the BIM delivery team of Pomerleau, the Design-Builder of the project, to evaluate and improve the quality of the as-built BIM deliverables and operation data in the form of a customized COBie database. AHS decided to mandate COBie delivery for their new construction project to reduce the extended efforts for data transfer at project handover.

5.2.1. 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 QC procedure mandated in the BEP was based on a random and partial assessment of information. Hence, it was necessary to include a thorough quality control checklist in the BEP, along with mandating the use of semi-automatic tools to perform the

Fig. 9. Photorealistic rendering of the BIM model of Willowsquare Continuing Care (courtesy of S2 Architecture).

quality control and adding the procedure that guides the use of such tools. In addition, aside from 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 standards, naming conventions and asset attributes outside of the COBie scope were not defined.

At the start of the construction phase, four existing design models were provided. Autodesk Revit was used 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 creation and configuration had occurred prior to the analysis of the content's quality.

The overall analysis of the existing design models showed major quality issues. Most of the required COBie properties were not added to the model, due to the lack of explicit contractual requirements. Additional quality problems included a lack of consistency in the naming of objects and their wrong placement in models, and the definition of Revit *Rooms* and *Spaces* (such as infant volumes, missing spaces, inaccurate height definitions) preventing the localization of all equipment around the building, on its roof, and between the ceilings and the slabs. Automatic quality control tools such as those presented in the proposed method were necessary to address these issues.

5.2.2. *Application of the proposed methods*

Although the use of COBie made it possible to define the AIR in a standard format, the weak definition of other information requirements led the researchers to propose clarifications in their definitions (e.g., the choice of classification system, guidelines related to naming conventions, or additional asset attributes) to mitigate most of the aforementioned issues. These decisions made it possible to address multiple gaps in the definitions of the requirements and improve the quality of the information.

Moreover, the checklist was adapted to suit the specific project delivery method (i.e., COBie format) and the research team implemented the proposed semi-automatic QC tools and dashboard to improve the quality of the models and make them compliant to the COBie standards and owner requirements. The tools and dashboard were supported by continuous self-checks performed by the Design-Builder to monitor the progress of the quality assessment. Identified errors were communicated to the corresponding designers when the client performed an external verification of the deliverables. Finally, the models were delivered in IFC format, and the FM database was populated by importing the COBie file.

The proposed framework (Fig. 3) was tentatively applied. Although a checklist (Box A) was produced based on the requirements (i.e., COBie deliverables and proposed QC checklist), several other QA items of the framework had not been present or performed when the research team joined the project (i.e., information management process B, resource capabilities C, model exchange definitions E). These missing steps are some of the causes that led to the identified issues in Section 5.2.1. Other aspects of the QA had been partially performed (i.e., testing procedure D, monitor modeling process F, periodic reviews G and communicate maturity of models H). The QC branch of the framework – further detailed in Section 5.2.3 – was overall better executed for every step, from setting up semi-automated QC tools (I) to correcting issues in the model (M). Likewise, the external QC (N) and the compatibility of the models' information (O) were correctly performed.

5.2.3. *Adapting the proposed QC tools and processes for COBie deliverables*

The BEP required that the COBie information comply with a set of rules developed by the NIBS (National Institute of Building Sciences, 2015a). These were applied to all the parameters in each COBie sheet. Common rules required for instance that the parameter not be null (a value needs to be filled), the parameter not be empty (a value or n/a needs to be filled) or that cross-referencing between sheets be maintained. Most NIBS rules correspond to various items of the proposed checklist (e.g., NotNull is similar to several items of the "Completeness" section, whereas Unique is similar to several items of the "Consistency" section). However, they also included items that are specific to the COBie deliverables (e.g., CrossReference or AtLeastOneRow).

To evaluate the compliance of the model's data with the COBie rules, two tools were customized. COBie QC Reporter, initially mandated by the client, was used to assess the content of COBie files. However, the tool was incapable of verifying all the required data values for the project. Hence, the research team developed new rulesets using Revit Model Checker.

Once the two tools had been customized to include all the required COBie rules, they were used to quantify the quality issues discovered in Section 5.2.1 and highlight the areas for improvement. Additionally, some non-COBie related checks proposed in this study were run to improve the quality of the model. For example, the developed Dynamo scripts (Section 4.2), were used to assess and automatically fix the height compliance of rooms and spaces and ensure the correct localization of each COBie component. Other Model Checker codes were run to detect misplaced elements (e.g., mechanical equipment in the architectural model), and errors in the geolocation of the models, and to ensure that generic elements would be replaced by specific object categories (e.g., mechanical equipment, light fixtures).

5.2.4. *Evaluation of results*

Once the various checks were applied and the changes were made to the models, a drastic reduction was observed in the number of errors in the resulting COBie file, such as the localization of assets, their categories, and the cross-referencing between the sheets. Therefore, the use of the QC tools and the application of the proposed procedures made it possible to notably increase the quality of the deliverables prior to the owner's final verification.

At the end of the intervention of the research team, the remaining missing or wrong fields missing to attain 100% compliance were mainly due to data missing from the designers (e.g., model number, manufacturer, warranty data) or the site team (e.g., installation date, serial number). This data was later obtained from the site team during the handover phase and involved mostly mechanical equipment that were identified as high priority.

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 (Fig. 10), after the intervention, towards the end of the construction phase. Fig. 10 displays the number of errors for each COBie rule compared to the number of elements. 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 Fig. 10). 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 score even subsequently improved as the missing information was progressively added.

The proposed checklist demonstrated its relevancy to improve the quality of the deliverables. The checklist and the tools improved the deliverables compared to before the assessment. 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. Specifically, the general contractor included the developed tools and QC checklist in a broader process of quality management of the models throughout the project lifecycle.

5.3. *Discussion*

Two case studies were performed at different moments of intervention and in different project settings. In both case studies, similar issues of low-quality models were observed. This was mainly due to a lack of

Fig. 10. Extract of the dashboard developed to visualize required improvements in a COBie set.

clear requirements and guidelines for modeling, and a lack of quality management in place such as QC processes. The proposed framework was applied to assess how the new method and tools could 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 (in this case, COBie). However, since the framework was mostly evaluated in isolated parts – for specific project phases, settings, partners, with time and contractual constraints – further work is required to evaluate the framework for every project phase and 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 these in the contract. 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 providing high-quality deliverables that complied with project requirements and that were useable for FM purposes. Moreover, the observations made during the case studies provided feedback and helped to finetune the definition of the artifacts' requirements established during the literature review (i.e., new items in the checklist). The observations are based on the involvement of the researcher in multiple project meetings, interactions 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. The data provision roles and responsibilities must also be clear 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 a 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 semi-automated tools that were used to verify 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 deliverables, address the incompliances, and transfer information to the FM platform. To complement the continuous QC of the delivery team, the owner can use the same semi-automated tools at defined milestones to track the progress of the preparation of the models.

The case studies showed that no one tool is currently able to adequately verify the entire content of the quality checklist. Therefore, a combination of tools is required to cover all the items of the checklist. The efficiency and accuracy of the developed tools were 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 the quality management of the deliverables. The proposed procedure was compared to those currently in place during the projects and made it possible to identify its influence on the quality of the deliverables. It can guide the appointing and the appointed parties by defining the necessary quality assurance actions to be undertaken, as well as by 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 be delivered to the client. It is as important to mention these procedures in the contracts as it is to define the requirements to ensure the smooth delivery of the FM-BIM.

6. Conclusions and future work

This study's contribution to the body of knowledge is its investigation of a checklist to evaluate the quality of delivered BIM models, its definition of quality assurance and quality control processes to ensure the delivery of useable models, and its development of semi-automated quality control tools.

This study 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 proposes the leveraging of 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 includes an FM-BIM checklist of items that must be included and items that are recommended to be purged. The checklist is accompanied by a detailed process flow, which includes the use of QC tools. To achieve this, various commercial tools were assessed and customized, and additional codes 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 the applicability of the framework and 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 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 deliverables, 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 operations data to the models during the design and construction phase to reduce efforts 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.

Although the developed tools addressed multiple items of the checklist, there are still quality control items for which assessment is not automated. Artificial Intelligence and Machine Learning could be leveraged to further improve the automation of quality control and enhancement of BIM models, for instance, by providing instant feedback 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, further work is required to thoroughly investigate the required changes in contract templates to enable the seamless digital delivery of facility information.

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. Finally, 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 need to be further investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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