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QUALITY ASSURANCE OF BIM MODELS IN PROJECT MANAGEMENT

ZAGOTAVLJANJE KAKOVOSTI MODELOV BIM PRI VODENJU PROJEKTOV

BIM A+ European Master in Building Information Modelling

Master thesis No.:

Supervisor:
Assist. Prof. Tomo CEROVŠEK, Ph.D.

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Izvleček:

Informacijsko modeliranje zgradb BIM (angl. *Building Information Modelling*) spreminja način, kako ustvarjamo projektne informacije in kako komunicirajo deležniki gradbenih projektov. BIM je po eni strani pospeševalna metodologija, po drugi strani pa zavira, saj povečuje potrebo po boljšem upravljanju projektnih informacij in nadzor kakovosti projektnih informacij, ki se ustvarijo skozi faze projekta.

Na splošno velja, da je kakovost in zanesljivost modela neposredno odvisno od tega, kako so predhodno uporabljene informacije strukturirane. Zato se pričujoča študija osredotoča na razvoj ogrodja za zagotavljan je kakovosti modelov BIM in naslavlja potrebo po presoji, upravljanju in vzdrževanju kakovostnih projektnih informacij v avtorskem okolju. Ogrodje obsega tri glavne dele: (1) priprava; (2) strukturiranje procesa modeliranja in (3) aplikacijo pristopa. Predlagamo tekoč delotok, ki je skladen z zahtevani in kriteriju sprejemljive stopnje kakovosti od začetka projekta. Ogrodje je izdelano na način, da se zagotavljanje in nadzor kakovosti (QA/QC) integrira v proces informacijskega modeliranja. Pri tem je področje preverjanje kakovosti obdelano iz organizacijskega vidika, da bi lahko zagotovili metodologijo, ki bo opolnomočila projektnim ekipam, da bodo lahko generiral visoko kakovostne projektne informacije in vzdrževale kakovost modelov preko več projektov. Predstavljano ogrodje se lahko implementira v kateremkoli avtorskem okolju.

Med bistvene prispevke pričujočega dela izpostavljamo uporaba pravil v formatu izrazno-definiranih pravil. Študija uporabnosti tovrstnega načina preverjanja kakovosti z izraznimi pravili je vodila do šestih identificiranih kategorij, ki so računsko preverljive in lahko kot funkcija vrnejo rezultat v obliki treh diskretnih zalog vrednosti: JE SKLADEN; NI SKLADEN ali NI RELEVATNO. Slednje omogoča, da se predmeti BIM samo-preverijo, kar se lahko na enostaven način vgradi v več faze modeliranja. Poleg tega, tovrstna preverjanje omogoča samodejno generacijo podatkov za presojo kakovosti modelov.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

Building Information Modelling (BIM) has been modifying how building information is produced and communicated among the AEC stakeholders. For one side, BIM acts as a facilitator methodology; from the other side, it slows down the process by increasing the need of managing and controlling the information produced across project stages.

It is acknowledged that the model quality and reliability depends directly on how the data is structured beforehand. Therefore, the study focused on defining a framework for quality assurance of BIM models addressing the need to assess, manage, and maintain the information quality inside the authoring tool. The framework englobes three main parts: (1) preparation, (2) structuring the modelling process, and (3) application. A fluid workflow was proposed by addressing the requirements and quality acceptance criteria from the start of the project and integrating QA/QC tools into the modelling process. Yet, the field of quality checking is taken from the organisational perspective to provide a methodology that supports the team in generating quality project information and maintaining the model's quality across different projects. The proposed framework has the potential to be applied in any authoring software.

Among the contributions of the current work, the application of rules in the format of expression-based properties is highlighted. The study regarding its applicability for quality checks resulted in the generation of six categories of computable rules that feedback with COMPLIANT, NOT COMPLIANT or NOT APPLICABLE discrete values. This feature allowed the BIM objects to perform automated self-checking that can be easily integrated into the modelling stages. Furthermore, the rules feedbacks enables the generation of data for the quality assessment of the BIM model.

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1 INTRODUCTION

1.1 Problem statement

For the last decades, Building Information Modelling (BIM) has been a key modifier in the information production for built assets. BIM has moved the industry from traditional paper-based procedures to integrated and collaborative processes in the digital environment [1].

The design stages usually involve stakeholders with different expertise [2]. Every construction project provides unique challenges related to its location, site characteristics, time consumption, cost, construction techniques, codes, local regulations, etc. Most of the time, the teams involved in a project will collaborate only a single time. Those aspects represent the high complexity one construction project can reach, resulting in challenges that other industries do not face. BIM supports the involved parties in dealing with those challenges. It facilitates the information flow and design changes by reducing error-prone manual tasks [3]. Additionally, the application of BIM methodology promotes the anticipation of issues that would traditionally be detected in the construction site and can now be early detected in the digital environment [3]. Due to the significant number of benefits, BIM has been largely applied in AEC industry across the world.

The quantity and complexity of information increase according to the development of the project stages. Therefore, information management should be present during the entire asset life cycle [4]. BIM provides intelligent means of producing project information. Nonetheless, the data produced must be consistent, accurate, and well-structured to increase the process's efficiency. A considerable amount of non-structured data can cause low efficiency and high cost [2]. Researchers have been discussing that lack of information quality in BIM models culminates in non-reliable outputs[2], [5], disables models for algorithms [5], and interferes in project and construction efficiency [6]. Yet, the team's ability to drive solutions suffers from the non-structured data inserted in the models [7]. The great availability of BIM software with friendly user interfaces facilitates the production of construction information, which needs to be constantly assessed and managed.

The discussion regarding information quality in construction projects is present in different research. Automated quality checks have been pointed as one of the most promising features that BIM provides to AEC industry [8]. Different approaches have been taken regarding code compliance checks, clash detection and information coordination throughout the use of IFC. Currently, there are software's dedicated entirely to it. The focus on IFC acquires high importance as the collaborative practices in AEC needs to be supported by a neutral file format. It allows information models to be generated in different authoring software and coordinated in a single and interoperable format. The different sources of errors in an IFC exchange have been pointed as the export/import activities as well as the modelling procedures [9]. The topic of IFC checks represents a promising improvement for the AEC industry. However, it is needed to address BIM quality checking from a broader perspective and as a discipline that should be part of every design stage.

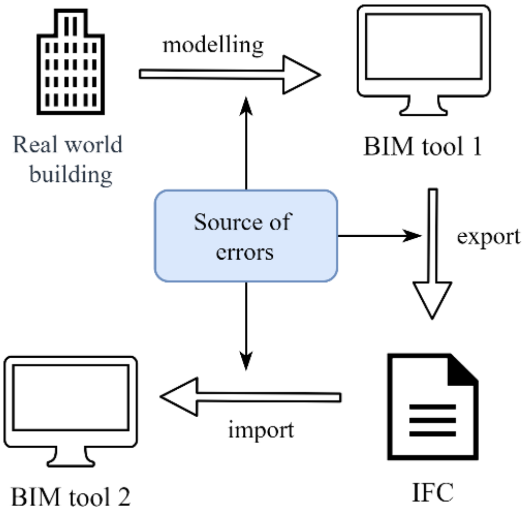

Figure 1: Source of errors in building model exchange [9].

Although different studies focus on model checking, few studies put effort into building the model in a structured manner by focusing on the final quality goal. Still, the literature shows a lack of studies focusing on the quality assurance plan to be implemented across all design stages [10]. In [5], Mirarchi and Pavan argue that looking to BIM quality checks as isolated tasks to be performed in IFC file format is limited, as it does not address how the generation of issues occur. Complementary to it, Donato, Lo Turco, and Bocconcino [10] propose a set of semi-automated practises to be applied in the design stages within a connection to the authoring tool. Other researchers look to the model checking from the perspective of the owner or facility management [11][12][13][14]. J. Abualdenien *et al.* [15] argue that uncertainty regarding the BIM models in early design stages may cause false assumptions or affect decision making. For that reason, it is necessary to assess the model as early as possible. In [16], the author concludes that quality control requirements are lacking in the current BIM standards and proposes applying quality control requirements to improve design quality using a dedicated model checking tool.

When it comes to the standards and best practices manuals, quality assurance has also been addressed. ISO 19650 series present a set of practices for information management within the context of Building Information Modelling [4]. The information management concepts consider that quality control actions should be taken prior to information container delivery. Quality checks are the responsibility of both parties involved in exchanging information [4]. From one side, the appointing party should check the information received while the task delivery team is responsible for checking its containers before exchanges. By applying BIM in alignment with ISO, the quality of information produced is increased, and a reduction of information waste should be expected [4]. Additionally, ISO introduces Level of Information Need as a framework to produce relevant and non-extra information.

From the understanding of BIM quality check as a broad discipline and not as isolated quality control tasks, this dissertation addresses the need of assessing, managing and maintaining the quality of information generated in the BIM environment. It presents BIM quality checking as a topic with two ramifications that address different purposes. The Figure 2 illustrates that one ramification is related to the project design quality while the second is related to BIM management. Hence, the dissertation focuses on BIM quality checks for BIM management purposes since it is acknowledged that any other process the model will go through depends directly on how the information is structured in the authoring tool. If the information does not contain proper organisation from the start, low-quality outputs should be expected [17].

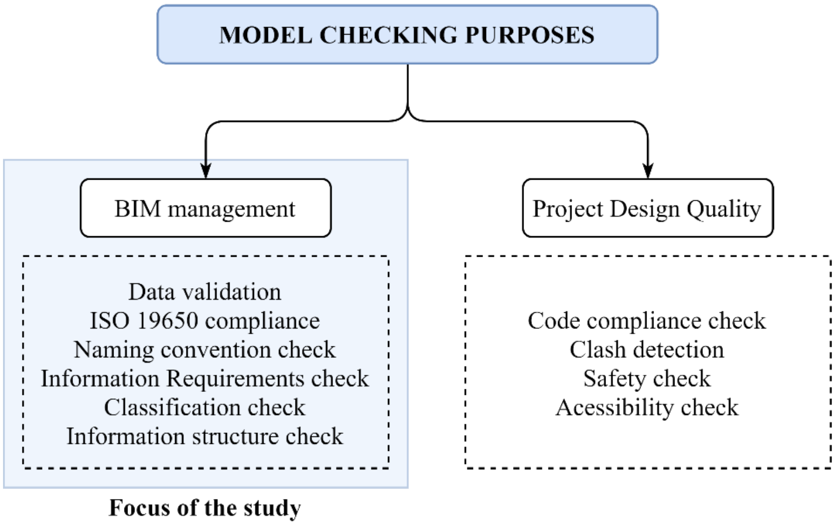

Figure 2: Focus of the study [own elaboration]

The dissertation will study procedures that can be integrated into the modelling process inside the authoring tool. Although there are great tools dedicated to IFC checks, the author believes there needs to improve quality checks in the authoring software. The authoring tool is the generator of the information. Therefore, it is where the issues regarding data structure should be controlled. Thus, the study proposes covering the topic of quality since the first start of the project. By connecting the project information requirements to the model uses, the study seeks to define a structured and fluid process of information generation focusing on creating high-quality models. In addition, this study aspires to support the management and measure the quality of produced data. Here, the field of quality checks is taken from the designer perspective to provide a methodology that supports the team in generating and maintaining the model's quality across the project.

1.2 Aim and objectives

This dissertation aims to define a framework for quality assurance of the information inside the authoring environment. Based on the literature and current actions practised by industry, this thesis seeks to provide a methodology that integrates quality control tasks into the modelling process from the start of the project to the final model uses. Yet, it aims to provide the design teams with means to prevent issues related to data structure by performing checks in the authoring environment, where the information is created and organized beforehand, resulting in reliable models.

1.3 The partner company

The thesis was developed in collaboration with TUU Building Design Management. The company is headquartered in Portugal and has been acting in design management and site inspection for the past five years. The project portfolio is mostly based in Portugal, and the more than 50 employees are from different fields, such as architecture, engineering, site inspection.

TUU has been implementing BIM in design processes and has well-structured project standards, templates, and definitions of stages. The projects are fully developed in Graphisoft Archicad, the chosen authoring software for the current dissertation. For collaborating with the study, the company provided two BIM models of medium-scale residential buildings fully modelled in the BIM tool.

1.4 Thesis structure

The structure of the thesis contains six chapters.

<u>Chapter 1-Introduction:</u> The chapter introduces the topic of quality assurance and states the findings that inspired this study. Then, by making an overview of the current BIM checking studies and quality control practices, this chapter introduces the gaps that the thesis seeks to address.

<u>Chapter 2-Literature review:</u> The literature contains four parts that support the understanding of the chosen topic.

(1) Information quality: it refers to the basic concepts concerning data quality and its measurement
(2) Quality Assurance and quality control refer to quality management concepts and their application in the AEC industry.
(3) BIM model checking: it refers to the concepts and scope regarding rule-based checking.
(4) ISO 19650: it presents the standard and principles that are appliable to the framework.

<u>Chapter 3-Framework:</u> The chapter presents the theoretical steps to create the quality assurance plan. It presents the concepts of each step to provide the reader with knowledge for adapting the framework according to the project needs.

<u>Chapter 4-Study Case:</u> This chapter explains how the framework is adapting to the real case scenario. In this section, the quality assurance plan is applied to the project provided by the partner company.

<u>Chapter 5-Discussion:</u> The chapter contains three parts.

(1) Framework review: it covers the strengths and limitations found during the framework development.
(2) Software review: it highlights the strengths and limitations regarding the use of the authoring tool.
(3) Implementation proposal: it proposes a stepped approach for implementing the quality assurance plan in a design company.

Chapter 6-Conclusion: The chapter presents an overview of the study, its results and proposes further development regarding the topic.

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2 LITERATURE REVIEW

2.1 Information quality

Quality and information quality has various definitions that authors of different disciplines and industries have addressed. This chapter will address the key definitions that will be the start point for the scope of this research.

2.1.1 Quality definitions

According to the American Society for Quality (ASQ) [18], quality is a broad concept that can reach different interpretations according to the context. Nonetheless, ASQ presents quality definitions in three concepts. The first concept refers to quality as a "*product or service free of deficiencies* [18]." The second refers to Juran's definition, which describes quality as a product's or service's fitness for a stated use [18]. Finally, the third one brings Philip Crosby's definition, which interprets quality as the product or service complying with the requirements [18]. Therefore, the three concepts presented in this section are complementary and will be applied in the framework.

2.1.2 Information quality definitions

Although information quality (IQ) has been recently enlightened by the AEC researchers, it has been addressed in the Computer Science domain for the past two decades [14] [11]. One of the first studies related to the dimensions of information quality was brought by Ballou and Pazer, who defined accuracy, timeliness, completeness and consistency as the four dimensions of information quality [19]. However, in 1996, the perspective of the customers (information users) in the evaluation of the information quality was first proposed by Wang and Strong [20]. In the research study, the authors captured twenty dimensions of data quality from customers perspectives. Furthermore, they grouped them into four major categories resulting in a conceptual framework of data quality (see figure 1). The conceptual framework was a great contribution to the field, but the discussion regarding the "fitness for use" from the customer perspective as meaning to "measure, analyse and improve data quality [18]" has also been influencing current research in the field.

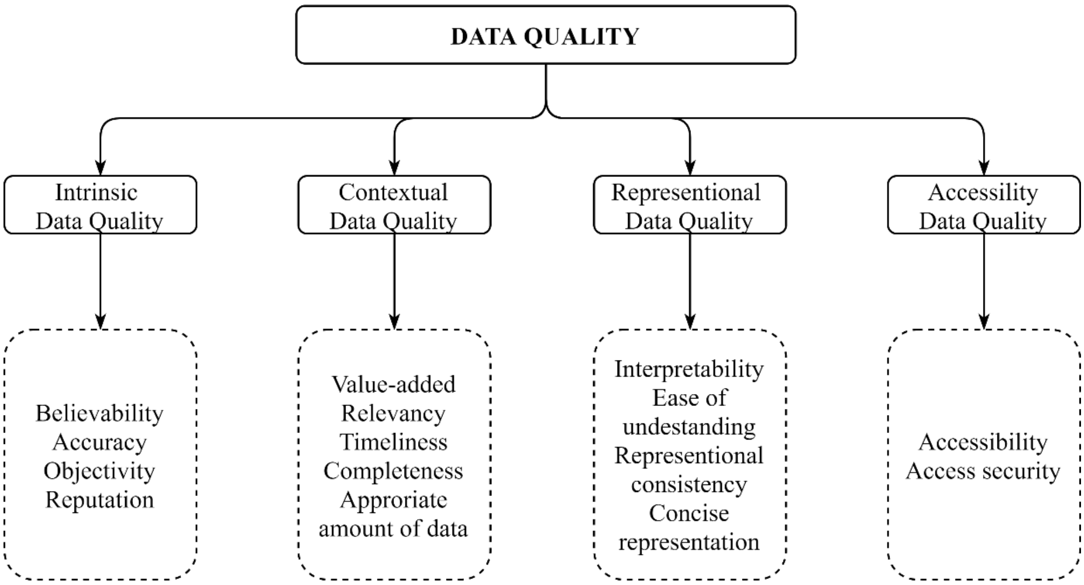

Figure 3: A conceptual framework of Data Quality (adapted from [20])

The information users are commonly architects, engineers, constructors, project managers, facility managers, and investors regarding the AEC industry. Therefore, the usefulness of the information in the AEC field should be evaluated from their perspective. In this direction, Guttman [21] brings up the idea that the value of information is related to its usefulness in making decisions. That is a point in which understanding the IQ dimensions proposed by [20] is a need. IQ dimension is a key criterion to evaluate the data to be used in a decision-making process. In simplified words, it suggests that if the information is high-quality, it is high-quality input for the decision-making process.

Information quality in a construction project is related to the ability to provide the appointing party with the information to fulfil the needs for the building construction [22]. Based on this concept and its identified criteria for information quality, Bengt [2] produced a deep investigation focusing on the construction sector. In the research, design information quality (DIQ) is introduced as equivalent to information quality (IQ) and defined as *"the conformance of the information supplied by the design team to a builder's specifications for planning and executing construction work* [2]*."*

In ISO 19650 [4], although information quality is not deeply defined, the standard indicates that information quality results from proper information management. It introduces Level of Information Need as a framework for defining the required information and related acceptance criteria. The Level of Information Need for each deliverable of the project should consider the quality, quantity, and granularity of information. The information managed in the CDE should be understandable by all parties and agreed in the following dimensions:

Information quality by ISO 19650 [4]:
Information format
Delivery format
Structure of information model
The means of structuring the information model
Attributes names for metadata

Level of Information Need should be determined according to its purposes and by the minimum amount of information needed to comply with the requirement that generates it [4]. The generation and exchange of not needed information is a waste and, therefore, directly impacts data quality. The detailed aspects related to ISO 19650 will be covered in section 2.4 of this document.

2.1.3 Information quality criteria

Information Integrity	Refers to the degree the information is accurate, consistent, complete and reliable [23].
Information Accuracy	Refers to data correctness and precision [11]
Information Consistency	*"The satisfaction of semantic rules defined over a set of data items* [5]*."*
Information Completeness	Evaluate if all required information pieces are present [11].
Information Importance	The state of how relevant and significant is the information [23].
Information Availability	*"The state of being able to locate, retrieve and use information [23]."*
Information Relevancy	Refers to how dependent is a task on information [23].
Information Latency	*"Delay in the effect of the information entity* [23]*."*
Information Timeliness	Evaluate if the data is updated for a task [5].
Information Authenticity	The state of the descriptors - content, originator, and time [23].

2.1.4 The role of the information quality in BIM projects

In construction, projects quality is usually related directly to the final product, the constructed building, and its ability to comply with codes and client requirements within the stipulated time and cost [24][25][26]. To achieve high-quality results in a project, it is essential that the requirements for quality are considered and managed from the concept phase and followed throughout the entire project life-cycle. [27]. The international standards ISO 9000 and 9001 provides guidelines for quality management systems that usually are applied by construction companies [24].

When it comes specifically to a BIM project, other aspects of quality are considered besides the quality aspects of the constructed building. In a BIM project, the design information should be consistent and reliable. BIM is defined as *"a set of processes to produce, communicate and analyse building models*

[1]." The information generated across project stages is crucial for the efficiency of construction. Therefore, the design information should be coordinated to ensure that it will be available at the right time and for the right stakeholder [2]. In construction projects, many resources are spent due to inefficient or non-existent quality management procedures [27]. BIM has increased the capabilities of stakeholders to generate and exchange information related to construction. However, it increased also the need for proper information management and quality assurance from the very first start of the project.

2.2 Quality assurance and quality control

2.2.1 Overview of QA/QC

Most BIM standards and guidelines cover the topic of QA/QC. For example, the Singapore BIM guide [28] indicates that quality control is a component of the BIM execution plan and as part of sharing the models for coordination purposes. The checks are to be performed by each discipline before being coordinated with others [28]. CoBIM presents checklists as a quality control tool for BIM projects [29]. Regardless of a set of international standards, model checking software, and best practices guides, the subject of BIM quality is still under development [10]. In BIM projects the quality control is usually applied at key decision points. However, the literature shows that the major focus is usually on isolated quality checks, whether in a quality assurance plan that integrates into the design process of a building. Further researchers made on this topic will be covered in section 2.2.3 of this dissertation.

Juran's philosophy emphasises the importance of planning for quality and setting the desired goals [30]. Rumane [30] summarizes the three main definitions of Juran's framework as follows: (1) Quality planning refers to a process capable of meeting the quality goals under operating conditions; (2) Quality control refers to the process of gathering and analysing data to determine how well the goals were met under operating conditions; (3) Quality improvement refers to a process that aims to improve the quality results [30]. The framework covers the importance of thinking about quality in an integrated process and highlights that quality needs to be planned and constantly improved [30].

Another important contributor to modern quality management systems was Deming philosopher [30]. In his framework, he highlighted the ideas that (1) quality management is decisive for a company survival; (2) The quality responsibility should rely on who is producing the work since simple inspections are limited in value; (3) there must be control and verification points, and the team needs to be educated regarding the application of it; (4) costs with education and training will be returned by higher quality results.

ISO 9000 [31] terms quality assurance as to the "*planned and systematic actions necessary to provide adequate confidence that product or service will satisfy given requirements for quality* [31]." Quality assurance covers all the activities performed through a lifecycle, ensuring that the building will meet the established requirements [30]. Quality control is a set of activities and techniques applied for product inspection [18]. In simple words, if QA covers all the actions within a project, QC is a specific application of the QA plan at a defined point of the process that needs to be measured and evaluated. In addition, ISO 9000 quality management systems also provide a framework that defines the components of a quality management system. See figure Figure 4.

Figure 4: Quality management system (adapted from [30]).

2.2.2 BIM QA/QC

The quality assurance (QA) in BIM aims to support the production of deliverables that comply with the specified standard and requirements. The QA plan is applied through a series of quality control (QC) points with the purpose of validation of the model against the quality and project requirements [10]. It is an integrated workflow that englobes (1) proper stakeholder's training, (2) proper mechanisms of ensuring requirements compliance and (3) proper tools of quality checks at key decision points.

Different software can be applied in a BIM project; consequently, it generates various workflows. However, independently of the file format, the building information model needs to be developed through an authoring tool by default [5]. And this is the central point of the QA plan. The content of the BIM model and how it is structured is the very first input for any other processes or uses that the model will have. Currently, many studies focus on the analysis of IFC models.

Nevertheless, few studies address the need of controlling quality directly in the native model. Some researchers have shown that the quality of outputs is conditioned to the quality of the input data [5]. Therefore, in QA planning, it should be considered that the authoring tool needs to be populated by high-quality and well-structured data by the beginning of the process.

Some best practices manuals and standards have covered the quality assurance topic. The Singapore BIM guide indicates that the QA plan should provide the users with a set of modelling requirements, modelling guidelines, and checking procedures to be carried out across the project stages [28]. In Common BIM Requirements guide 2012 (CoBIM) [29], QA is identified as the means to improve the quality of the final building by improving the quality of designed solution, the conformance to the client requirements, the predictability of schedule, cost and the construction itself [29]. Additionally, CoBIM also indicates that quality should be checked constantly by the design team, which is the only one responsible for the related design quality [29]. In both manuals, the quality checks are indicated to be performed by each discipline individually before the coordination meetings and model submissions. Nevertheless, COBIM highlights the need for discipline related quality procedures to be performed directly in the native format files.

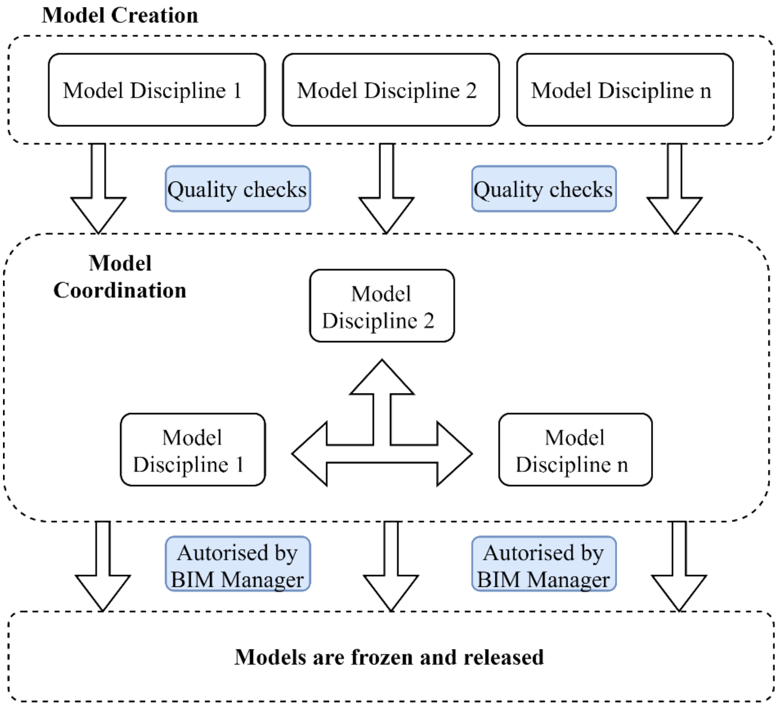

Figure 5: BIM Modelling and Collaboration Procedures (adapted from [28]).

The modelling guidelines and document templates are vital components for the quality assurance plan [28]. The proper modelling guidelines should be produced to guarantee that the modelling process is being carried out in alignment with the final purpose of the information content. The document standards provide the users with a preset document that complies with the quality plan and enables the modellers to reduce time and human errors in the modelling procedures.

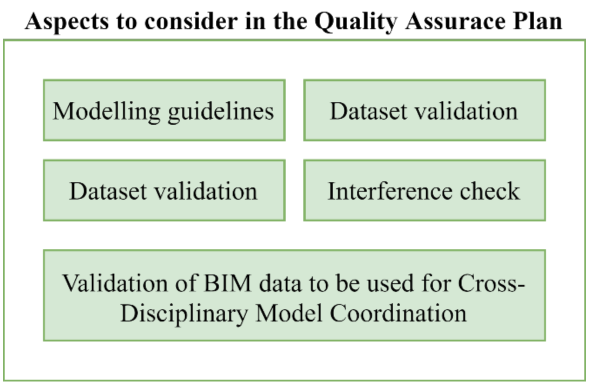

Figure 6: Aspects of Quality Assurance Plan according to Singapore BIM guide (created from [28])

2.2.3 Research background on BIM QA/QC

Donato, Turco, Bocconcino [10] propose integrating semi-automated QA/QC procedures into the design stages to improve design quality and ensure information flow. The aim was to enhance design quality by constantly monitoring the client requirements and predictability of schedules and costs [10]. The method is to apply checklists and queries in an external database management tool that connects to the native file, model-checking tool or IFC. The study outlines a semi-automated method by performing queries in a database management software that connects and feedbacks the BIM model with the quality assurance status of BIM object models (BOM) represented by graphical colours [10]. The method is applied across the design stages, and quality control points are defined.

In addition, the studies propose an evaluation of the BIM quality by creating measurables factors. However, the author indicates a limitation to the evaluation since some criteria are still subject to interpretations. Nevertheless, the research validated the methodology in three study cases and documented the benefits. The method benefits the daylight ratio compliance checks, optimising internal distance flows, optimising circulation layouts for better management of the buildings, visibility diagrams for interior spaces, window/door ratio calculation [10].

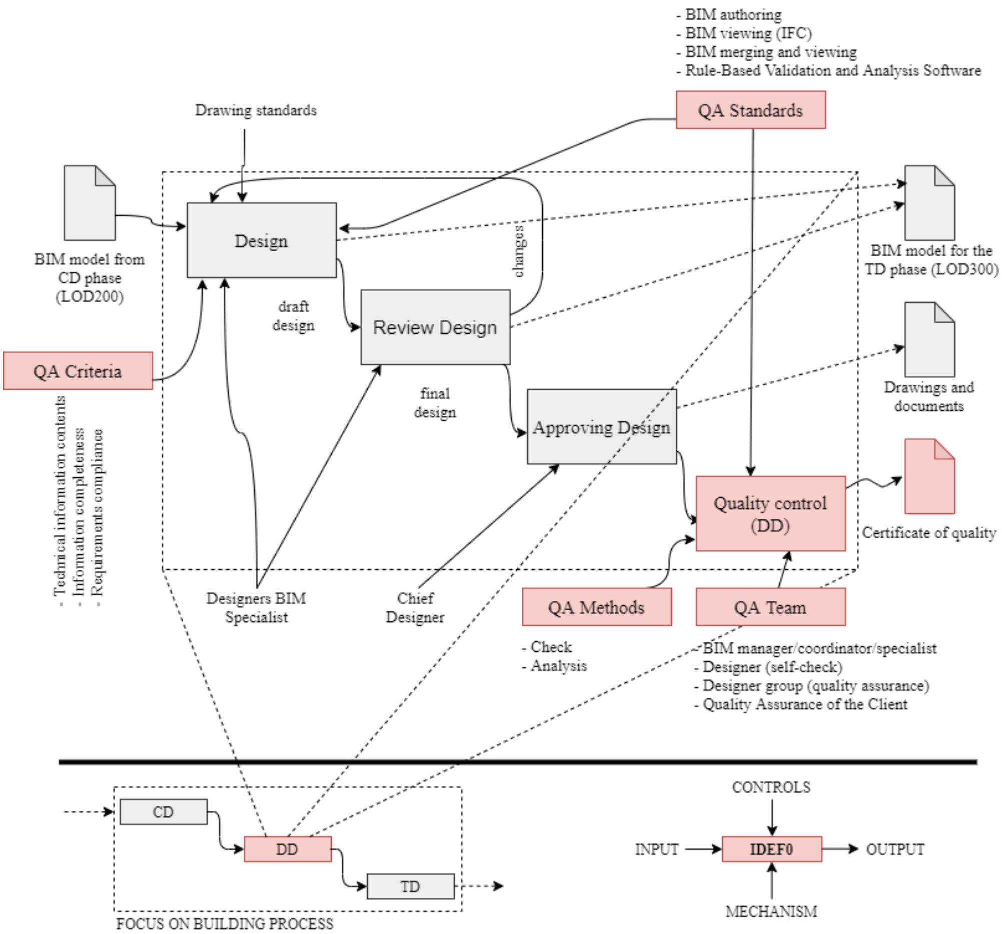

Figure 7: Quality control for Developed Design Phase [10].

Cavka, Staub-French, and Poirier [32] present a methodology for structuring the owners' requirements and transforming them into a computable rule to check their compliance in the project handover phase. It makes use of the Solibri Model Checker to apply rule-checking procedures. Although the methodology focuses only on the handover phase, the article proposes a good methodology for checking by covering three elements: "model structure verification, model content verification and design compliance review". The perspective of building owners in the requirements definition and asset model validation is also covered in [33].

Complementary to this topic, the authors in [11] and [14] develop frameworks for quality assessment of BIM models focusing on the model's usefulness for future management. Both studies encompass evaluation of the information quality based on the dimensions: Completeness, Accuracy, Redundancy and Well-formedness. The article [11] focuses on space information, while [14] analyses assets such as equipment and systems.

Zadeh, Wang, Cavka et al. [14] propose that visual, semi-automated and fully automated checks are performed in the model to compare the required information to the constructed building. The fully automated check is applied when there is no need to compare the BIM object with another external element or document. The semi-automated checks refer to filters performed in the format of schedules. The schedule feedbacks the information that the user needs for performing a visual inspection. Finally, the visual checks refer to the verification that requires manual inspection comparison on information containers with the built environment or other documents.

Furthermore, the framework proposes grouping the queries into three proxies indicators: (1) the existence of IQA subjects, (2) query and compare IQA subjects, and (3) query and present the IQA subject. The last one is related to the semi-automated checks, and it still needs human interpretation, while 1 and 2 can be fully automated. The author performed checks that can be done through the authoring tool or quality check specific tool.

The studies do not address the quality checks as an integrated plan into design stages. Instead, since they are focused on FM needs, they presented mechanisms for quality inspections to be performed in the model handover. Still, both studies provided useful frameworks for facility management that can be adapted and inspire quality analyses for design information across the project lifecycle.

In [15], Abualdenien *et al.* address the early evaluation of models. The study brings a perspective of managing the design information, its variants, and its uncertainty from the beginning of the project to enable early analysis and ensure consistency across design development. Once more, information quality management shows to be a necessary aspect to be considered since the first step.

Another relevant work regarding information quality in design stages is done by Mirarchi and Pavan [5]. The authors discuss the importance of analysing the quality issues source: the authoring tool – where the model is generated and populated with data. Additionally, the authors argue that having well-structured and high-quality input data influences the development of automated algorithms and further applications based on the information contained in the model [5]. It raises the discussion of lack of data quality regarding the dimensions: completeness, consistency, and accuracy. For the matter of the research, four teams with common industry backgrounds participated in the study. The study focused on the comparative analysis of information models created by the teams. They received the same instructions related to the requirements and to the software to be used. The modelling process was not the focus of analysis but the outputs of it. The analysis of the collected data led to the findings of issues in three main dimensions of quality:

Accuracy	Consistency	Completeness
- Inconsistency in information fields. - Blank information fields due to unknown reasons: (1) information is unknown or (2) designer did not fill the field. -Other human related accuracy issues;	- Incorrect use of modelling tools and objects categorization provided by the authoring tool. - Information written in the wrong field. - The same information field used to communicate different types of information	- Different volumes of information. - Different information structure. - Required information missing

Figure 8: Information quality issues found (adapted from [5])

The study outlines the need to analyse the information inside the authoring environment and reveals that many issues result from human activities and limited features provided by the authoring tools [5]. Even if the analysis were not done through the modelling process but with its results, the authors indicate that the processes play an important role in the final quality since the studies outputs resulted from processes that started from equal requirements. Therefore, the evaluation of the data throughout the modelling process is necessary to guarantee reliable and standardised outputs.

Other relevant research is developed by Bengt [2]. In his thesis, he defines a framework for assessing design information quality as it acknowledges that the success of the construction phases relies on the information provided in the planning stages. Thereby, the framework encompasses the (1) understanding of design information problems (DIP), (2) defining the criteria for design information quality and (3) assessing the design information quality [2].

Another study was carried out regarding design issues [6]. The research focuses on investigating coordination issues and their causes and proposes a taxonomy for the design issues found in a means of enhancing efficiency in coordination. The study was applied in two case studies, and the analysis confirmed that the most common issues found were design errors, discrepancies, clashes, and lacking information.

The results from a one year QA/QC analysis procedure performed in over one hundred projects of a Nordic design company was investigated in [34].

2.2.4 Summary

In a BIM project, it is important that a quality assurance plan is considered at the start of the project and carried out throughout the lifecycle. Quality construction results from high-quality project management in which decision making is always based on the available information. [35] For efficient project management, information should be available, accurate, consistent, and complete. The QA/QC should be understood as a set of standardised activities and systematic checkpoints that will provide the model's reliability. Hence, the QA should cover all the activities related to the production of the information model, ensuring that each information container will meet the requirements and be suitable for future model uses.

Thus, in a BIM project, the quality assurance plan defines the requirements for the quality of BIM models and provide the stakeholders with the means of acquiring the proper structure in the model. Since quality needs to be checked and monitored constantly [29], the plan should be integrated into the design process and applied as efficiently as possible.

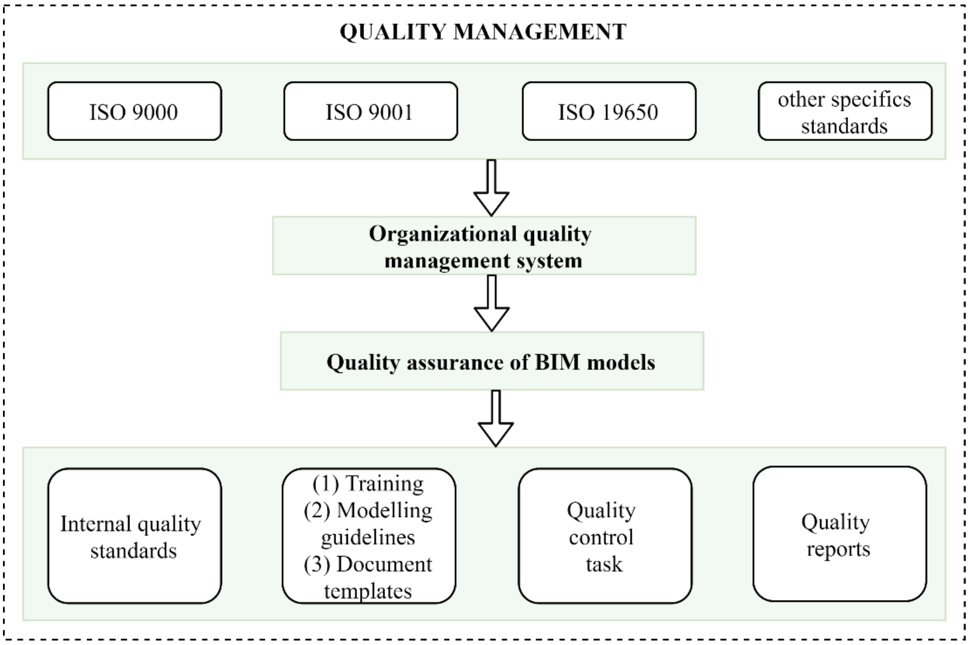

Figure 9: Quality management of BIM models [own elaboration]

From the read research regarding quality assurance and for the matter of this dissertation, the author defines as the main aspects for a quality assurance plan of BIM models the following:

- Definition of quality requirements
- Defined modelling workflow

- Modelling guidelines, document standards and team training
- Quality control points
- Reports

2.3 BIM model checking

There are international standards and best practices related to BIM implementation and information management, but the topic of BIM quality control is still not profoundly referenced [10]. Recently, studies have been carried out with the purpose to fill this gap. Therefore, this chapter will approach the different definitions of BIM model checking found in the literature.

2.3.1 Definition

BIM model checking refers to the process of applying rules to the information model to inspect against a set of predefined requirements, principles or regulations/codes [35], [36]. The term automated model checking refers to the application of machine-readable rules [35]. Yet, automated rules checking does not modify the design but assesses its information to check it against a requirement and feedbacks with values such as yes/no, pass/fail or unknown [37]. Automated model checking has been pointed as one of the most promising benefits of BIM methodology for AEC [1][36]. A benefit of automated model checking is re-using the rules among the same project or even among different projects. The re-use is possible when the building model always has the same data structure [35].

There are two main parts of model checking: the BIM model (information source) and the rules for querying this information (algorithms) [38]. The rules are defined as algorithms that will query the model with a specific focus. In order to apply the rules efficiently in the model, it is essential to have control over how the information is organised. For that, classification, naming convention, standardised modelling guidelines acquired great importance in model checking. Additionally, the re-use of rules again raises the need to think about the structure of the information. The model checking will check the quality of information, but the information needs to be at a minimum level of organization to be readable by algorithms. Non-standardised data formats are the main obstacles to model checking [35]. In other words, to check the model efficiently, the information and the rules need to communicate by the same logical structure. Moreover, the efficient formalization of the requirements, codes and guidelines from natural language into machine-readable rules has an enormous impact on the efficiency of the checking procedure [36].

2.3.2 Model Checking – Concepts Classification

This chapter will be based on the classifications provided by Hjelseth [38].

Concept type 1: Validation checking:

Validation checking refers to comparing a set of constraints present in the model against constraints of the predefined set of rules. In order to be considered compliant, the BIM element needs to be within the conditions set by the rule [38]. There must be a list of requirements that, after being translated into a machine-readable format, can be compared to the elements/ parameters/ relations contained in the BIM model. The rules constraints relate to values conditions or existent/non-existent conditions. For the proper application of these concepts, it is of high importance that the structure of the BIM model matches the system of the rules and queries that will be applied to it [38].

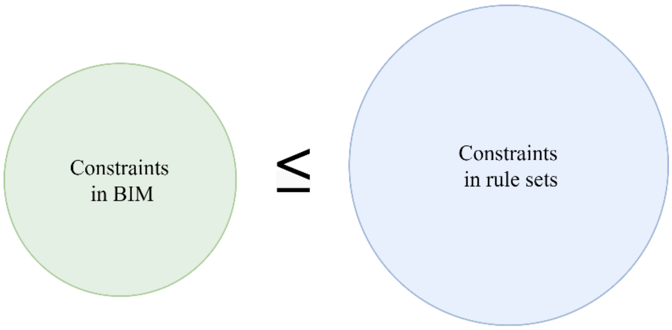

Figure 10: Principle of validation checking [38]

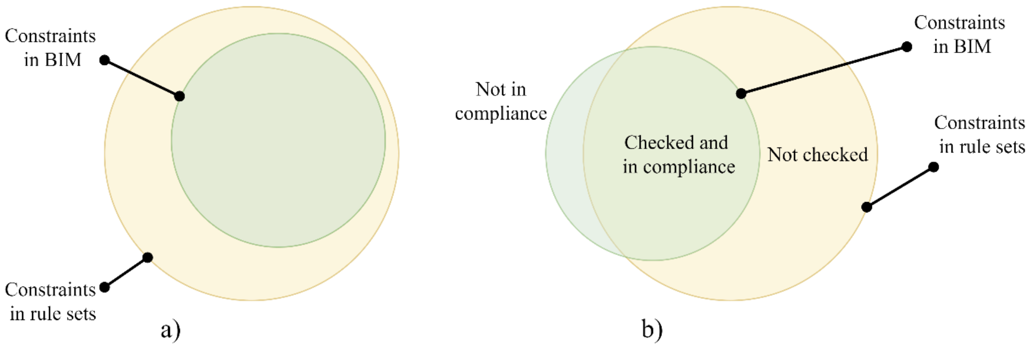

Figure 11: Validation checking illustrated as Venn diagrams [38]

<u>Concept type 2: Model content checking</u>

Model content checking refers to the inspection of specific information in the BIM model. In this case, a set of algorithms filters the model and feedbacks with yes/no values [38]. This type of rule verifies if the BIM model is populated with the required content. Therefore, the focus of these rules is not validating the semantics of the information. Nonetheless, systematic and automated model content checking is useful in the design process, not only for checking the information existence but also to control the amount of information in an exchanging process [38].

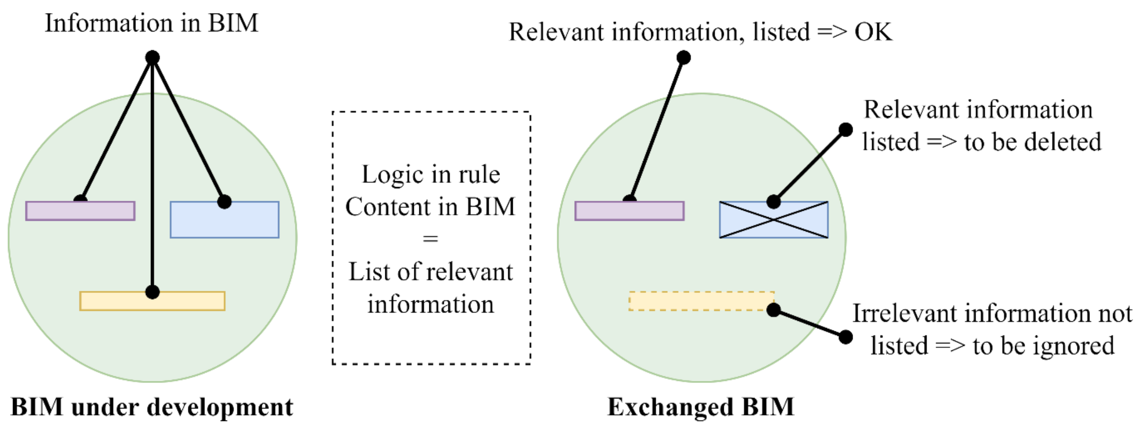

Figure 12: Principle of model checking content [38]

Concept type 3: Smart object checking

This concept refers to objects with embedded rules that respond to geometric or non-geometric changes performed in the model [38]. Although the parametric objects can be automatically linked and responsive to the ruleset constraints, they can generate unwanted modifications in the model from the designer point of view. Therefore, the smart objects need to be structured so that the designer will still have control of what changes if a specific parameter is modified. On the other side, applying embedded rules directly to the objects is useful in quality control. For example, a set of algorithms embedded in the BIM object is useful to generate specific parameters and compliance status feedback.

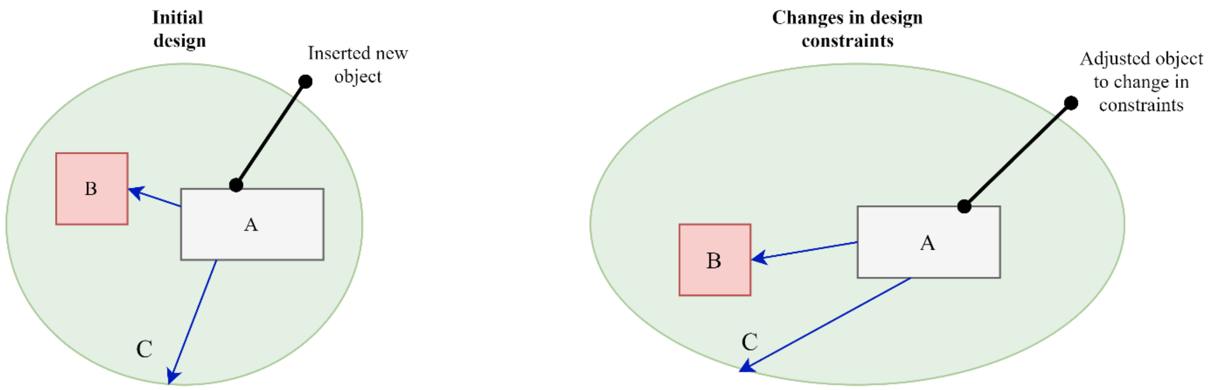

Figure 13: Principles of smart objects [38]

Concept type 4: Design option checking

Design option checking refers to rules that identify a predefined situation, search on a knowledge database and feedbacks the designer with solution options. According to Hjelseth, this type of checking is still at an immature level in AEC, and there are no software solutions to apply it [38].

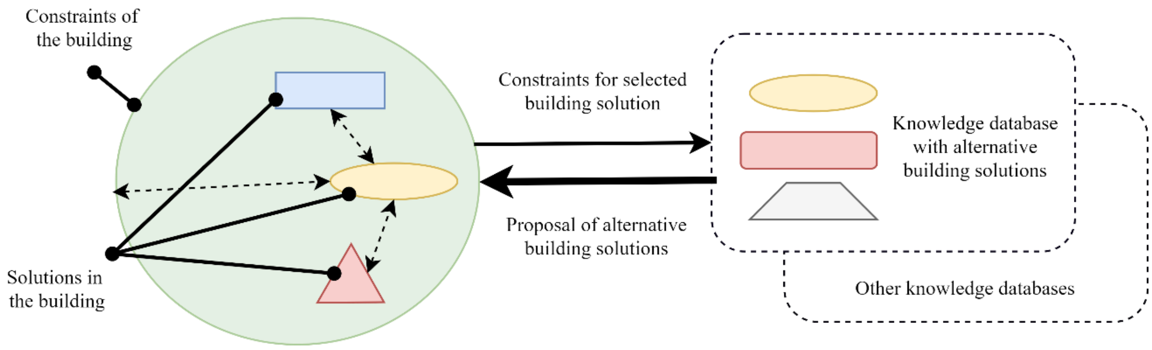

Figure 14: Principle of design option checking [38]

2.3.3 Model Checking – Scope

Code compliance: Code compliance refers to the automated checking of the models by applying algorithms to validate the compliance of building models against a specific code or regulation. The codes need to be translated into machine-readable language and compared against the data contained in the model [17]. The biggest challenge is to provide clear rules from the codes that are usually complex and subjected to human interpretation [17].

Clash detection: Clash detection is the automated inspection in the building models to find geometrical collisions between construction elements to be coordinated, tracked, and solved[39]. It is one of the widely applied Models Uses related to BIM methodology as it provides significant savings in cost by detecting clashes in the early stage of design [1]. However, by default, it provides a huge number of conflicts. Therefore, the clashes, the model and the rules should be structured in advance [39].

BIM data validation: It refers to the process of applying rules to validate the information contained in the model against a predefined information requirement. (1) specific client requirement (4) warranty approvals (3) BIM data completeness for model handover to facility management.

Other scopes: In [8], Solihin and Eastman highlight the most common scopes of model checking (1) specific client requirements, (2) constructability, (3) safety, and (4) construction scheduling.

2.3.4 Model Checking – Rule classification

Class 1: Rules that require a single or small number of explicit data [8]

The rules are of low complexity as it relates to simple queries to the BIM model. This class refers to the rules that check explicit parameters contained in the model. Examples of explicit parameters are the naming convention, classification, material attributes, position, structural function, etc. There is no need to generate other parameters in this rule as the attributes are naturally part of the BIM element, from its own attributes or from the relationship to others. For this rule, the model is simply queried, and feedbacks results by following steps.

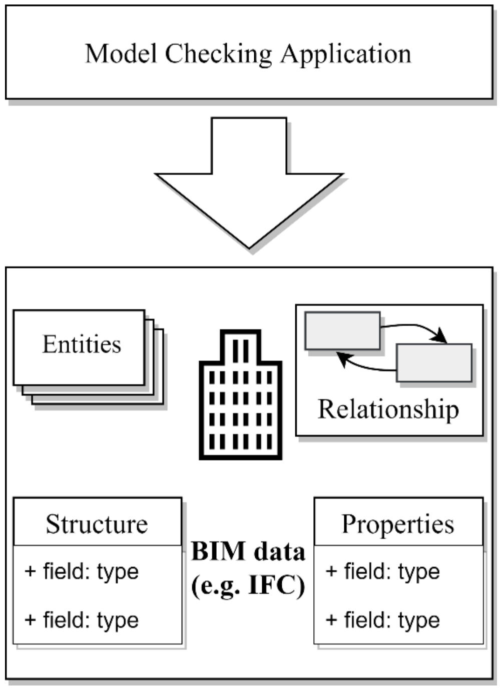

Figure 15: Diagram for typical application implementing Class-1 rules [8]

Class 2: Rules that require simple derived attribute values [8]

This rule requires values to be first derived and then checked. It involves a more complex logic as the value or attributes that are not naturally generated by the software need to be generated often by implicit relationships or specific conditions set by the user.

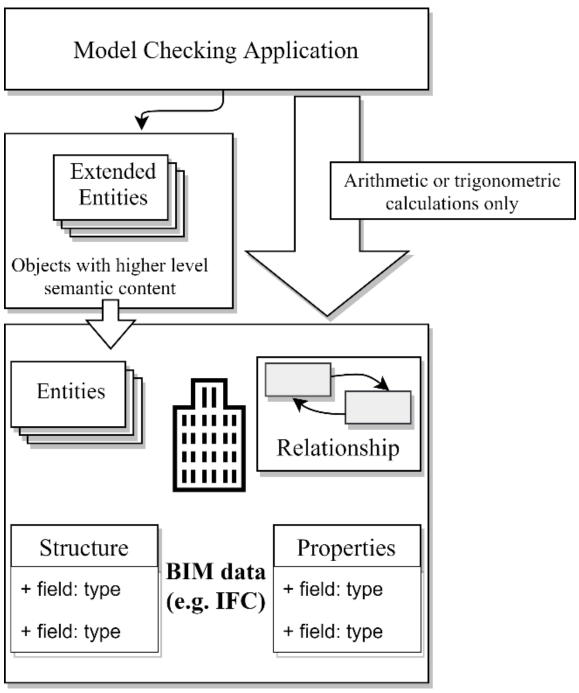

Figure 16: Diagram for typical application implementing Class-2 rules.[8]

Class 3 and Class 4: Rules that require extended data structure or a "proof of solution" based on a knowledge database are also defined in [8]. However, they will not be described in this dissertation as they are not the focus of this study.

2.3.5 Model Checking - The process

The rule-based model checking is more than simply rules implementation. In [40], Eastman, Lee, Jeong et al. structured the model rule-checking process into four central parts. A shared convention must exist among the three first parts to enable the rules to be efficiently implemented to the existing model. In addition, for the applicability of the process, the information must be explicitly available. It means that the designer must have created it, or the computer must generate the missing data before the checking start. Hence, the model-checking process requires a well-structured connection between transforming requirements into computable rules, the data generation, and the rule execution. The method defined in [40] is summarized as follows:

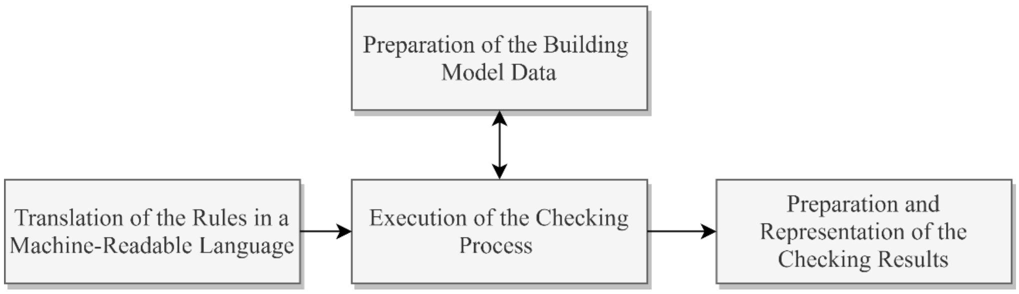

Figure 17: Common structure of an automated Code Compliance Check [17]

(1) *Rule interpretation* [40] refers to the transformation of natural language codes into processable rules. This step represents a challenge for model checking as the regulation is subjected to the human's interpretation, which is not always consistent. For this reason, the logic of the interpretation and the ontology of names and properties must be considered to support the rule translation process.
The logic-based interpretation widely used is named First Order Predicate Logic. It consists in translating the rules into executable statements. In other words, it breaks down the rules into two parts where one (predicate) defines the second (subject). The predicate can be evaluated into TRUE, FALSE or UNDEFINED values.
When it comes to the ontology of names and properties, the classification systems are essential since they are means of controlling the applicability of the rules into the model elements.

(2) Building model preparation [40] consists in generating the data needed for the checking. In object-based building models, unlike traditional building representation, the objects must be adequately modelled and classified to be interpreted by the computer. For example, it means that if a beam is modelled from a wall tool, it will not be interpreted as a beam unless it is classified accordingly. In BIM projects, the requirements for model checking must be exposed as earlier as possible. In

addition, the data needed must be generated as automatically as possible to avoid erroneous data production.

(3) *Rule execution* [40] refers to the application of the rule into the prepared model. This task requires some pre-checking, such as verifying if the model contains all the needed data and an updated version.

(4) *Rule reporting* [40] refers to the generation of a report discriminating all the rules tested, the instances it was applied to, and the test results.

2.3.6 Software Review

Among the available software for model checking, the most widely used is Solibri Model Checker (SMC), a stand-alone tool dedicated entirely to automated rule-checking. Other software vendors are not exclusively devoted to it, but they provide data validation, compliance checking, issue management, or clash detection features. Yet, those tools rely on IFC and provide plugins that connect their interface to the authoring tool. Still, some efforts have been raised from the need to validate the project data in the authoring tool. Therefore, Autodesk Revit and Graphisoft Archicad released supporting tools in that direction: Model Checker for Revit and Collision Detection for Archicad. Nonetheless, they still have limited application.

Solibri Model Checker [41] is the most used stand-alone model checker based on the IFC format. By applying automated rule-based checking, it provides geometry and spatial operations, especially regarding building codes [42]. Furthermore, the vendor offers a basic library of rule templates that can be manipulated to adjust to project requirements and stores and rulesets. Although the rules could be adjusted through the user interface, they represent hard-code functions that require data modelling expertise to manipulate it [17]. Therefore, the adjustment of rules is mainly used by experienced users.

BIMcollab [43] is a viewer of the IFC format and provides powerful features for data validation. For example, the Smart Views and Rules for clash detection are dynamic filters to colour-code objects based on their selected properties. Those features are manipulated through the user interface and shared among team members. The data issues found can be tracked and communicated through the BCF manager to the authoring tool.

Simplebim [44] is a software focused on IFC data management and validation. According to the vendor, it focuses on standardising IFC data from different sources in a project lifecycle. The available functionalities enable the user to modify, delete or add metadata and information that exceeds or lacks automatically, resulting in better quality data.

Graphisoft Archicad [45] has recently released the Collision Detection tool, dedicated exclusively to detecting clashes among geometries selected by user-defined criteria. In addition, it does clearance checks between BIM elements but with limited application. Regarding data validation, Archicad provides a set of features for filtering the elements and creating visualisations with different model representations and colours. Further aspects of Archicad will be covered in the case study of this dissertation.

Autodesk BIM Interoperability tools [46] are a set of add-in tools for Autodesk Softwares that allow users to check compliance standards inside the authoring environment. Applying the tool makes it possible to manage classifications and project parameters, populate Revit families with data, verify and check the model against requirements, and create real-time reports.

Revit Model Review [47] is another add-in tool that enables the user to define rules to apply in the native model.

BEXEL Manager [48] provides a wide range of functionalities for BIM management, from 3D to 6D management. Although it is not exclusively dedicated to data validation, it offers useful features such as clash detection operations, metadata management operations, advanced filters, grouping and colour-code operations based on defined properties.

dRofus [49] is a platform that supports teams in creating a data-driven model approach. Although it is not a rule-based checking platform, it provides features regarding design requirements validation through an integrated workflow and a centralized project database available for the project stakeholders. Additionally, it offers a bi-directional connection to some authoring tools such as Archicad and Revit.

FORNAX™ [50] is one of the first approaches to model checking developed by the Singapore CORENET effort. It has been pointed out as one of the advanced solutions regarding compliance checking [17]. Among the variety of functionalities, it provides automated regulatory checks, BIM data and quality checks, as well and customisable rules [50].

BIM Assure [51] is a young online platform released in 2016 by Invicara. The main functionalities are related to data visualisation and manipulation in the cloud. Also, it offers some features regarding rule checking, data analysis and reporting. The results can also be synchronized back to Revit.

BIMQ [52] *i*s another recent cloud-based platform focused on BIM management and interdisciplinary communication.

2.3.7 Summary

BIM systematically changes its purpose, goal and uses across the project lifecycle, so the model checking does. As pointed out in this chapter, model checking has different definitions, and the scope is still not a defined opinion between the specialists. Nonetheless, there is one single point of convergence of the scopes pointed in the section. All checks need as input a pre-structured information model that communicates with the algorithms to be applied. It is independent of the type, size, location, complexity of the project. Every single model needs to have controlled information to be useful for future model uses. The author in this dissertation highlights the need for quality assurance of the data produced in the authoring tool and brings the designers the responsibility for maintaining the quality in the design itself and the data structure of the models.

The integrity of the inputs for the model checking process is essential for acquiring quality outputs in any analysis or use that will be applied in the BIM model [17][5][8]. To check specific information, geometric or non-geometric, the data needs to be available, accurate, correct and consistent [17]. In addition, the analyst must know where to locate the information and how to filter it properly. The efficiency in the application of automated rules relies on data availability and accessibility [42]. The model can be queried in many ways, such as the hierarchy of objects, classification, materials, layers, naming convention, properties, geometry, element type, family type, or any other parameter.

The rules are seen as the neutral tool that can be applied for different checking procedures after having a purpose or model use in mind. The model uses are quantity take-off, code compliance, clash detection, cost estimation, scheduling. The rules need to be applied in any authoring tool to guarantee the model is being produced accordingly to the final use.

2.4 ISO 19650

2.4.1 Overview

The International Organisation for Standardisation (ISO) set a series of principles and requirements for information management in the context of Building Information Modelling (BIM). ISO 19650 [4] defines a set of recommendations that support the interested parties in the management processes and technical solutions for implementing BIM in a built asset or construction projects [4]. According to UK BIM Alliance, the adoption of BIM in alignment with the ISO 19650 series provides beneficial outcomes, such as efficiency in information transfer, reduction of information waste, improvement of data quality, and clearance in the requirements for all involved parties [53].

All asset and project information in the asset life cycle should be specified through a set of requirements by the appointing party. The relevant information requirement should be handed to each lead appointed party that will manage and deliver the required information. The delivered information will be then checked and accepted by the appointed party. Figure 18 illustrates the concept of information specification and delivery.

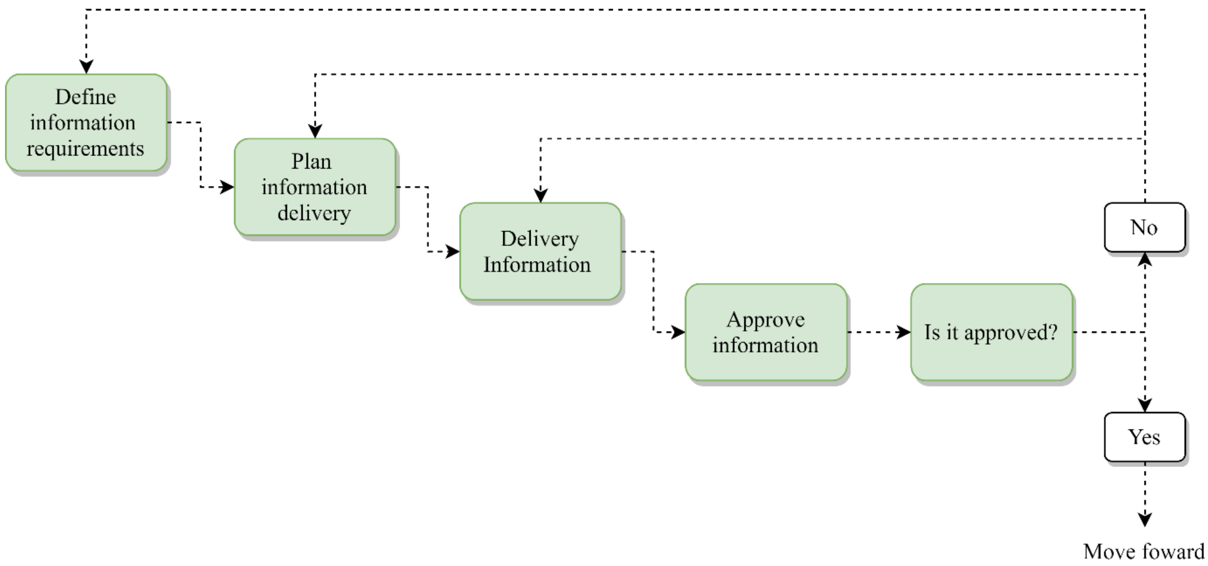

Figure 18: generic specification and planning for information delivery (adapted from [4])

The information is required to support the appointing party in a key decision point. The information to support the decision is delivered in information exchange points that should be defined, detailed, and distributed by the appointing party to each lead appointed party. Figure 19 illustrates the relationship between the decision-making process and information delivery [4].

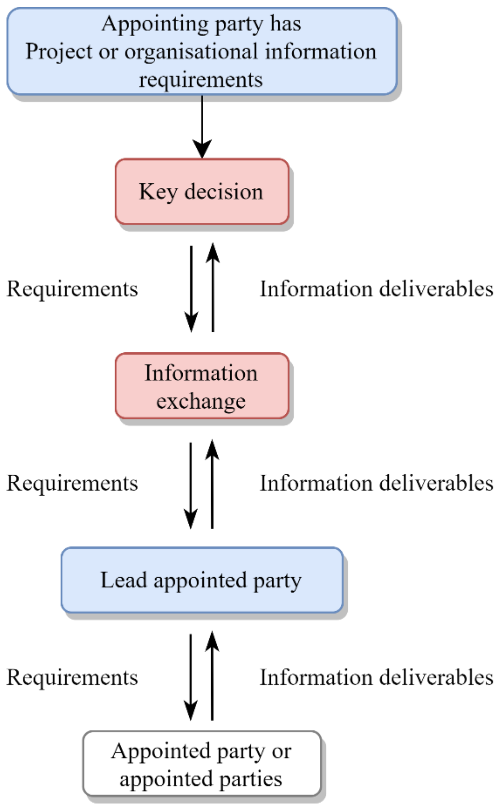

Figure 19: Information flow in key decision points (adapted from [4])

The information should be exchanged in a CDE solution. The management of exchanged information containers should be supported by the workflow described in Figure 20. The proposed workflows improve efficiency in the collaborative production, management and coordination of the exchanged information between the interested parties [4].

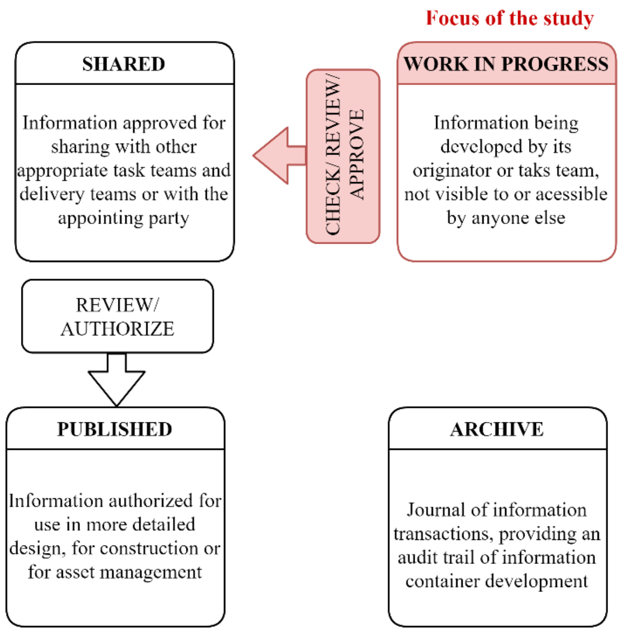

Figure 20: CDE workflow (adapted from [4])

2.4.2 Information requirements

According to ISO 19650, the information requirements should relate to the project stages that the information that will be used [4]. The different types of requirements are explained below.

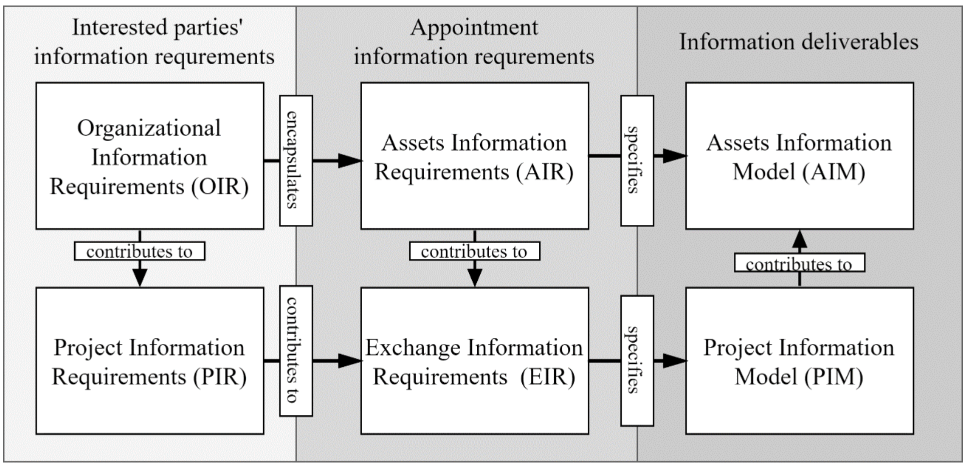

Figure 21: Hierarchy of information requirements [4]

<u>Organizational Information Requirements (OIR):</u> refers to the information need that is aligned to the high-level strategy of the appointing party [4].

Asset Information Requirements (AIR) [4]: refers to the *"managerial, commercial and technical aspects of producing asset information* [4]*."* The managerial and technical aspects should include a definition of how appointed parties should produce the information. It details the aspects from OIR that relates to the asset. Therefore, the requirements should be specified with the purpose of requiring the information need for organizational decision making. AIR can also be incremented by lead appointed parties. It, however, should be coordinate with others AIR, resulting in a single AIR that is aligned to the organizational requirements.

Project Information Requirements (PIR) [4]: refers to the requirements related to a specific built asset project. As well as AIR, it also answers aspects specified in OIR, and it should be defined for each of the appointed parties.

Exchange Information Requirements (EIR) [4]: refers to the information requirements that answer the specificities of PIR and AIR for each appointment set in the project lifecycle. It details how the information should be produced, delivered, structured, and content for each project delivery. It should be defined to be incorporated in the project deliveries and across the related appointed parties.

Those four pieces of requirements will be developed into two different containers of information: Project Information Model (PIM) and Asset Information Model (AIM). The first supports the project development and deliveries, while the second supports the built asset management. Both models are rich information packages that can be applied in different uses and workflows.

2.4.3 Level of information need

The level of information need defines the granularity of the required information in OIR, AIR, PIR and EIR. The main purpose of it is to prevent the production of extra or not-needed information. Therefore, the level of information need is determined by the minimum amount of information needed to fulfil the specific requirement [4].

The European Standards (EN) defines in the standard EN 17412-1:2021 [54] a methodology for specifying the Level of Information Need. The information should be defined by geometrical information, alphanumerical information, and documentation. These aspects should be determined for each point of information exchange to guarantee that the purposes and requirements will be met at every stage [54].

Geometrical Information: refers to the aspects related to the details, dimensionality (1D, 2D, or 3D), location, appearance, and parametric behaviour of objects [54].

Alphanumerical Information: refers to the identification (name, id, classification, index, numbering) and information content of the objects (list of all properties required) [54]. The identification relates to the model breakdown structure and its hierarchy. It supports the management of objects that populates to model.

Documentation refers to the documents that will support decision making. It can be linked or attached to the information containers [54]. It can be reports, manuals, drawings, signed documents, specifications, calculations, etc.

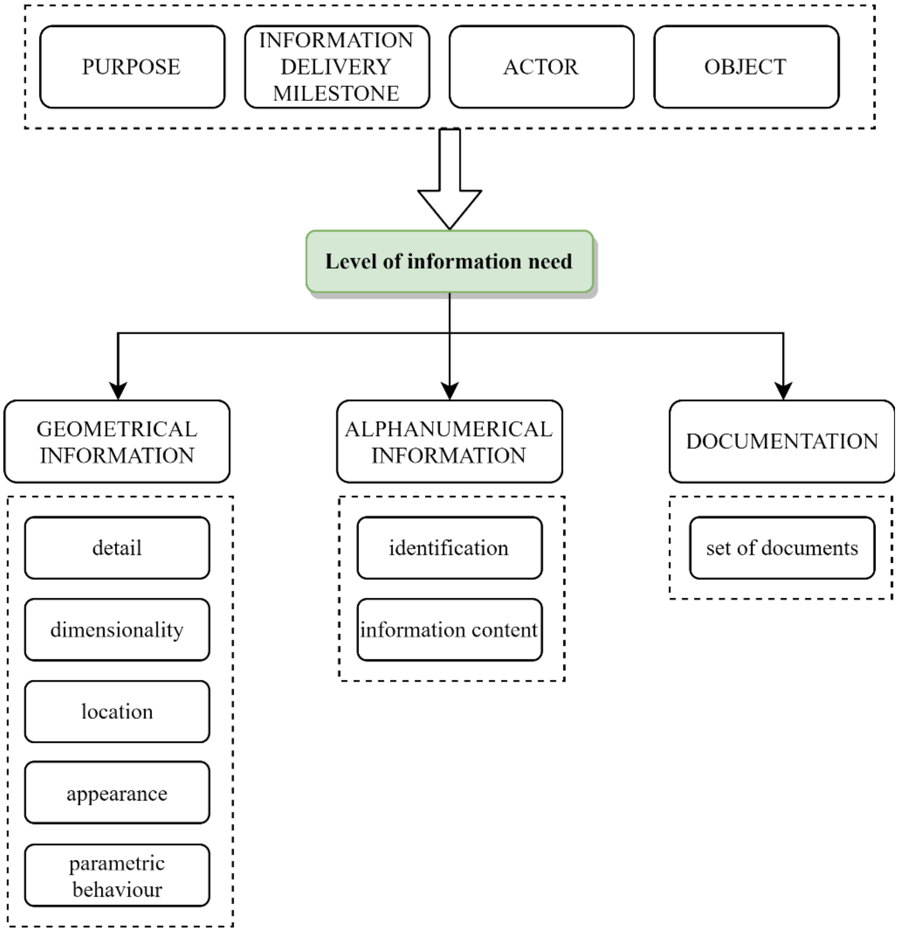

Figure 22: Level of information need diagram (adapted from [54])

2.4.4 Information verification and validation

The Level of Information Need, the Information Requirements and the acceptance criteria enable the verification and validation procedures of delivered information [54].

At every information exchange, there should be a checking procedure performed by the appointing party. According to ISO 19650, each information delivered should be checked against the related requirements through verification and validation processes. Additionally, double-checks should also be considered in some specific situations. For example, when the information will be used by another lead appointed party that has not produced it or when there was a delay between the end of one stage and the start of the following one. In those cases, the usability of the provided information should be analysed.

Verification: *"confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.*[54]*."*

Validation: *"confirmation, through the provision of objective evidence, that requirements for a specific intended use or application have been fulfilled* [54]*."*

In addition to the checks done by the appointing party, the delivery teams are responsible for checking the deliver containers before submission. The task team's responsibility is to produce information following the level of information need and requirements related to methods and technical requirements for the information and not to generate extra information to what was specified. The results from the quality assurance check should be documented whether the information container was approved or not. When not approved, the author should be informed, and corrective actions should be taken.

Prior to proceeding with the information container submission, the task team should perform checks in both the information container and in the information within it., these two tasks are represented by the numbers 6.3 and 6.4 in the figure below. The information shared will then be coordinated in 6.5 and reviewed in a coordination context. Before the checks, the task team should consider:

(1) The lead appointed party information requirements
(2) The level of information need
(3) Information needed for coordination purposes

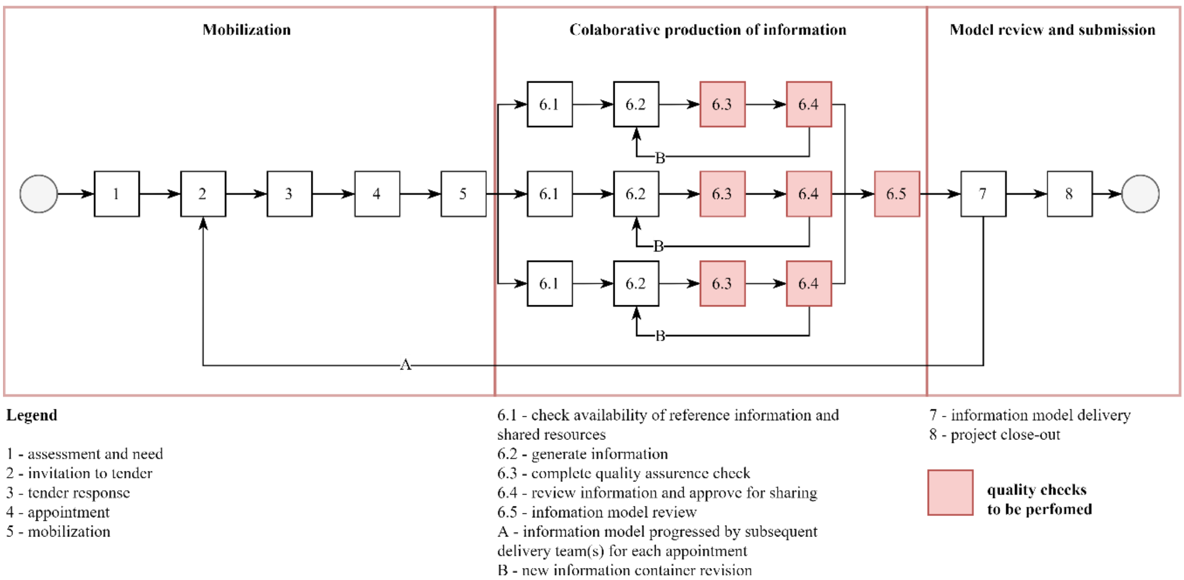

Figure 23: Collaborative production of information (adapted from [4])

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3 FRAMEWORK

This chapter will explain the theoretical part of the framework, which is compounded by three main steps: preparation, structuring and application. The methodology proposed in this chapter includes structuring, controlling, and evaluating the information generated throughout the modelling processes.

3.1 Overview: aim and objectives

This framework aims to structure a methodology for the quality assurance of BIM models by compiling the main tools and methods covered by current studies and industry. It proposes understanding the BIM models of different projects from a broader and integrated perspective. The quality assurance plan addresses the specific needs of single projects by looking at the organizational level of BIM management. Finally, it seeks to provide guidance for AEC companies and support them in managing BIM projects.

The main objectives are listed as follows:

<u>Primary goals:</u>

1. Guarantee quality and reliability of BIM models by ensuring completeness, consistency, and accuracy of information.
2. Ensure the creation of models that fit the final purpose and comply with the project requirements.
3. Integrate quality checks in the design process and the authoring tool by automated and semi-automated steps.
4. Ensure the company's internal models are structured similarly and consistently.
5. Ensure software template is aligned to the needs of the company and being applied correctly by designers.
6. Support decision making by providing measurable criteria for quality evaluation of the data contained in BIM models.
7. Prevent issues related to the data structure.
8. Provide a methodology applicable to different projects.

<u>Secondary goals:</u>

1. Ensure proper storage and transfer of information among projects. Support the company in the standardisation of ongoing projects, libraries, and storage of finished projects.
2. Support managers in the evaluation of team performance.
3. Support the company in the evaluation of outsourced projects.

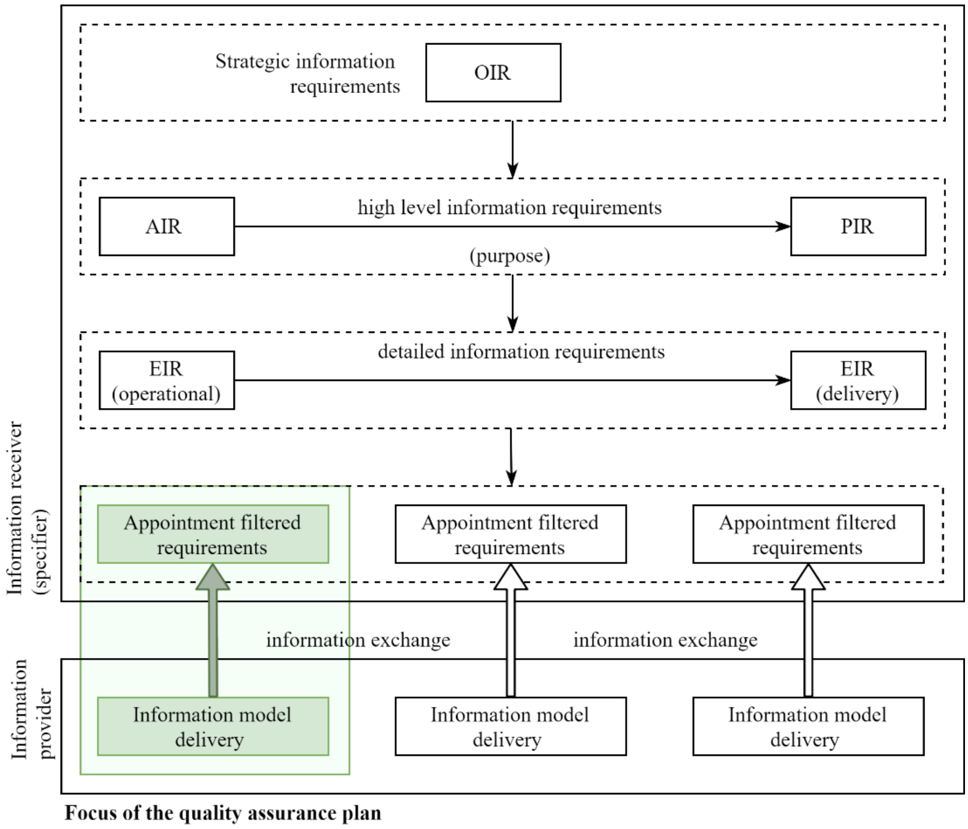

Figure 24: Focus of the quality assurance plan (adapted from [55])

Object self-checking: the methodology uses the concept defined in [38] by directly applying expressions provided by the authoring software in the BIM elements. Those expressions are generally applied to create specific parameters to fulfil information needs not covered by the standard parameters available in the modelling software. In the case of the Quality Assurance Plan proposed by this dissertation, the expressions are applied with the purpose of object self-compliance checking. The rule embedded in the BIM element enables it to check itself and feedbacks with a compliance status.

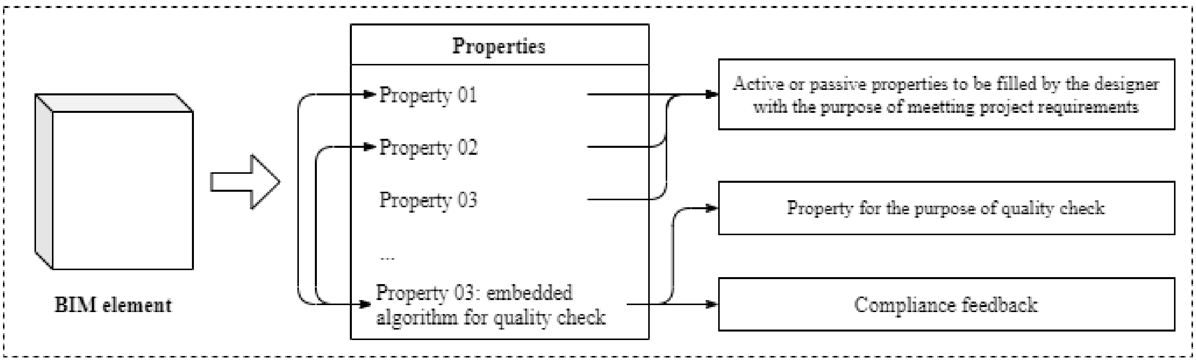

Figure 25: embedded algorithm in the BIM element [own elaboration]

3.1.1 The quality assurance on the organizational level

The quality assurance plan can be created on the organizational level to keep the different projects at a standard of consistency. In other words, the method may be applied to a design company with a variable project portfolio and various stakeholders. The figure below illustrates the connection between organizational and project levels in the quality assurance plan.

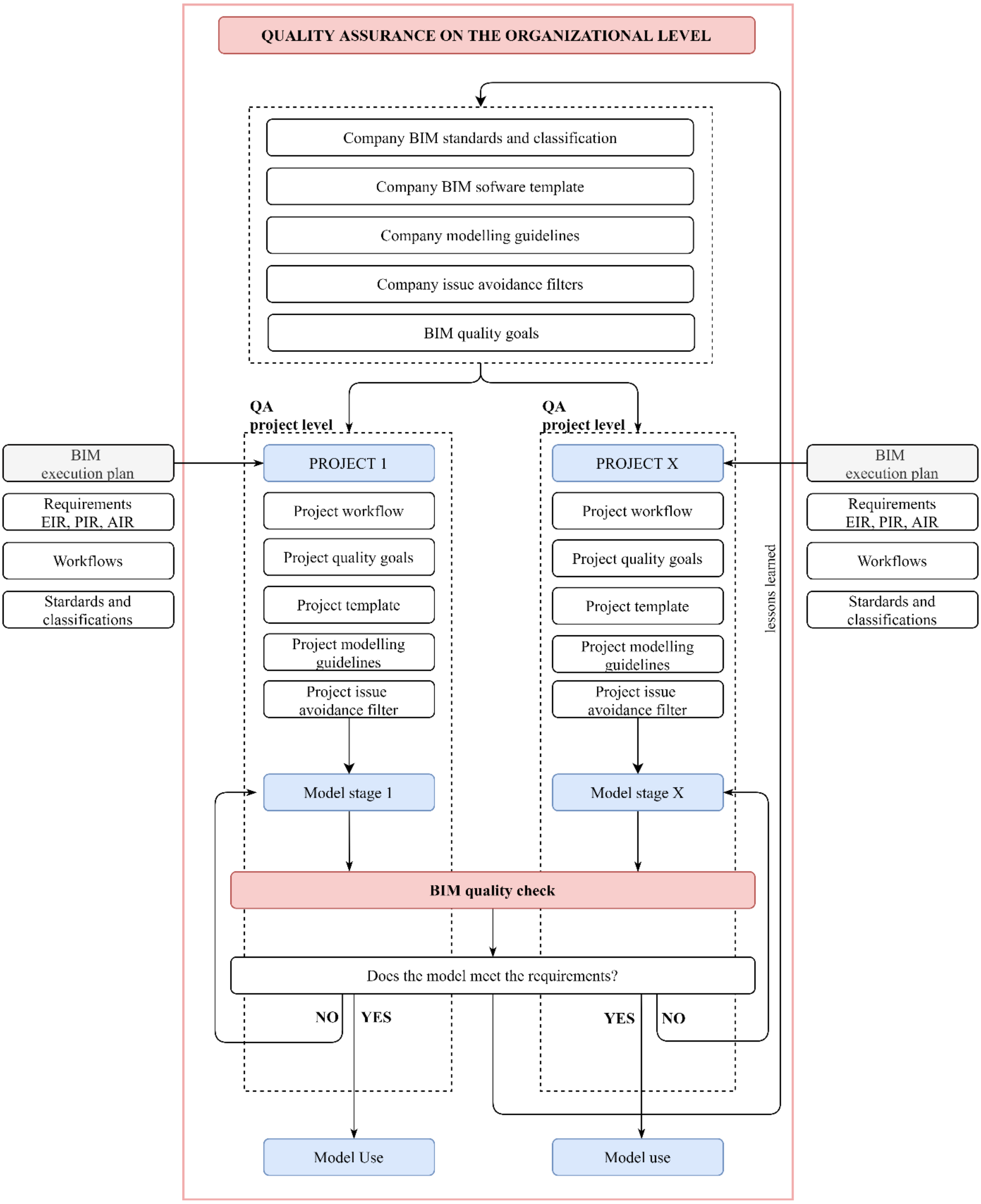

Figure 26: Quality assurance on the organizational level [own elaboration]

Even though the projects always have specificities, they should be interpreted as a single system under the same rules and requirements. All the projects under the umbrella of the organizational quality assurance plan follow the basic information structure, naming convention, hierarchies, modelling guidelines, and templates. Additionally, the projects should go through the basic rules and filters to ensure the company standards are being followed. It enables the company to keep the different projects consistent while assuring that the knowledge acquired in each project is structured, shared, and later stored correctly,. The specificities and requirements of the single project should be englobed at the start by applying the organizational plan as the primary input.

3.2 Workflow definition

The framework is divided into three stages: preparation, structuring and application, which are summarized into six steps illustrated in Figure 27. The stages will be covered in the following chapter.

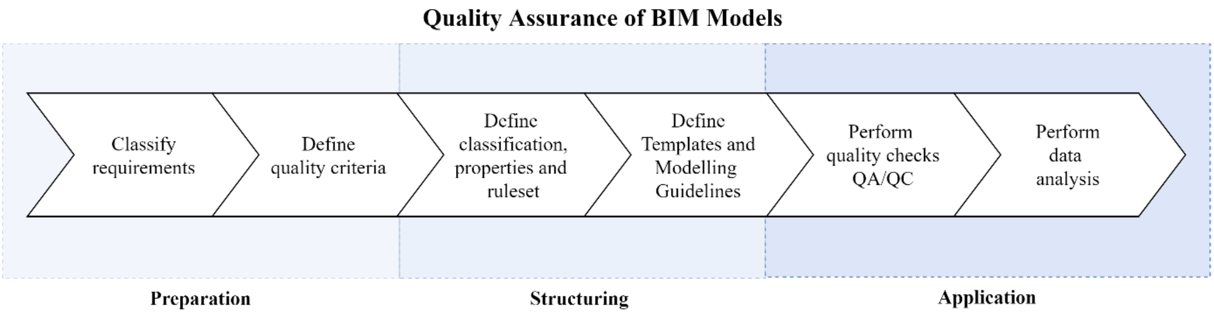

Figure 27: quality assurance of BIM models [own elaboration]

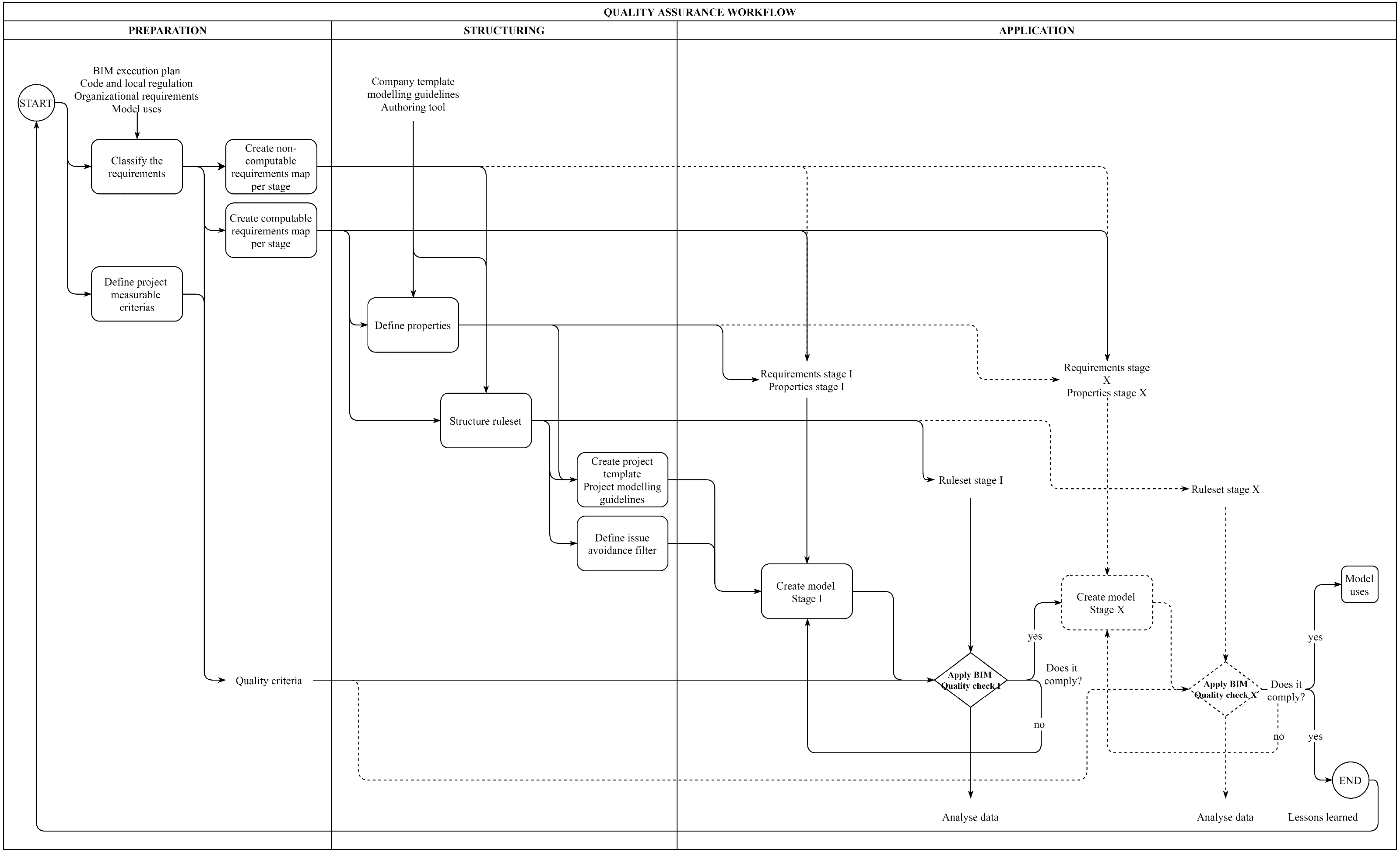

Figure 28: Quality assurance workflow [own elaboration]

3.3 PREPARATION

The preparation refers to the compilation of requirements and the definition of quality criteria for the model. The stage output supports the team in understanding what needs to be produced and which results are expected in each design stage. The key to attaining information quality is having the final purpose and goals for the model well-established from the start. The steps of this stage are detailed in this section.

Two tasks compound the preparation stage: (1) Classify requirements and (2) Define project measurable quality criteria's.

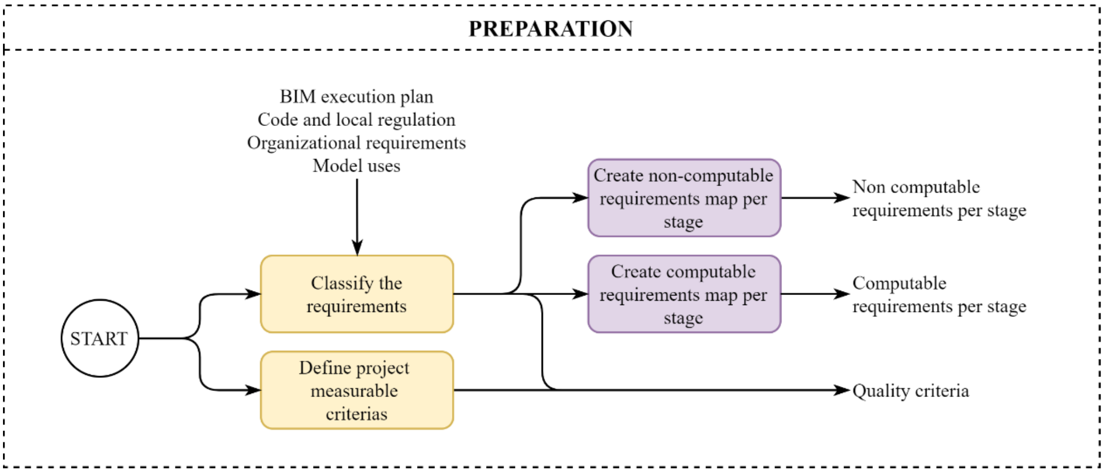

Figure 29: Framework stage I – preparation [own elaboration]

3.3.1 Classify requirements

The first workflow step is the definition of computable and non-computable requirements. The computable requirements are defined as follows:

Computable requirements: those that can be translated into computable rules to be automated or semi-automated interpreted. For example:

-BIM object's property set required in the model;

-Minimal areas required for the building;

-Building materials required for specific areas;

-Minimal dimension for specific building materials or equipment;

-BIM object's naming convention.

Non-computable requirements: those that cannot be translated into computable rules. For example, aesthetic aspects of the building or functional relationship between spaces. For example:

-Aesthetics characteristics of the building;

-Functional aspects of the building (e.g. distribution of rooms, furniture positioning);

-Aspects related to the file organisation (e.g. distribution of drawings in paper sheets, correct placement of plan dimensions or texts in the sheet).

Completing the computable and non-computable requirements is crucial for structuring the entire process since it is the input for defining the rules. The requirements should be mapped according to the project schedule for determining at what stage they will be met and checked.

The framework considers that the requirements are previously defined in the contractual documents and the BIM execution plan, inputs for the preparation stage. However, as authoring design is an iterative process, other sources for getting the requirements may also be considered. The primary sources for defining computable and non-computable requirements are described below:

BIM execution plan (BEP): is the document that addresses the delivery team's strategy for meeting and managing the information requirements across the design stages [56]. Therefore, it is the main input for the first step of the quality assurance plan.

Information requirements: refers to the requirements defined in ISO 19650 – Asset information requirement (AIR), Project Information Requirements (PIR) and Exchange Information Requirements (EIR). For a detailed explanation, see section 2.4.2.

The model uses: refers to the information requirements that need to be delivered or embedded in the 3D digital models to fulfil some specific purpose [57]. The BIMe initiative defines three main categories for model uses subdivided into nine series. The most known model uses are cost estimation, quantity take-off, clash detection, and code compliance checking. The different model uses lead to another information need. Therefore, having the uses for the models well-established across the modelling process is necessary for producing the correct information.

Code and local regulation: refer to the standards and regulations pointed in the BIM execution plan and the contractual documents or are specific to the type of project and its location.

Appointed party information requirements: refer to the conditions related to the company's organizational level, which is creating the BIM model. For example, internal modelling guidelines, document templates, naming conventions, or other internal standards. In this framework, these requirements hold high importance as the goal of the quality assurance plan is to support the proper management of a package of BIM models, not limited to a specific project or client.

This stage output is the map of requirements per stage that will be used for the Ruleset Structuring (3.4.2) and the Application (3.5).

3.3.2 Define project measurable quality criteria

The next step in the preparation stage refers to the definition of quality criteria's and the exposition to the team. The evaluation criteria must be mapped and defined priorities. The framework suggests four dimensions of evaluation for the models.

Compliance rate: refers to the percentage of model compliance or non-compliance when analysed the requirements attendance. Every element will have a "compliant" or "not compliant" status which refers to a specific rule. One element can have different rules applied, and so it will hold more than one "compliance status". The compliance rate is be calculated as per image Figure 30. The project lead should define the desired rate according to the project needs. The compliance rate relates to the general analysis of the model and has no application of filters.

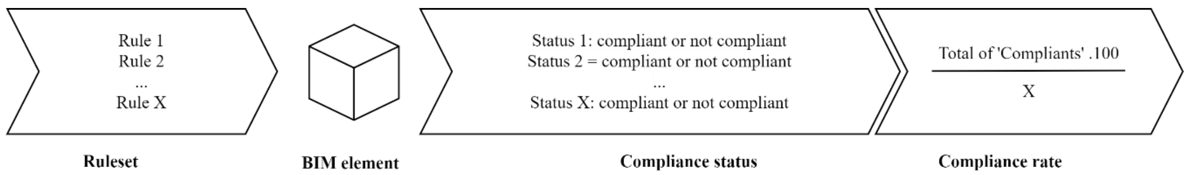

Figure 30: Compliance rate [own elaboration]

Completeness rate refers to the percentage of model compliance calculated by rules that specifically check the dimension of completeness.

Accuracy rate: refers to the percentage of model compliance calculated by rules that specifically check the accuracy criteria.

Consistency rate: refers to the percentage of model compliance calculated by rules that specifically check the dimension of consistency.

The completeness, accuracy and consistency rate are calculated as per image Figure 31. The project lead should define the desired rates according to the project needs and goals.

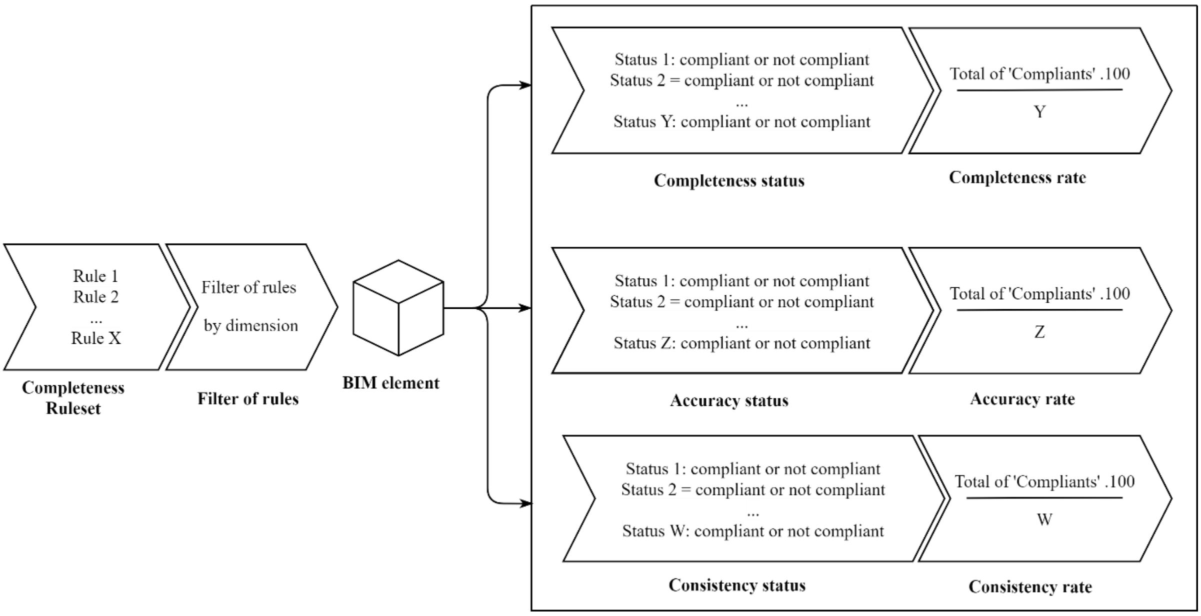

Figure 31: Completeness, Accuracy, Consistency rates [own elaboration]

3.4 STRUCTURING THE MODELLING PROCESS

The second stage refers to structuring the tools to ensure that the modelling process will be carried out correctly. The inputs for this stage are the map of computable and non-computable requirements per stage. The output is the tools suggested by this framework: Project Template, Project Modelling Guideline, and Issue Avoidance Filters.

Four tasks compound this stage: (1) classification and properties definition, (2) ruleset structuring, (3) project template and modelling guidelines definition, and (4) issue avoidance filter definition.

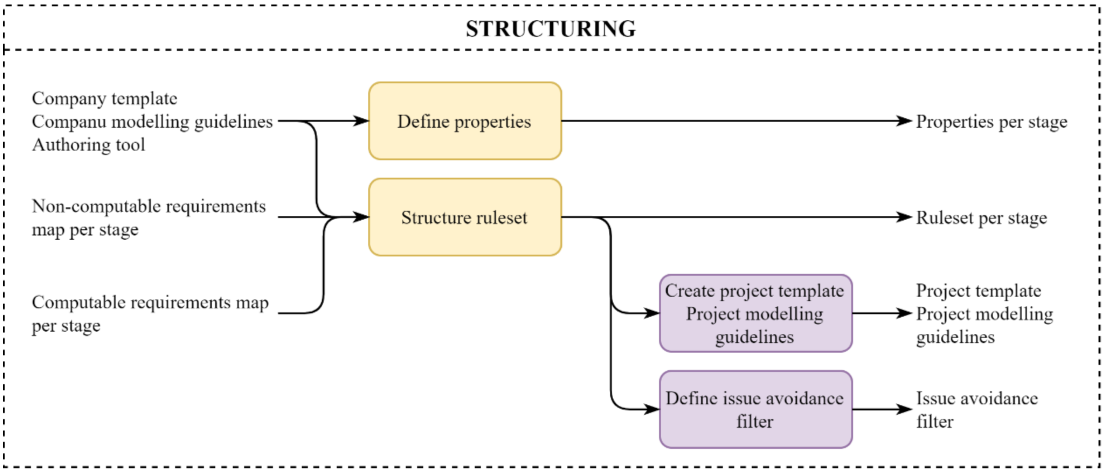

Figure 32: Framework stage II - Structuring the modelling process [own elaboration]

3.4.1 Define classification and properties

Properties refer to the non-graphical information that is related to an instance element in the BIM model. Properties are defined by arguments (inputs) that are controlled or not through the user interface. Properties can cause modification in the geometry or the non-graphical information.

There are two classifications for properties: active and passive [23]. Active properties are the ones that can modify geometry information or can be modified by geometry manipulation. The active properties are controlled by users. Nonetheless, passive properties are of different types. On the one hand, they can be alphanumerical information that does not connect to geometry. It means that they are simply alphanumerical information attached to the instance, such as manufacturer name, warranty date or product price. On the other hand, they can connect to the geometry, but the user does not control it - for example, the volume of a wall [23].

Usually, the modelling software provides default active and passive properties. However, the generation and management of the properties are different across the lifecycle. For example, properties related to the structural or environmental analysis do not need to populate the model in the design stage. However, they need to be added at some point.

This framework proposes dividing the properties into groups that refer to the stage they should be included in the model - as defined per requirements. The model should contain only the parameters necessary for the current design phase. No needed parameters should be in the model if it is not part of the requirements.

The output of this stage is the properties containers. The properties containers will input the project template (3.4.3) definition and the application stage (3.5).

3.4.2 Structure ruleset

The Ruleset definition defines the rules that will check the model against the requirements previously mapped. The rule should be understood as the filters the models should pass through to be approved for further stages or not. Therefore, it needs to be defined by understanding what requirements need to be attended in the modelling process. However, it must be clear that rule checking is not responsible for keeping the quality of the models. Instead, it is the tool that supports the coordinator in the control of quality. As the primary goal of the quality assurance plan is to ensure the model is correctly structured to fits the final purpose, the rules must be structured seeking to answer the following questions:

- What requirement will be assured by this rule?
- What is the priority of the requirement?
- How is the rule helping to guarantee the proper final use of the model?

To be measured and evaluated in the future, the rules should be structured for the purpose of feedbacking with a COMPLIANT or NOT COMPLIANT value. Thus, it reduces the need for human interpretation while providing data that can be analysed and measured later.

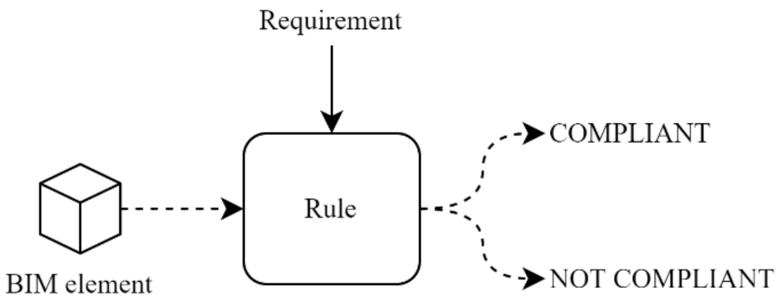

Figure 33: the rule concept [own elaboration]

3.4.2.1 Rule Taxonomy

In order to support the process of creating the rules, the following taxonomy is applied. The rules can be classified into different categories at the same time. The rule categorization is essential to understand how it behaves and what kind of feedback it will provide to the user. This current framework addresses four main categories of rules subdivided into subcategories. See Figure 34.

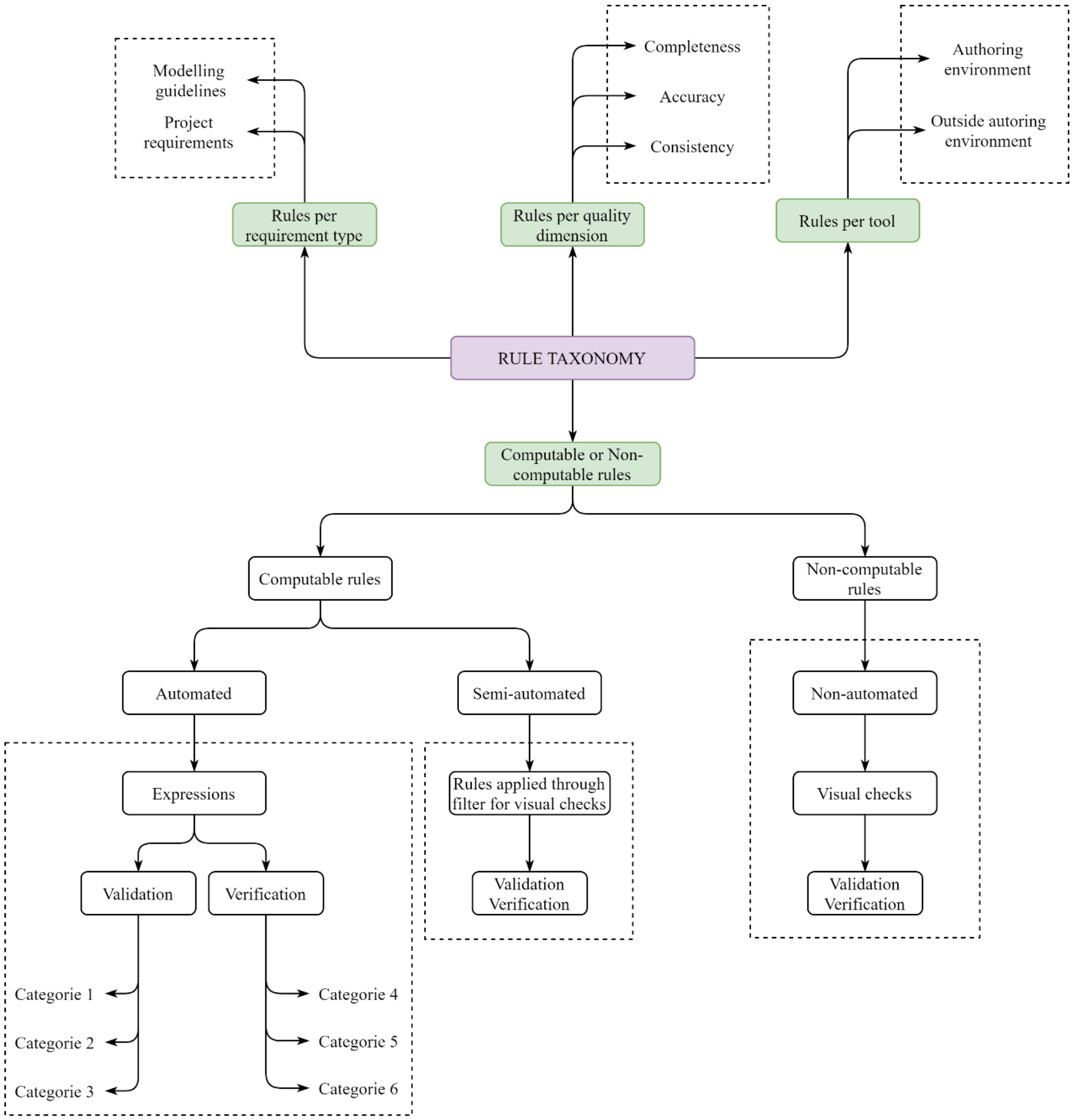

Figure 34: Rule taxonomy [own elaboration]

RULES PER REQUIREMENT TYPE:

This category classifies the rules according to the requirements type that is being checked. The classification of the rules should consider the previous classification done in section PREPARATION3.3. As pointed out previously, there must be different requirement types according to each project, and all types should be addressed when structuring the rules.

The framework considers at least two types: (1) rules to project requirements and (2) rules to check modelling requirements. The first is specific to the project instance and will address the requirements defined in the previous stage. The second usually relates to model uses and the design company internal standards, aligned or not to the international standards.

RULES PER QUALITY DIMENSION:

This category refers to the classification of rules regarding the information quality dimension it is checking. It supports the management board to check the overall quality of the model.

RULES PER TOOL:

It refers to rules applied in the authoring tool or those that need extra software to support the checking process.

COMPUTABLE OR NON-COMPUTABLE RULES

It refers to the rules that check the computable or non-computable. The current framework was intensely focused on this category since it represents a more significant improvement for the modelling processes. The computable rules are subdivided into automated and non-automated.

Automated rules consist of expressions embedded in the BIM object through the properties structure, enabling the object to self-check and feedback with compliant or not compliant values. The expressions apply for validation or verification purposes. See Figure 35 and Figure 36 for further understanding.

- Validation: refers to the rules that check if the property is embedded in the model.
- Verification: refers to the rule that checks if the property value is correct by comparing it to a given requirement value

Semi-automated rules refer mainly to rules applied through the structure of schedules and feedback with information that needs to be visually checked by the user. It consists of pre-setting queries and filters to the model so that the users do not need to do it every time they make quality checks. In addition, it has validation or verification purposes.

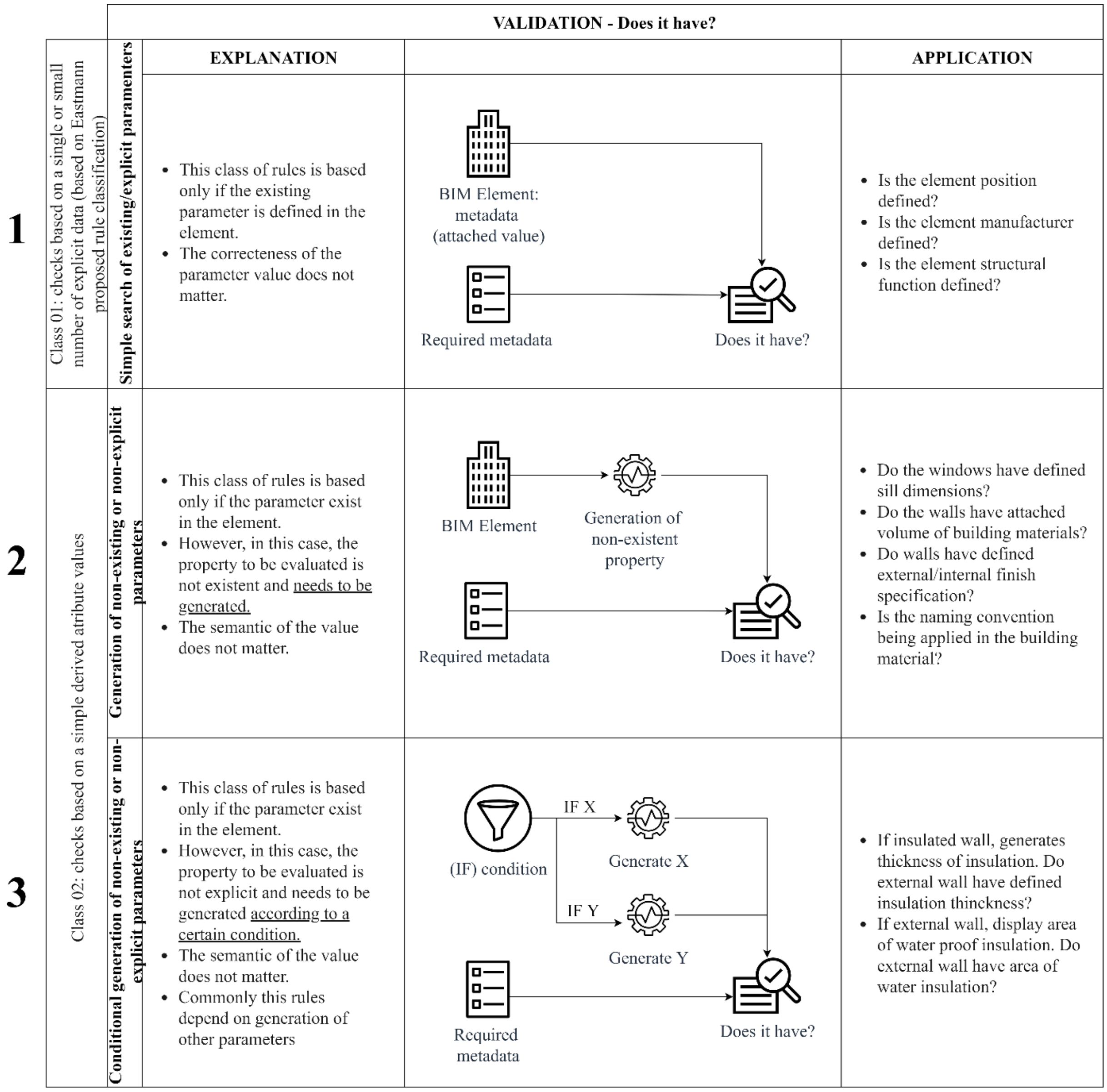

Figure 35: Automated rules for validation purpose (own elaboration - inspired by [8])

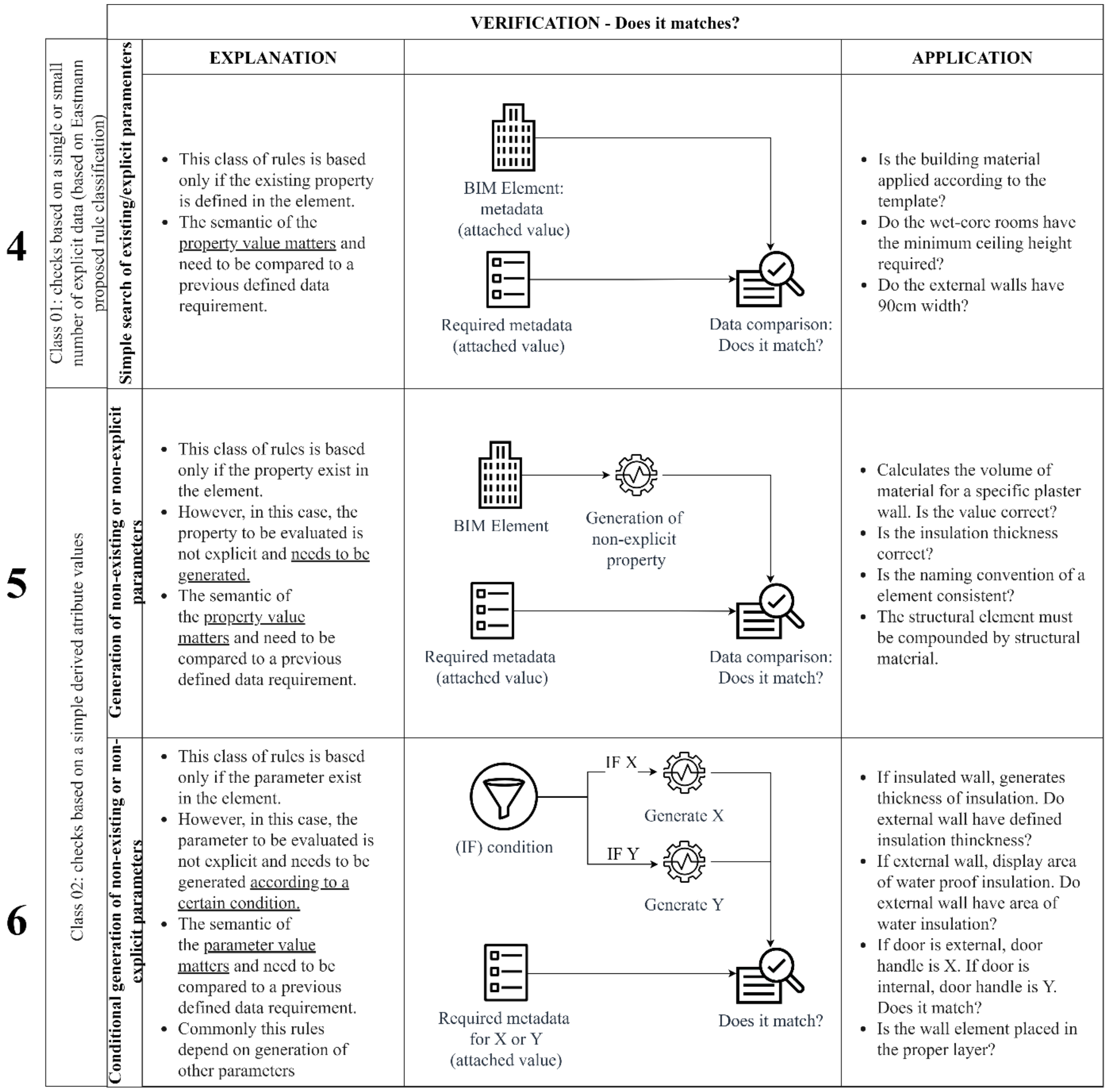

Figure 36: Automated rules for verification purpose [own elaboration – inspired by [8]

3.4.3 Create the project template and modelling guidelines

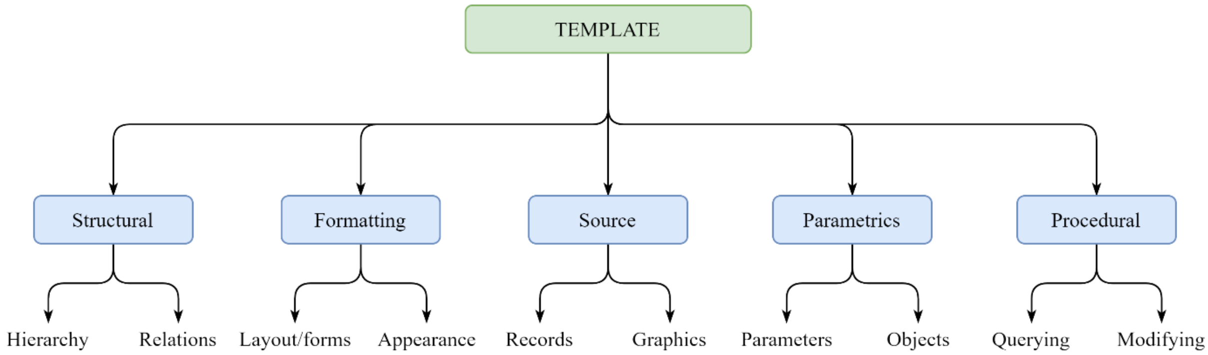

Figure 37: Template structuring [23]

The different domains of a software template focused on the BIM process are illustrated in Figure 37. The template should be structured in an integrated way, considering what outputs are needed for the generic projects, what information can be standardised, how it will be communicated and used by other stakeholders. Moreover, it must be considered that the model is a container of information that may be filtered and queried in different manners to generate data representations. Figure 38 and Figure 39 illustrate it.

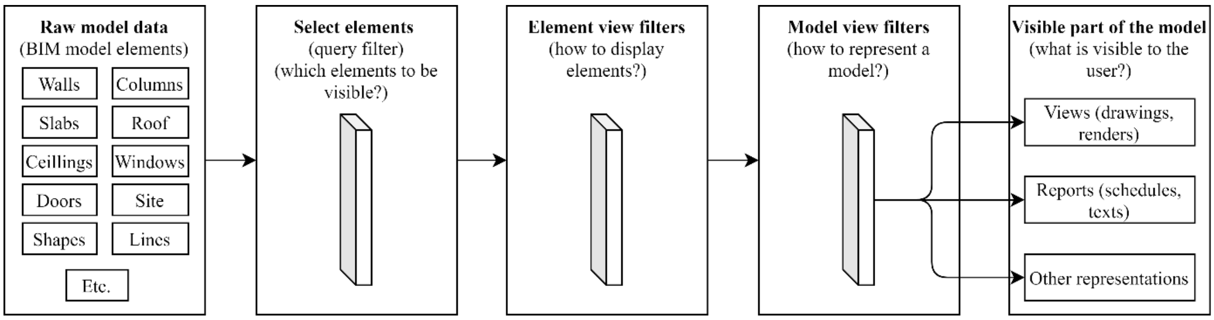

Figure 38: Aspects of template structuring (adapted from [23])

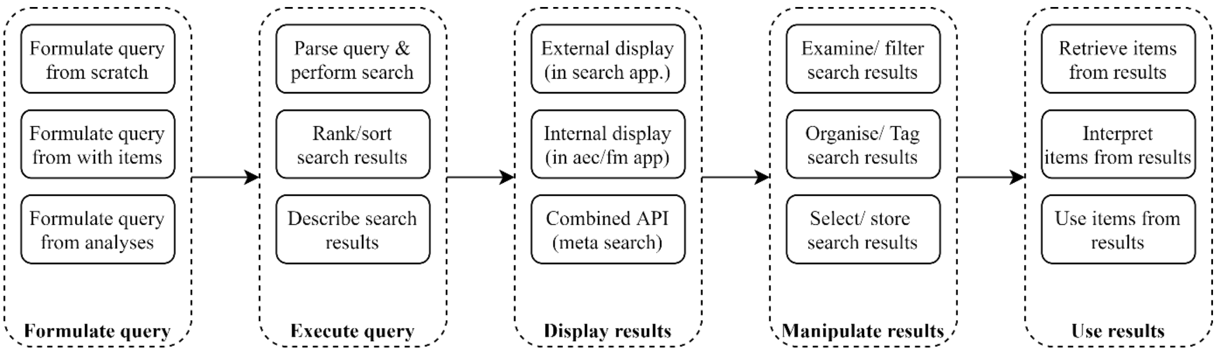

Figure 39: The query process [23]

On the one side, the template is the tool that takes the best advantage of the software and supports the modelling process. It guides the user to produce the information while reducing human error. On the other side, the documented modelling guideline is the educative tool that shows the users the proper use of the template.

In the proposed framework, the rules and the requirements are the inputs for the template and modelling process definition. Therefore, the template should align with the rules, requirements, and the company's modelling guidelines. Documented modelling guidelines combined with well-structured templates are potent foundations for the quality assurance of BIM models.

Anyone in the company who is trained to use the template and modelling guidelines should be able to manipulate the model produced by another designer since the information is standardised.

Ensuring consistency throughout Classification, Layers, and Naming conventions

In order to efficiently apply the rules, there must be precise control of what to ask for and where to find the information. In the authoring environment, there are several ways of querying the BIM elements. For example, it is possible to query by materials, layers, properties, element type, etc.

The variety of possibilities is promising but is also a source of mistakes when applying algorithms to the model. If the metadata is not consistent, the information take-off is willing to be inaccurate. Therefore, the template must be in alignment with model uses and information take-off. It must consider the metadata, naming convention and classifications that are the main criteria for future filters or rules. The consistency of the model is potentialized when there is a logic for the naming convention of Classification, Discipline, Layer, Composites, Building Materials and Elements ID.

Figure 40 suggests a logic for naming conventions.

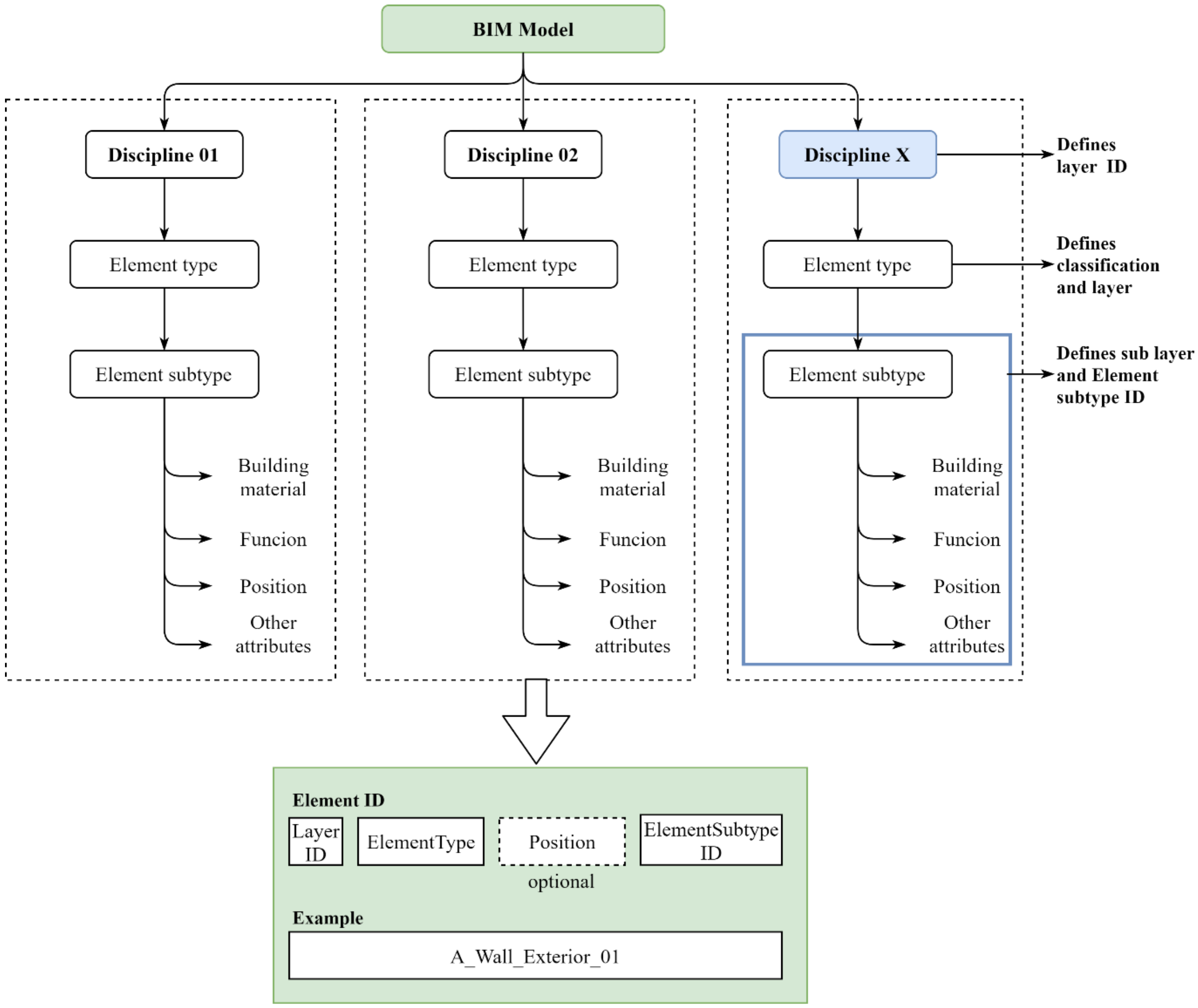

Figure 40: Consistency in naming convention [own elaboration]

Discipline: Refers to the project discipline the element belongs.

Classification: Refers to the classification to which the element belongs. The classifications are used to identify the BIM elements regarding real-world construction elements. Usually, the umbrella of classification systems is wider than the tools provided by the authoring software. Therefore, classification systems can set specific classifications to the BIM elements that are not available by default tools. Some BIM standards, such as NBS [58], recognise software limitations regarding modelling needs and orient the user to apply the standard tool to specific elements (for example, model a suspended ceiling with slab tool in Archicad). Still, it needs to be correctly classified and transferred to IFC [58]. There are different types of classifications available, such as Omniclass, Uniclass 2015 and Uniformat.

Element type: It will be related to the Classification with a higher degree of granularity.

Layers: The layers mainly refer to internal visualization filters and internal data management for modelling and documentation production. The layer naming convention refers to the element type also.

Thus, it has subdivisions that may vary according to the model needs. In addition, layers might also represent elements that will not contain 3D geometry representation but need to be organised for documentation purposes.

Element Subtype: refers to the differentiation of element types by Composite Structure, Building Material and Surfaces.

The element ID: refers to the unique ID that identifies the BIM element at an instance level. It is the unique identifier inside the authoring environment and summarizes the hierarchy that generated the element.

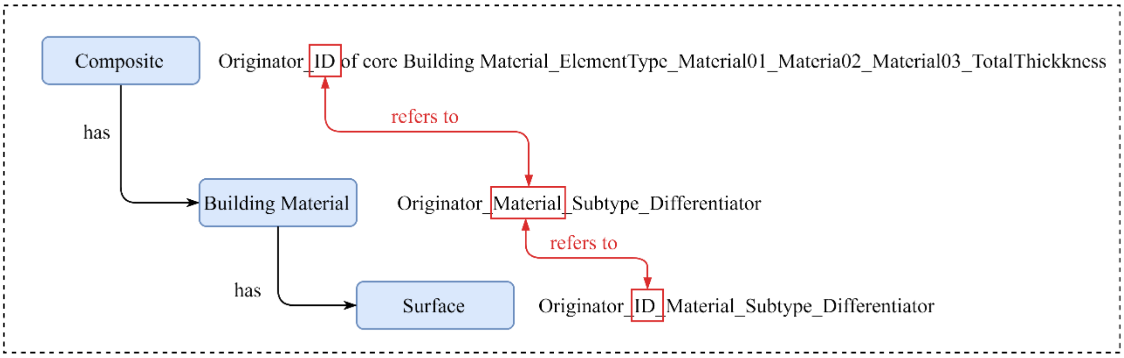

Figure 41: Consistency in the naming convention of element attributes

3.4.4 Define the issue avoidance filters

The issue avoidance filters support the design team in the modelling. It helps to avoid the generation of the issues related to the data structure. Furthermore, it supports the designer to perform the correct use of the template. The filter is applied in different manners and adapted to the features provided by each software. The concept is that by applying a set of filters, the incorrect information is displayed so the designer can correct it. Figure 42 explains its concept.

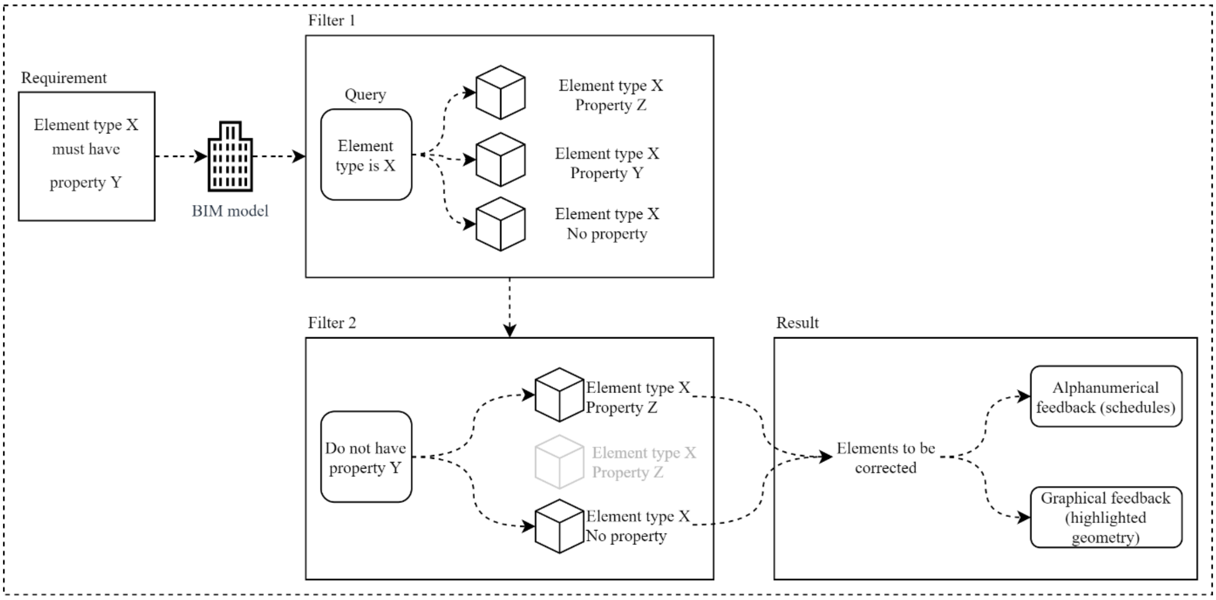

Figure 42: Issue avoidance filters concept (source: own elaboration)

3.5 APPLICATION

The last part of the framework refers to applying the tools created previously into the modelling process. From one side, the inputs for this stage is the project template, the modelling guidelines and the issue avoidance filter. On the other, the requirements, properties and rulesets related to the project stage.

Four tasks compound the Application Stage: (1) Create the model, (2) Apply BIM quality checks, (3) Analyse data, and (4) End the project.

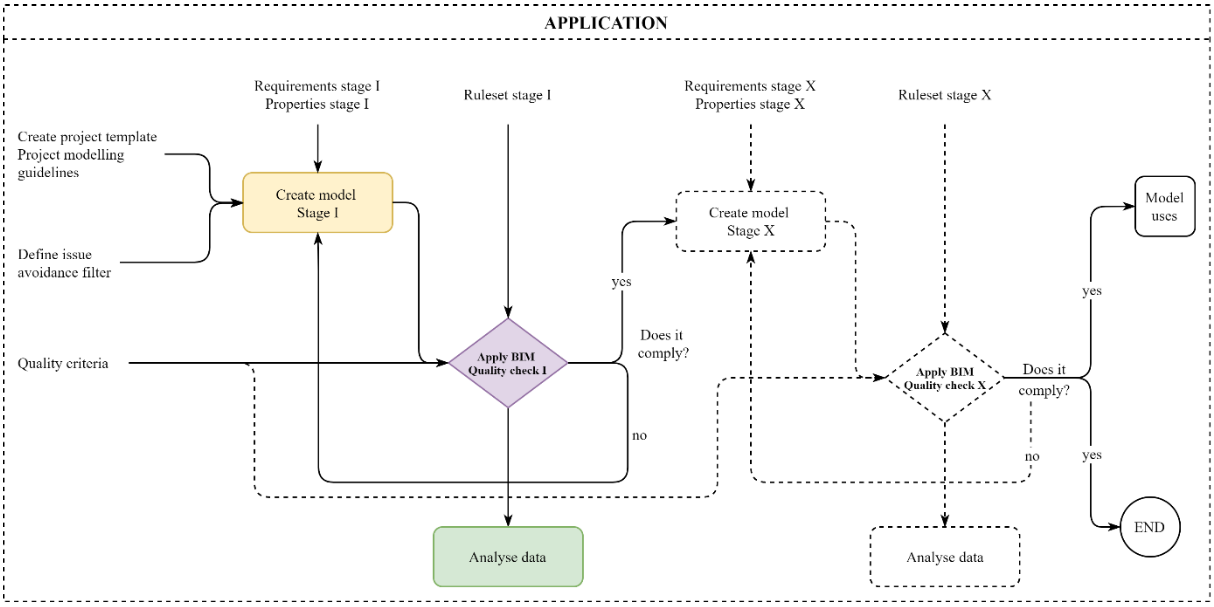

Figure 43: Framework stage III - application [own elaboration]

3.5.1 Create the model

Create the model refers to the development of the model itself. The inputs for the model are the project template, modelling guidelines and issue avoidance filters. Following the guidance of ISO 19650, no extra information should be produced unless it meets the requirements and fits the final purpose. Therefore, only properties and the computable requirements related to the project stage must be inserted in the model. It helps to avoid that extra information is produced without need, reduces time consumption, and guides the modeller to focus on the project's primary goal.

Furthermore, as the main objective of the framework is to keep and produce high quality and well-structured information, the issue avoidance filters should be constantly applied throughout the modelling

3.5.2 Apply BIM quality checks

Quality checking is the process of querying the final structured model to check compliance with the requirements and detect issues not corrected previously. Thus, it supports the model approval decision and generates data for future analysis.

It must be pointed that the BIM checking is not responsible for the generation of quality. BIM checking is the means that support the team in measuring and evaluating the quality of the models. Therefore, applying the checking as an isolated tool will not enhance the quality of the model. Nevertheless, when combined with the other means, it is powerful. The quality checks are as efficient as it is the complementary tools set in the previous stages.

At every check, the ruleset specific to the design stage should be applied. No check should be done on data that is not required for the stage.

By default, quality checks are performed at decision points when the model needs approval for further stages or multi-discipline coordination. If approved, the model will be finally moved to other project stages. If disapproved, it will move back to the modelling stage, where the improvements must be made. The main objective is that through the compliance feedbacks, measures can be taken to improve the quality of the model.

3.5.3 Analyse data

The data analysis consists of retrieving the model's compliance feedback to be analysed in an outside data analyser. This step seeks to visualize the results of the rule checking and measure the quality of the model. In addition, the quality reports aim to provide information regarding model improvements, coordination, or handover.

The input for this step is the compliance values generated from the BIM quality checks, the ruleset taxonomies, and the quality criteria's. The output is the quality report.

3.5.4 End the project

At the end of the project, the data collected across the stages will be used to improve the company templates and modelling guidelines. Hence, improvements need in the quality assurance plan for future projects is also expected. The quality assurance process will be updated based on lessons learned.

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4 STUDY CASE

The framework was applied in the projects shared by TUU Building Design Management, with headquarter in Portugal. The company has been acting for the past five years and has expertise in design management and site inspection. The project portfolio is mainly based in Portugal, and the more than 50 employees are from different field experts, such as architecture, engineering, site inspection. The clients for the projects are usually the final investor with no AEC background.

TUU has been implementing BIM in design processes and has well-structured project standards, templates, and definitions of stages. The projects are fully developed in the software Graphisoft Archicad which is used for 2D documentation, 3D modelling and quantity take-off. The company provided two BIM models of medium-scale residential buildings fully modelled in the software Archicad to collaborate with the dissertation.

The existing template makes use of the best features provided by the tool, such as filters, views templates, layers, element attributes settings, properties manager, composites and building materials. The naming convention and classification system is based on internal standards. When it comes to model checking, the checks are mostly visual inspections. However, some filters are already set for quality checking, such as internal classifications or structural functions. Usually, the quality checks are embedded in the design processes and do not hold a specific stage in the design process.

The framework was developed first in a generic model and then applied to the case study. For the application of the framework, the model was manipulated to be in alignment with the quality check purposes.

Although this study seeks to provide a framework for quality assurance and measurement, the evaluation of the models is not the purpose of the case study. Instead, the focus is to validate the applicability of the framework in a real project.

Additionally, it is essential to acknowledge that the model was taken as an independent element unconnected to its actual requirements. For that purpose, the requirements and measurable criteria were defined specifically for the application of the framework. Nonetheless, the study also focused on questioning how deep the expressions could be applied in the models and the benefits of using embedded rules in the authoring environment. Finally, the framework's focus is to provide means for managing the quality by providing the designer or coordinator with automated and semi-automated tools that can become integrated tasks in the design process and take the best from the features already provided by the authoring software.

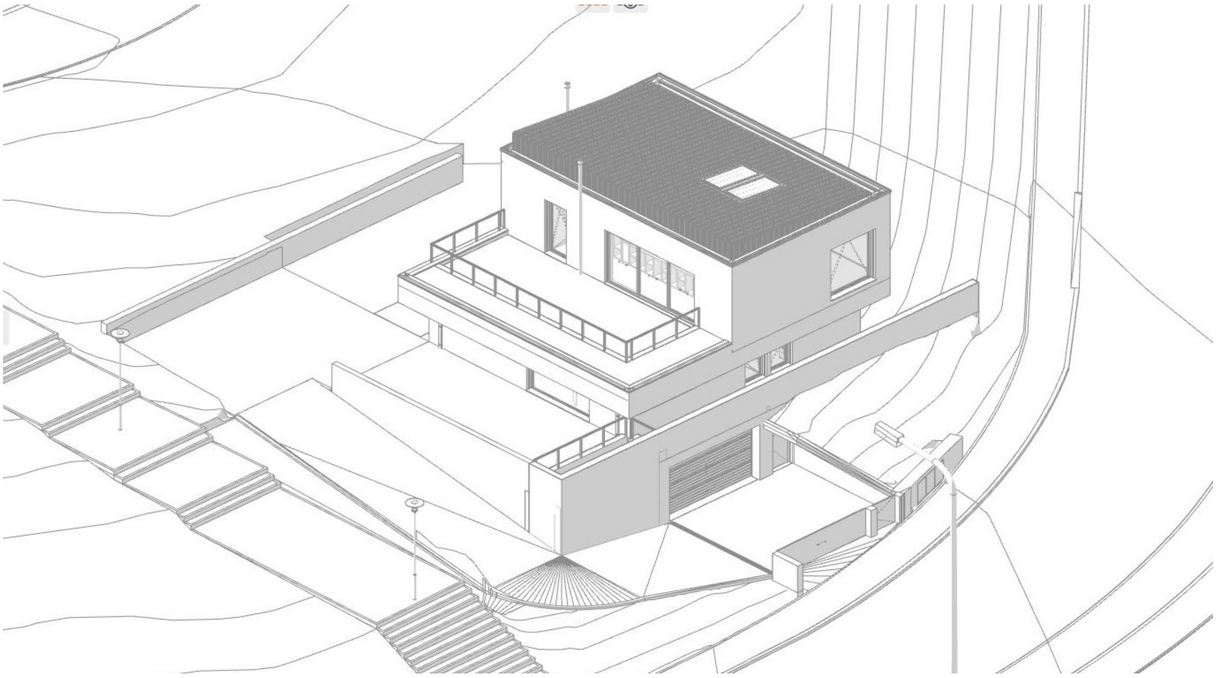

Figure 44: Case study model - produced by TUU Building Design Management.

4.1 PREPARATION

4.1.1 Categorize requirements

The model was taken as an independent element unconnected to its actual requirements. For this dissertation, the scope of requirements was based mainly on the existing codes, standards, and guidelines, such as CoBIM [29], Singapore BIM Guide [28], and NBS [58]. Additionally, the scope also englobes requirements related to the project type and needs identified from the project documentation provided for this study case.

Requirement Type:

First, it was identified two main groups: (1) requirements related to the project specificities, (2) requirements related to the company modelling standards. The main categorization of requirements will be a guidance for setting the hierarchy of the rules in the further stages. The categorization proposed clarifies what is required by the project/client and what is required by the organization that is producing the model. It is acknowledged that the Exchange Information Requirement is adaptable to the project, while the Modelling Requirements are adaptable to the organizational need.

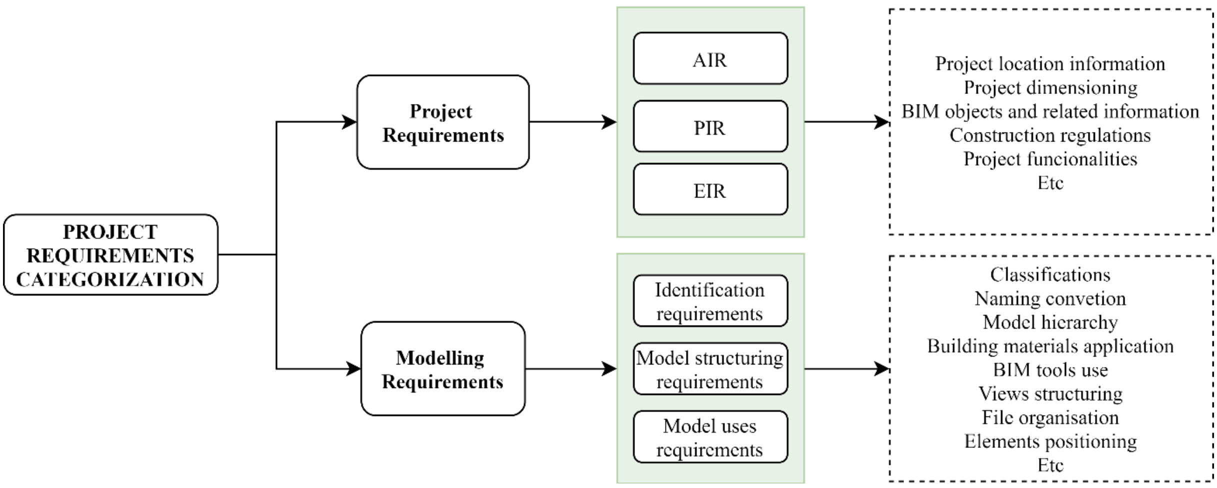

Figure 45: Requirement categorization [own elaboration]

Computable and non-computable requirements:

After the first categorization was done, the requirements were classified as computable and non-computable. The computable requirements will be translated into automated or semi-automated rules, and the non-computable will become visual checks. The visual check was not the focus of the case study, although they might also be considered in the Quality Assurance Plan.

4.1.2 Define project measurable quality criteria

The criteria for measure the quality were defined as per section 4.1.2. The quality rates were not defined for the study case as it is an isolated model with no connection to the actual requirements and further project stages.

4.2 STRUCTURING THE MODELLING PROCESS

4.2.1 Define classifications and properties

The first step taken in the Structuring stage was to set the classification system. The model has already classified according to the company's internal standards. However, to be in alignment with international standards, it was proposed an additional classification provided by Uniclass 2015. Both classifications were kept as it is needed for internal Archicad's organization. The basic step of any query or algorithm application in a model is the proper classification of building elements. From the proper classification system, it is possible to generate a well-structured property manager and, consequently, well-structured project data.

<u>Archicad Property Manager:</u>

The property manager in Archicad enables the user to organise the properties globally in the model. The properties are attached to the BIM elements according to their classification and regarding the element type. What guides the software to understand which property one element will contain is the classification. However, default parameters will permanently be attached to the object since it is part of the object characteristics. When the property manager is well-structured according to the project needs, it becomes a powerful tool for BIM data management.

Archicad provides two valuable tools for data management, which are the Property and Classification Managers. Those tools enable the designer to manipulate the properties and the classification system in the model. Once the classification system is structured, the availability can be defined, and properties are distributed according to the classifications. When a BIM element belongs to a class, it will contain the class-available properties set in the property manager. Easily the properties can be modified globally in the model and redistributed.

Properties have different data types. They can be number, string, integer, yes/no, true/false, length, area, volume, angle, or option set. In addition, there can be values added by the user or expressions that generates the value according to an expression. In Archicad, the expressions are algorithms that calculate, filter, query or modify the BIM the chosen element parameters to generate the needed data for the project. In this study case, the property manager is the central element for quality assurance, since it is the generator of the data and the checker.

In the study case, the properties were organised in three main categories highlighted in Figure 46.

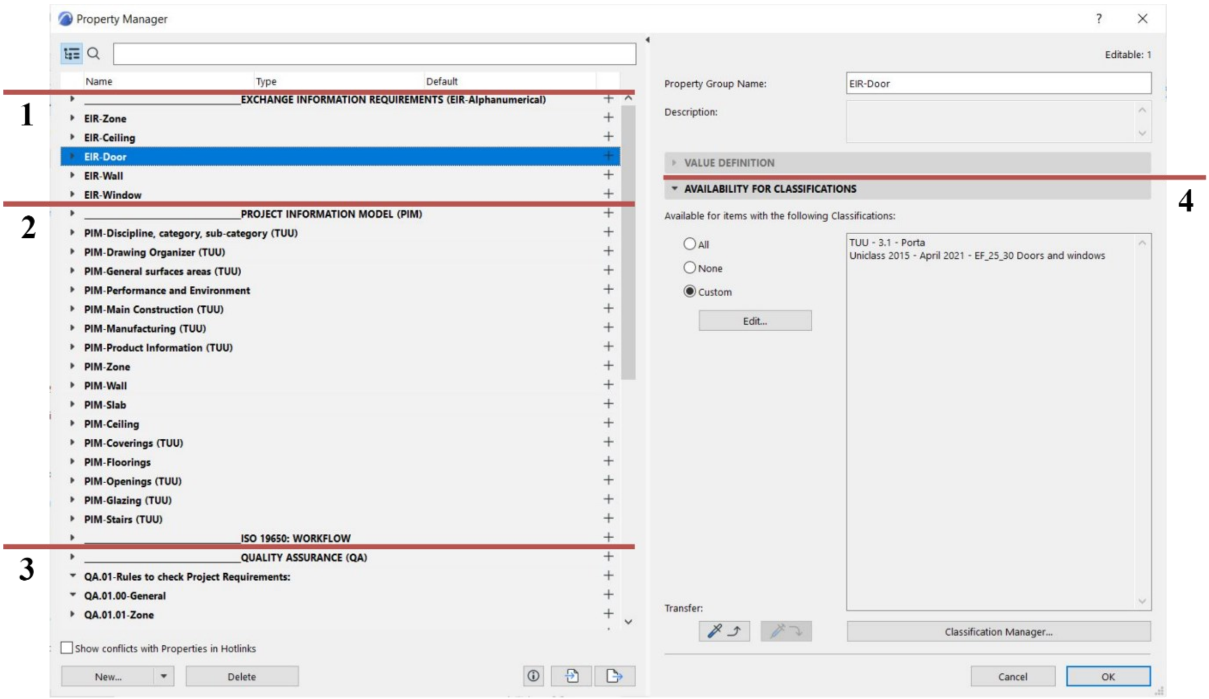

Figure 46: Property Manager in Archicad [source: to be confirmed]

(1) Exchange Information Requirements (EIR): it refers to the computable requirements that the designer needs to meet. The EIR properties are to be set in the Project Template before starting the modelling stage so that it is easily accessible by the modellers. Additionally, the EIR properties will be the inputs for the rules used for verification purposes, which means rules that will check if other property values are correct. Additionally, the requirements must be easily found in the property manager since they are constantly updated as the project moves on. The EIR properties are the requirements that need to be in the model when it is delivered.

(2) Project Information Model (PIM): it refers to every property that needs to be filled by the designer. The PIM properties are to be input in the model as needed - according to the map of requirements created in the Preparation stage. Following ISO 19650 guidance, no information should be added to the model if it is not necessary. Thus, it avoids errors, facilitates model maintenance, and helps the designer/modeller keep the project's focus. The PIM properties are also input data for QA properties. As EIR properties, the PIM properties can have different value types, such as expressions, number, area, length, alphanumeric, etc.

(3) Quality assurance (QA): it is the group of properties that contain expression with the only purpose of checking the BIM elements against the requirements defined in the Preparation stage. They do not need to be in the model when the modelling is being developed but can be input when the quality checks are done. The input for the rules is the EIR properties, PIM properties and other Element Parameters related to the element type that is being checked. The outputs are

always COMPLIANT or NOT COMPLIANT VALUES. The QA properties are divided into subgroups that will be explained in section 4.2.2.

(4) Availability for Classification: as the name points, it enables the user to choose to which classifications the properties will be available.

The advantage of the embedded rules is the possibility to have all the rules organised in one single group of properties. In addition, the embedded rule enables the element to check itself and feedback with values that are simple and do not need human interpretation. Although the requirements need to be interpreted by a human before being transferred to a rule, the possibility of having compliant/no compliant values simplifies the process of checking. Another advantage is the possibility of transferring rules among files by XML. It enables the standardisation of the model checking among a project of the same company or models of the same project when the same standards are being followed.

The limitation of the properties is that as they are set to instance elements, they do not check properties or parameters of other elements that may have a relationship to each other. It means that clearance checks, clash detection, and relationships between BIM elements cannot be checked by embedded rules in the property manager. However, when it comes to BIM management and keeping the model well structured, enabling a proper set of algorithms, the embedded rules in the property and classification manager is powerful.

4.2.2 Structure ruleset

The QA rules were directly created on the Property Manager. First, the rules were created for a generic model, and later they were transferred and adapted to the study case using an XML file.

The rules were categorized in alignment with the requirements categories. Different types of categorizations for rules are essential to support the user in understanding how the rule works, what is being measured, and which requirement type is being checked.

It was created 30 rules which check more than 2000 elements in the model in a different manner. For proper management of the rules, a hierarchy was created according to Figure 47 and applied to the property manager according to Figure 48. It was considered not only the rules category but also the existing hierarchy in the authoring software. Archicad provides different parameters availability according to the element type. Therefore, the element type must be considered when creating a rule. For example, a wall has parameters that a door does not have. Consequently, the rules will also need to be structured in a different manner. If not, the feedbacks of the rules will also contain error values.

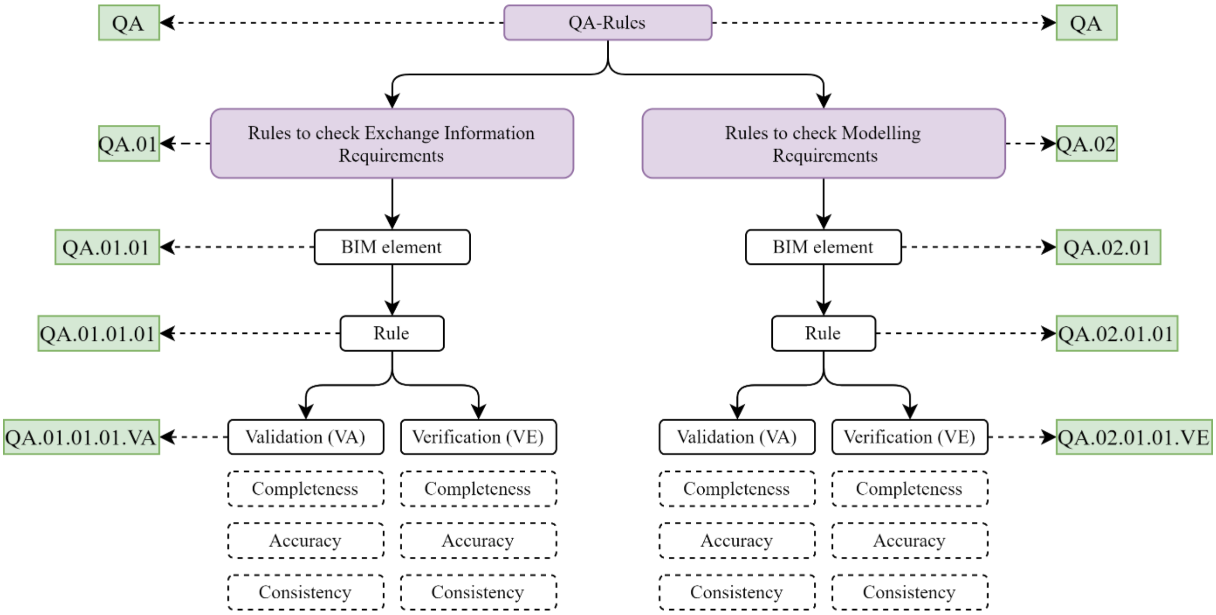

Figure 47: Rule hierarchy [own elaboration]

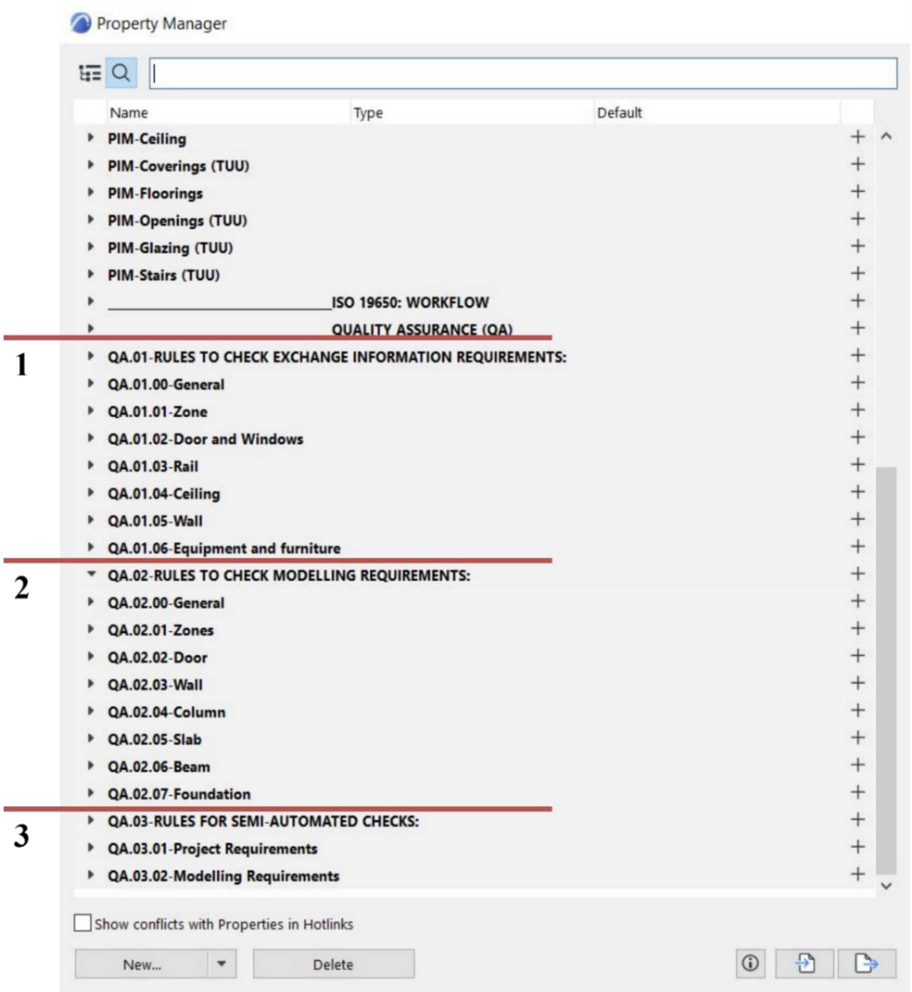

Figure 48: Rule embedded as properties [source: to be confirmed]

(1) Rules to check Exchange Information Requirements
(2) Rules to check Modelling Requirements

The QA properties refer to the properties with embedded expressions whose main purpose is the check the BIM element against a specific requirement. The expressions are algorithms that calculate, filter, query or modify the BIM the chosen element parameters to generate the needed data for the project.

Archicad provides a variety of expressions. The expressions library are available in [59] for guidance and explanation for users. The expressions are divided in

(1) Constants
(2) Operators
(3) Logical Functions
(4) Mathematical Functions
(5) Trigonometrical Functions
(6) Statistical Functions
(7) Text Editing Functions
(8) Data conversion

The rules were based mostly on groups 2, 3, 7 and 8. However, the functions contained in the Logical and Text Editing group showed the most useful functions when needed to control data and queries in the model. The expression can be used individually or combined with others. The inputs for the rules are the functions provided, the element parameters and properties that were be combined to generate the algorithm need for checking. By default, the output depends on the function type, but all the expressions were built to feedback the user with COMPLIANT OR NOT-COMPLIANT value. The expressions were built according to the classification created for automated rules. For more information regarding the Automated Rules Classification, see Figure 35 and Figure 36.

Below is explained how the rules apply in the study case.

Rule Class 1 – Example: in this case, the property already exists in the BIM element and needs to be checked if the designer filled it.

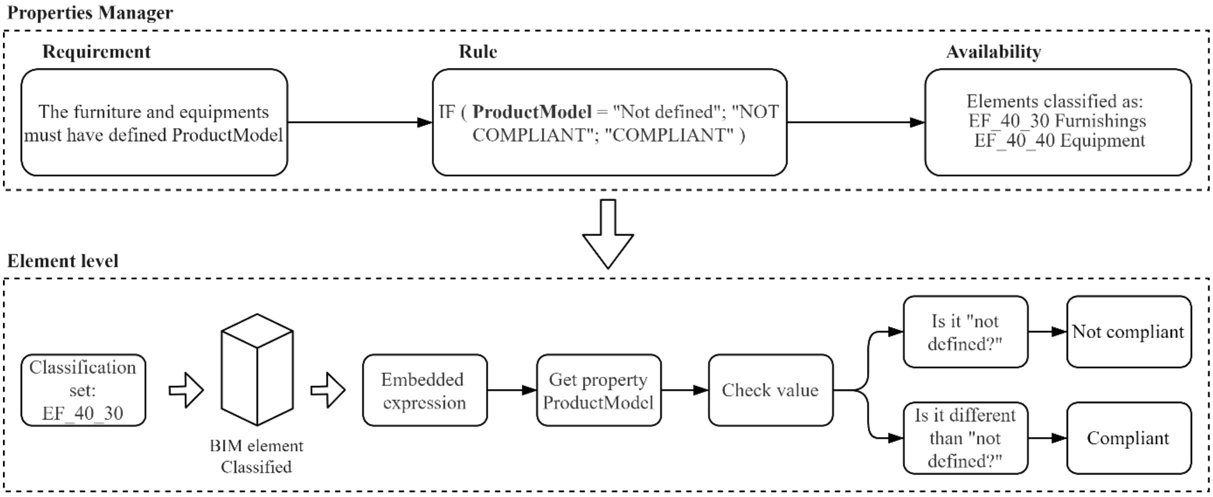

Figure 49: Rule 01.06.01.VA applied in the model as an example [own elaboration]

Rule Class 2 – Example: the focus of the check cannot be found as a single property. Therefore, it needs to be generated first and then checked.

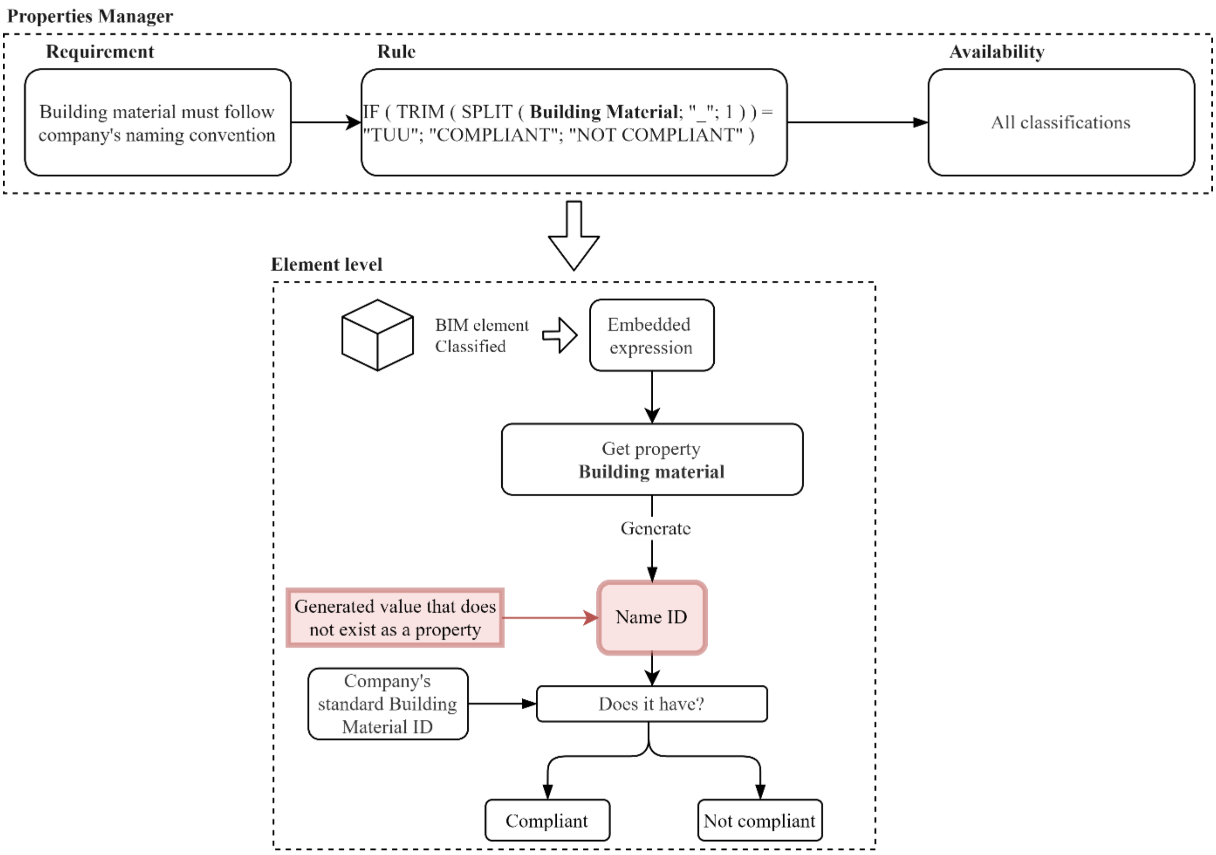

Figure 50: Rule 02.01.04.VA applied in the model as an example [own elaboration]

<u>Rule Class 3 – Example:</u> in this case, the focus of the validation cannot be found as an explicit parameter. Therefore, it should be generated under some specific condition. The conditional function filters the model and generates the parameter only in the elements that are the focus of the requirement.

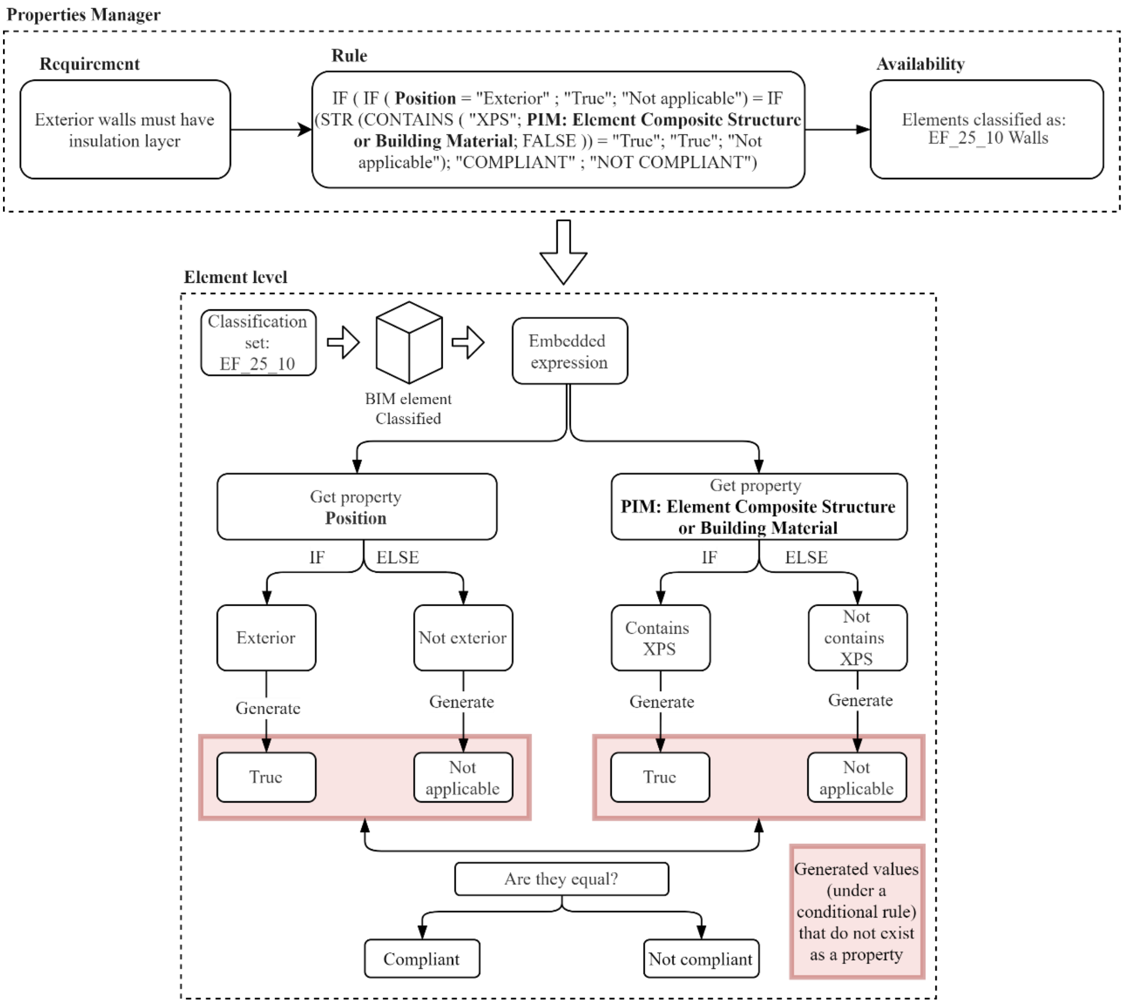

Figure 51: Rule 01.05.01.VA applied in the model as an example [own elaboration]

<u>Rule Class 4 – Example:</u> the algorithm checks an explicit parameter against a known required value.

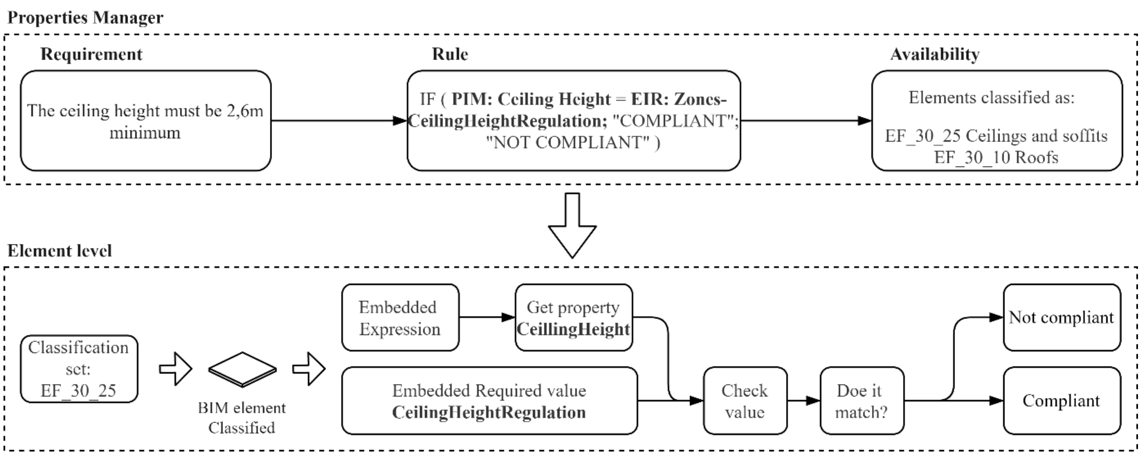

Figure 52: Rule 01.04.01.VE applied in the model as an example [own elaboration]

Rule Class 5 – Example: the rule checks if the value matches the required value. However, in this case, the required value is conditional and depend on which type of composite ID the element holds. The required value is generated through an algorithm that uses as an input

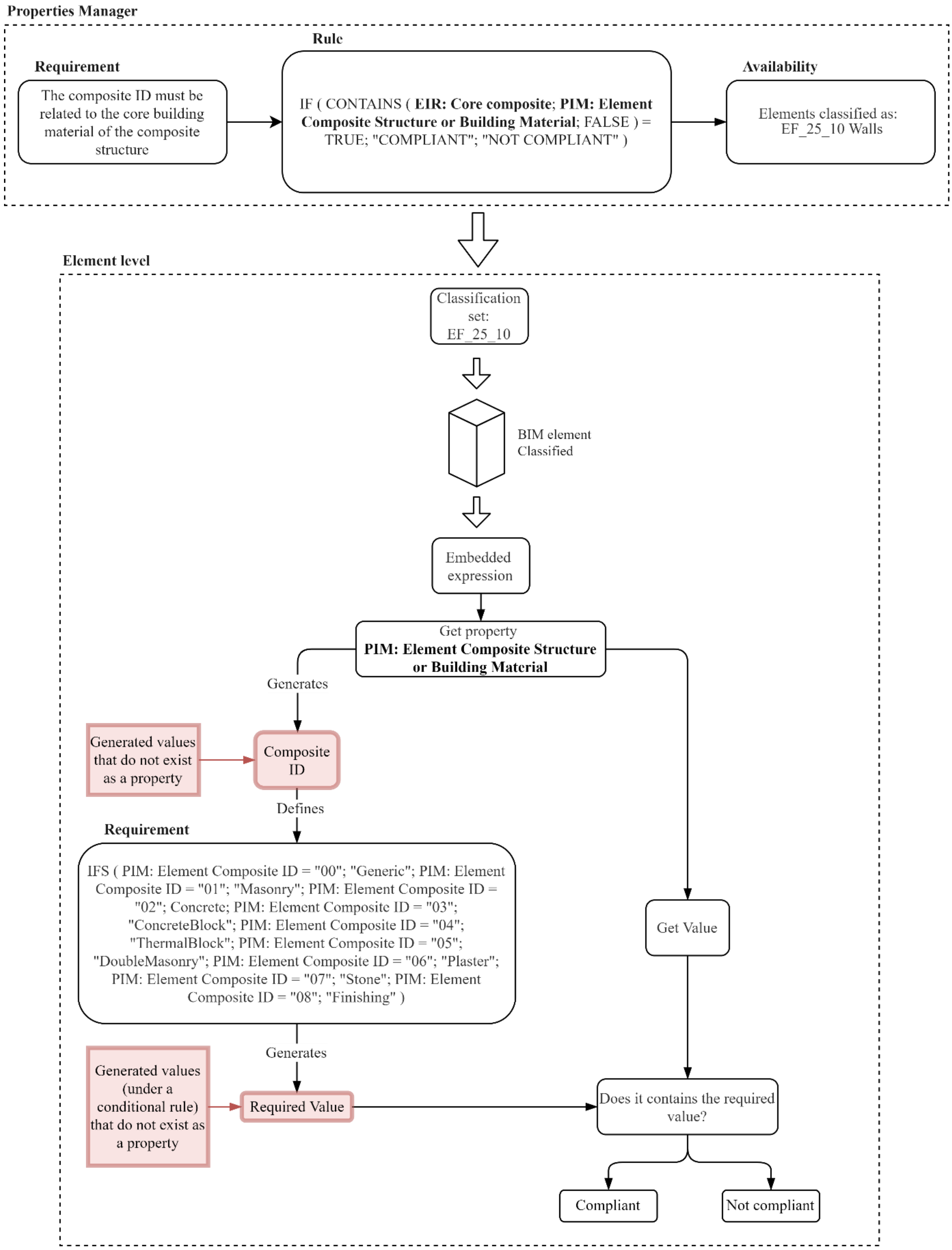

Figure 53: Rule 02.03.05.VE applied in the model as an example [own elaboration]

Rule Class 6 – Example: the rule must check if a specific value matches the required value. However, for this check, the conditions are not explicit in the model. Therefore, a property must be generated, and then the element can the checked against the known value required.

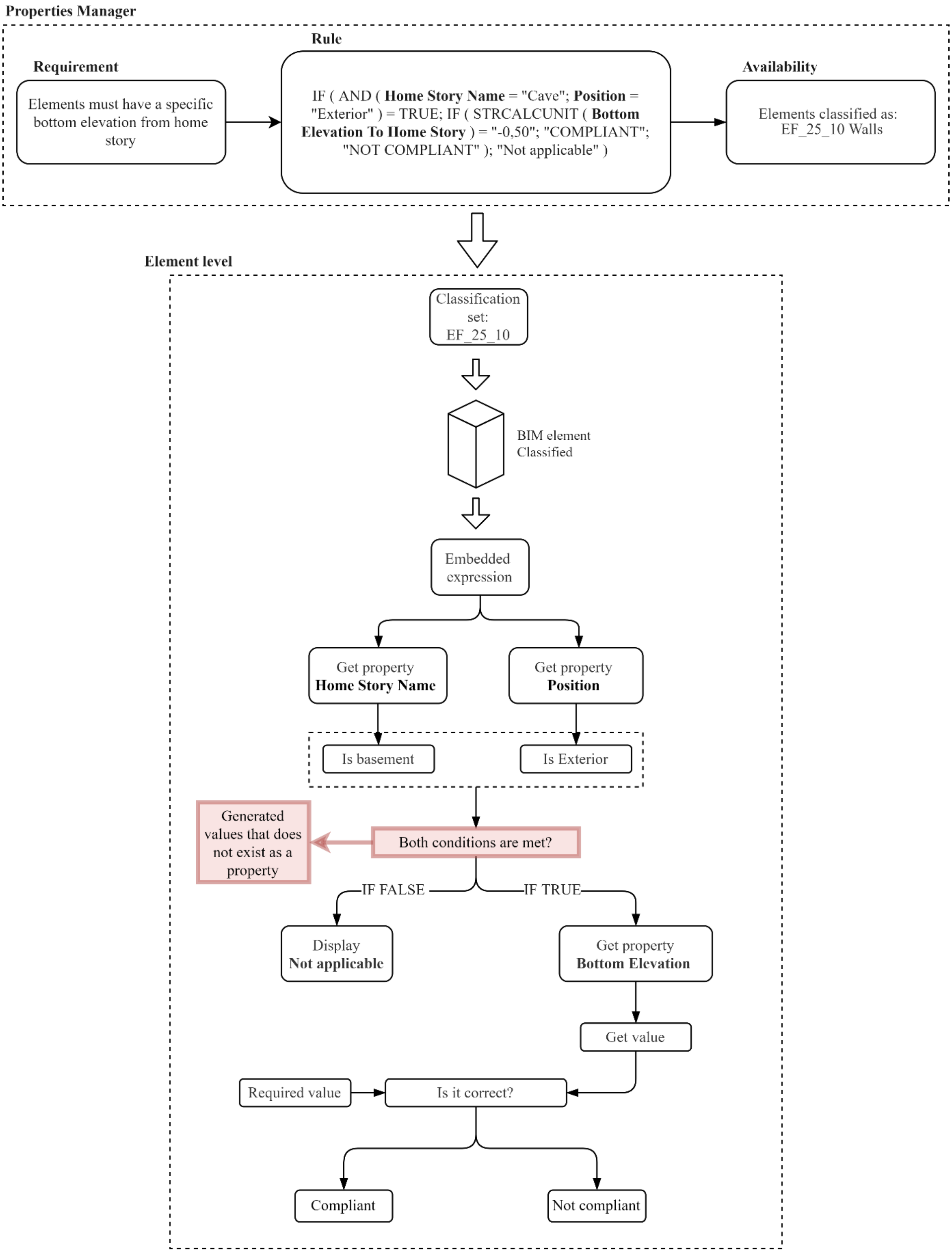

Figure 54: Rule 02.03.03.VE applied in the model as an example [own elaboration]

4.2.3 Create the project template and modelling guidelines

The study case template was adapted from the original template provided by the company to be in alignment with the purpose of this framework. The modifications done are mostly related features that need to be consistent when the quality assurance plan is built, such as naming conventions and data structure. For assuring that the data is complete, accurate and consistent, the first step is to ensure that the template is prepared to allow a good structure for the data that will populate the model. It means that the naming convention for the building materials, composites, layers, libraries, element IDs, and other attributes must follow rules that connect to the model's overall structure.

In the case study, the naming convention followed the steps defined in 3.4.3 and was structured to align with the structure of properties (4.2.1) and rules (4.2.2). Although this framework addresses the Structuring of the Modelling Process as a step-by-step procedure, it is acknowledged that it is also an iterative process, and one task is interdependent of the other. In addition, the template must be structured from the perspective of the model uses and documentation needs.

This framework proposed naming conventions that are aligned with NBS [58]. A consistent naming convention makes it possible to control where the attributes are applied and check if they are correct.

<u>The proposed naming convention for Composites:</u> seeks to avoid issues caused by human misunderstanding of what compounds the structure. Also, it seeks to provide metadata that the user can easily recognize without the need for interpretation.

Naming Convention	Example
Originator_ID of core building material_ElementType_ Material01_Material02_Material03_TotalThickness	TUU_04_Wall_Plaster_XPS_ThermalBlock_Plaster_35,5

- Originator: refers to the company name
- The ID of core building material: refers to the main material that structures the composite
- Element type: refers to the construction element that the composite should be applied to. For example, the composite showed above cannot be applied to other elements except by walls.
- Materials: refers to all materials layers that compound the composite structure. It should be listed in the same order placed in the Composite Tab in Archicad.
- Total thickness: refers to the final thickness of the composite wall

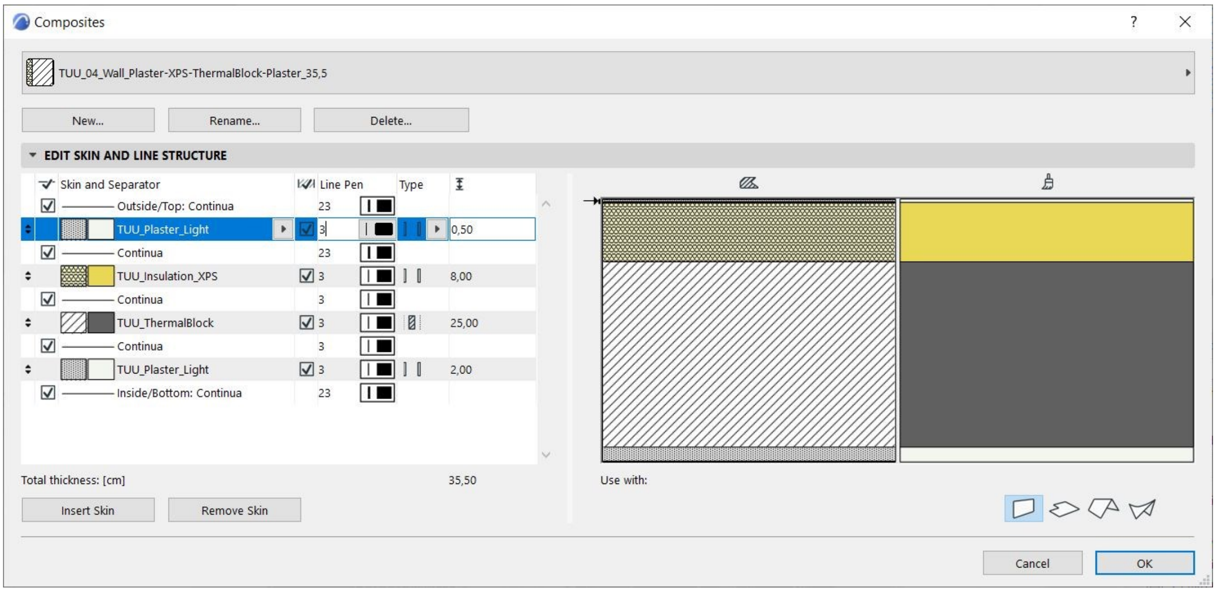

Figure 55: Composite tab in Archicad and applied naming convention

<u>The proposed naming convention for Building Materials:</u> like the composites, the material must be identified by metadata that allows the user to recognize the material quickly. In the building material attribute tab, it is set an ID to each material type. This ID is also used in composites and surfaces naming, so the consistency of naming is guaranteed.

Naming Convention	Example
Originator_Material_Subtype_Differentiator	TUU_ThermalBlock_Structural

- Originator: refers to the company name
- Material Type: refers to the type of material, such as masonry, concrete, thermal blocks, etc. The material has an ID set in the attributes tab and used to identify composite and surface names.
- Subtype: refers to the function or variations in the material composition.
- Differentiator (optional): refers to variations such as dimensions, format, and colour.

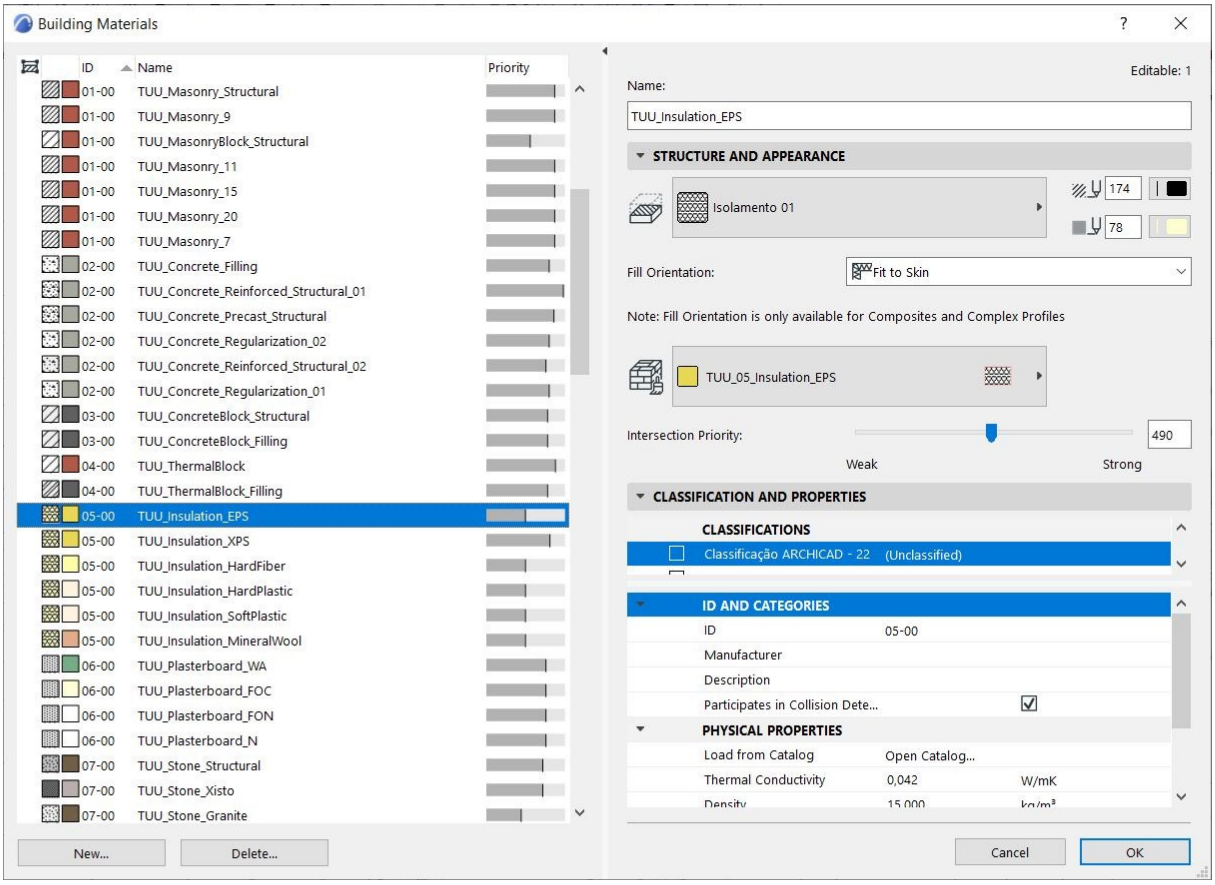

Figure 56: Building Material tab in Archicad and applied naming convention

The proposed naming convention for Surfaces: also contains metadata that allows easy recognition. The proposed naming convention contains the building material to which the surface will be applied, avoiding the missing use of surfaces in the wrong elements.

Naming Convention	Example
Originator_ID of Building Material_Material_Subtype_Differentiator	TUU_04_ThermalBlock_Structural

- Originator: refers to the company name
- Material ID: refers to the ID of the building material it will be applied to
- Material Type: refers to the type of material, such as masonry, concrete, thermal blocks, etc.
- Subtype: refers to the function or variations in the material composition.
- Differentiator (optional): refers to variations such as dimensions, format, and colour.

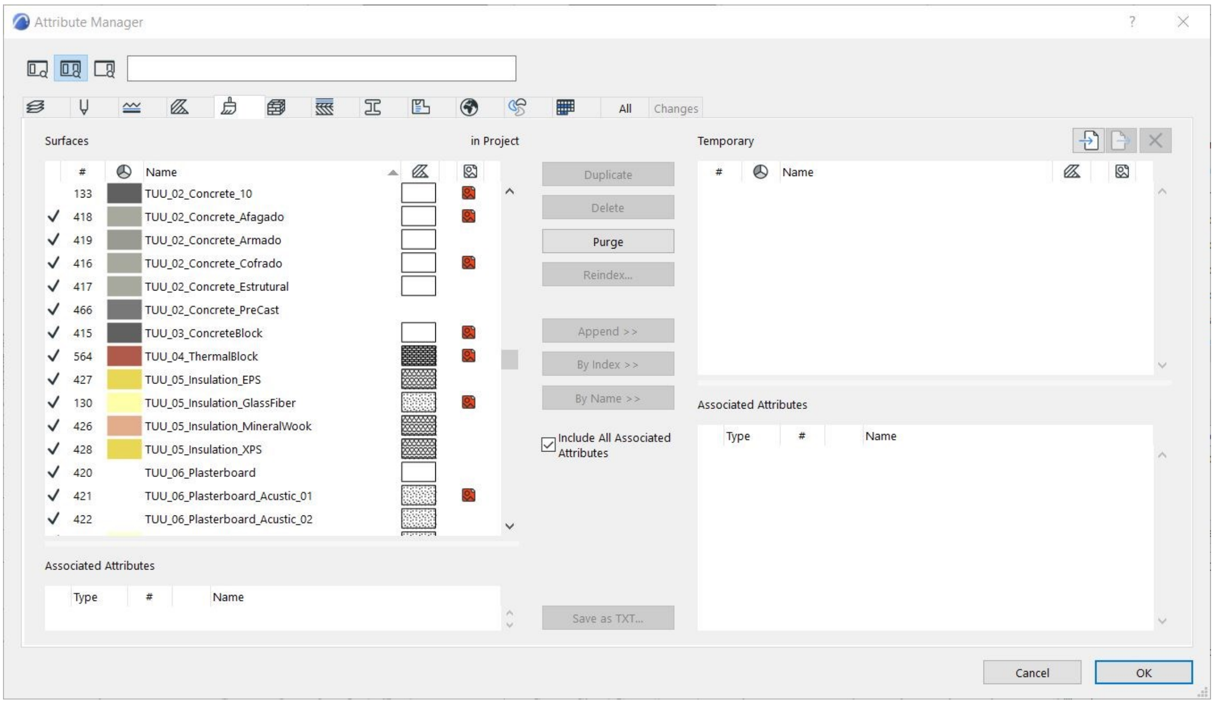

Figure 57: Surfaces in Attributes Manager in Archicad and applied naming convention

4.2.4 Define the issue avoidance filters

As pointed in section 3.4.4, the issue avoidance filters are queries created in the model to support the designers in the modelling process. The filters query the elements that do not comply with some specific requirement, whether it is a client or a modelling requirement, and show the modellers if something needs to be fixed. It should be built simply so that the modeller quickly understands and recognize the issue.

In Archicad, there are three ways of filtering the model. (1) graphics overrides, (2) schedules, and (3) find and select tools. The three filter types provide different complexities of querying and feedbacking with results. The graphics overrides and schedules enable the documentation of the results of the queries through the use of View Maps and storage of the view settings. When the elements are modified, the results are automatically updated in the view. The Find and Select tool provide a dynamic and straightforward manner of querying. However, when the elements are filtered through this tool, it is not possible to save the results as view in the project. The three types of filters can be exported to other projects by XML.

<u>Filter through Schedules</u>: it is the most powerful tool for filtering the model as it provides an extended variability of parameters and functions combinations. Also, the properties created in the Property Manager can be filtered by schedules with no limitation, which does not happen by the other two types of filters. It is possible to create complex filters that respond to the project changes and feedback the user with updated results. Additionally, the schedules can be saved as a view to be checked throughout

the modelling process. The schedules select elements in the 2D view as well as 3D views, where they can be easily modified. Also, in the schedule itself, it is possible to alter the parameters without the need to navigate through the plans and perspectives.

The example below shows the filter of columns that are not modelled separated by stores. Instead, they are modelled as a single element from the basement to the top floor. It can be considered as an issue if, in the future, the volume of concrete by pavement will be needed for quantity take-off, for example.

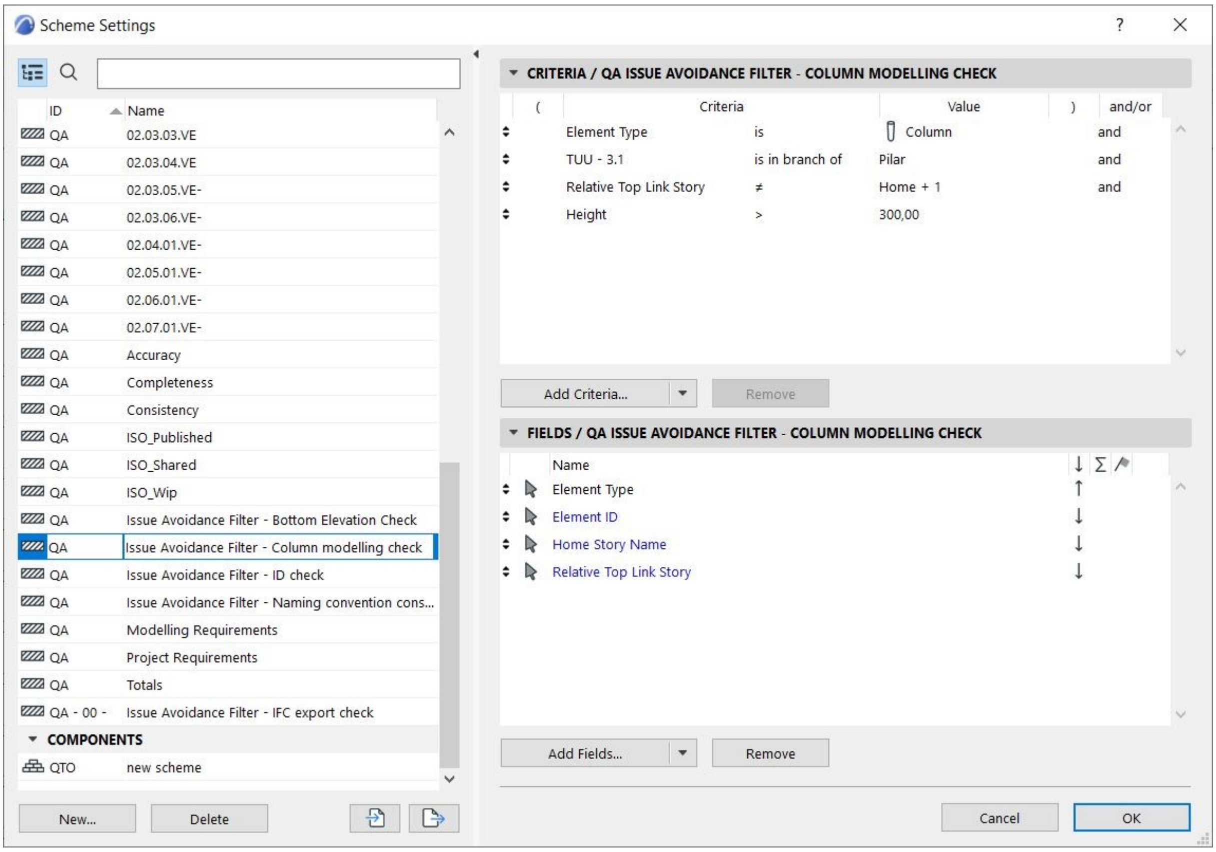

Figure 58: Issue avoidance example 01 – Schedules

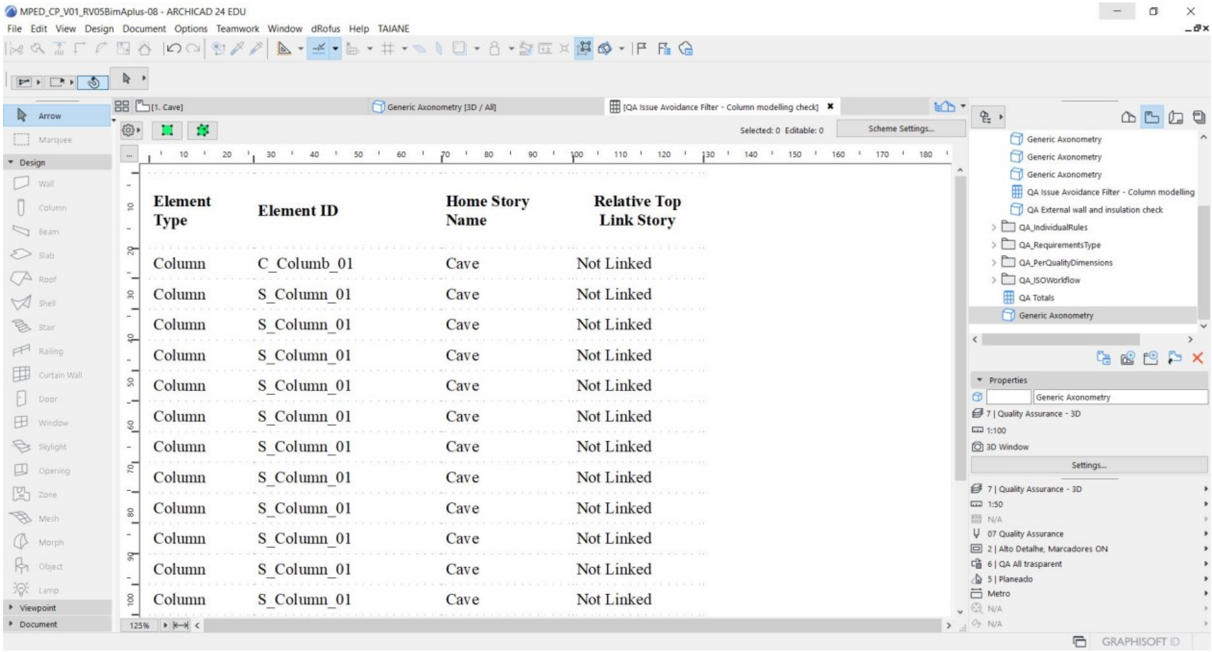

Figure 59: Issue avoidance example 01 – Schedules feedback

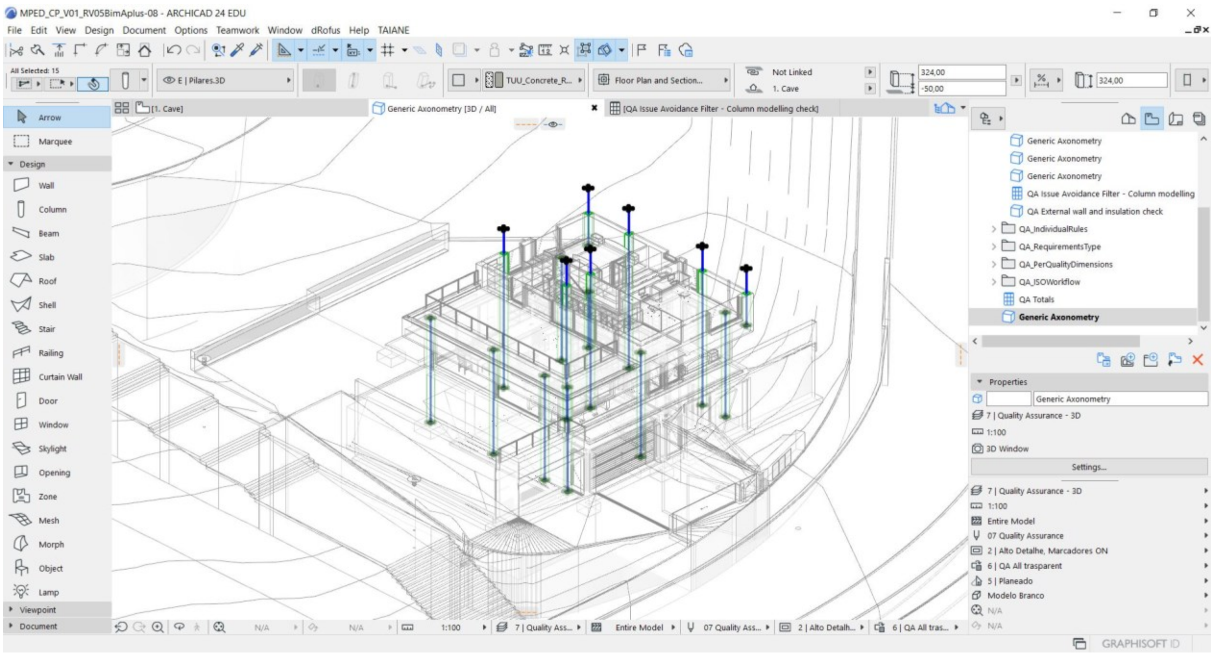

Figure 60: Issue avoidance example 01 – feedback highlighted in the model

<u>Filter through Find and Select Tool:</u> It is a dynamic tool to filter and select the elements simultaneously. It is a helpful tool to be applied when it is not needed to monitor the elements many times. Although the filters setting can be saved inside or outside the model and transferred among projects, the filter results cannot be saved as a view in the view map. Also, the functions provided are not as extensive as they are in the schedules. However, as well as the schedules, the “Find and Select” tool allow filtering elements by any property created in the Project Manager.

In the example below, the tool filters and selects walls that do not have consistent positioning. It means that the wall position is exterior, but they are placed in the wrong layers.

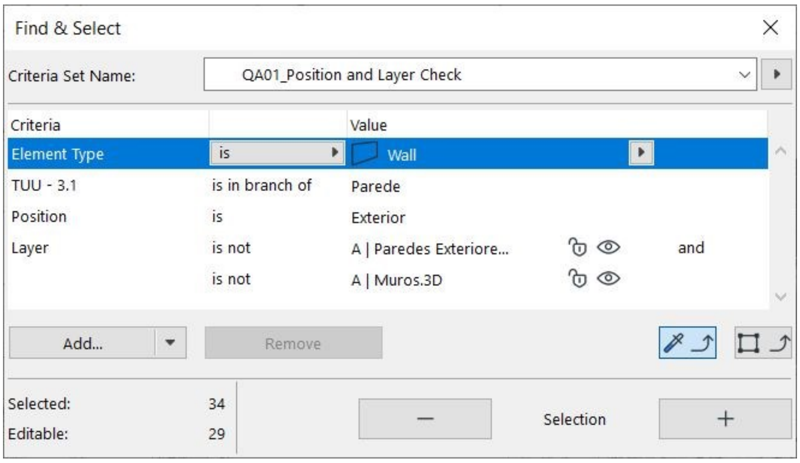

Figure 61: Issue avoidance example 02 – Find and Select tool

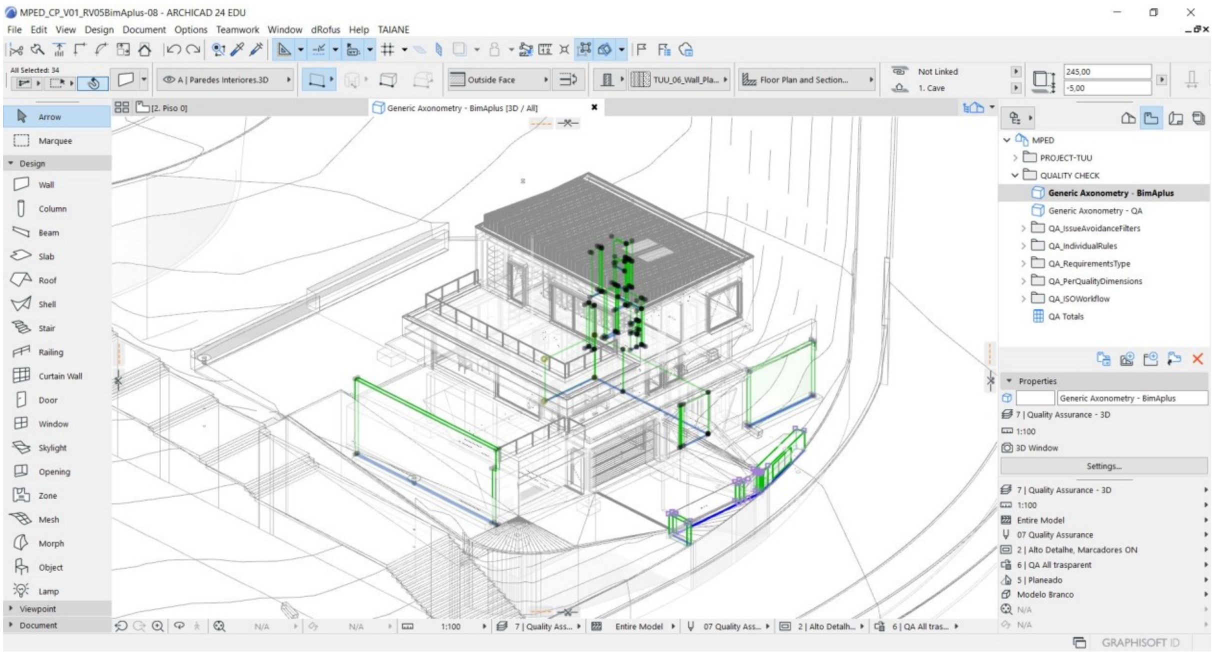

Figure 62: Issue avoidance example 02 – selected results

<u>Filter through Graphics Overrides</u>: it enables the user to filter, highlight the elements with different colours in plan and perspectives. Also. It is possible to save the results as a view that responds dynamically to the modifications in the project. Due to these possibilities, it is a powerful tool to be applied as issue avoidance filters, as well as the schedules. However, there are limitations in its uses as it does not enable the filtering of every parameter and property created in the Property Manager. For example, properties that need to generate 3D to be calculated cannot be used as a criterion for the filters in Graphics Overrides. Also, there are limitations in the creation of functions and expressions, which means that complex queries cannot be done.

In the example below, the graphics overrides were used to filter and highlight exterior walls that do not contain an insulation layer.

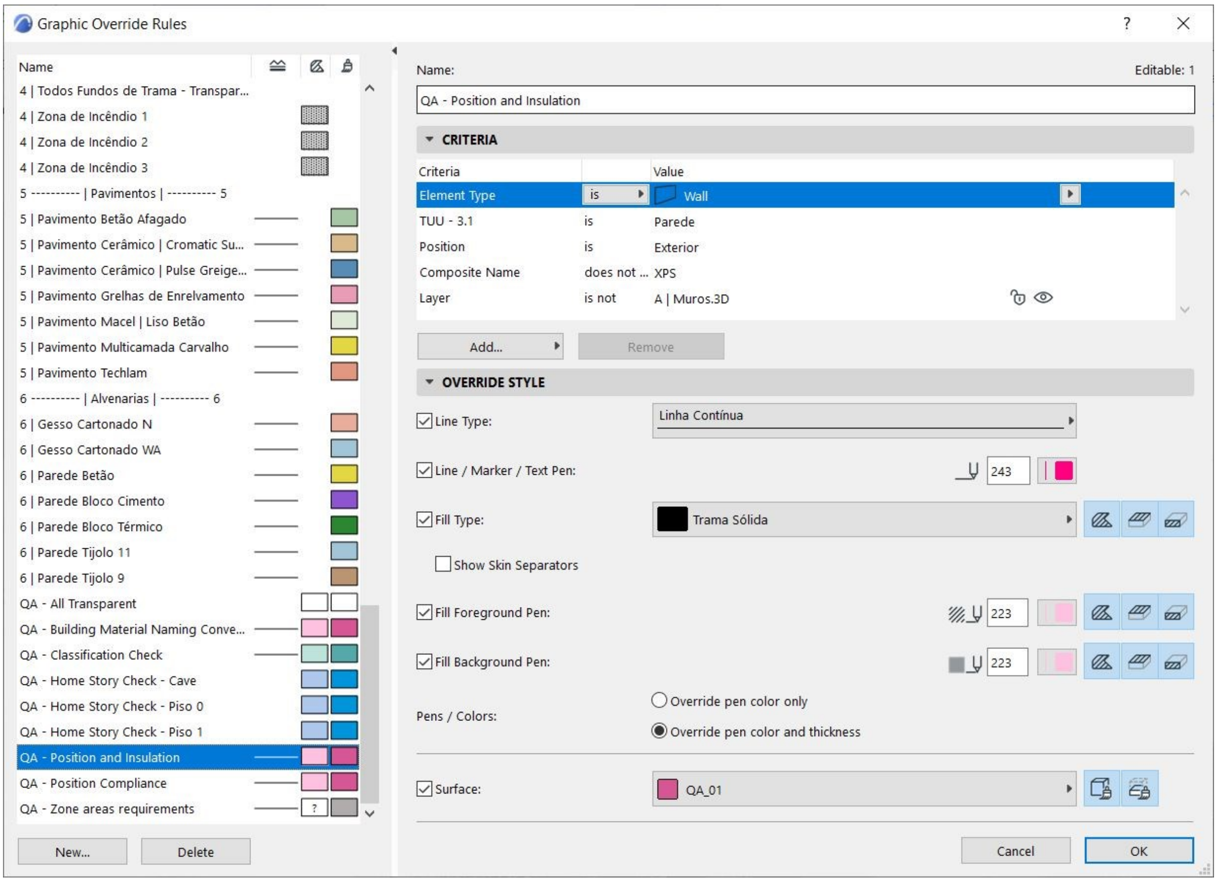

Figure 63: Issue avoidance example 03 – Graphics overrides

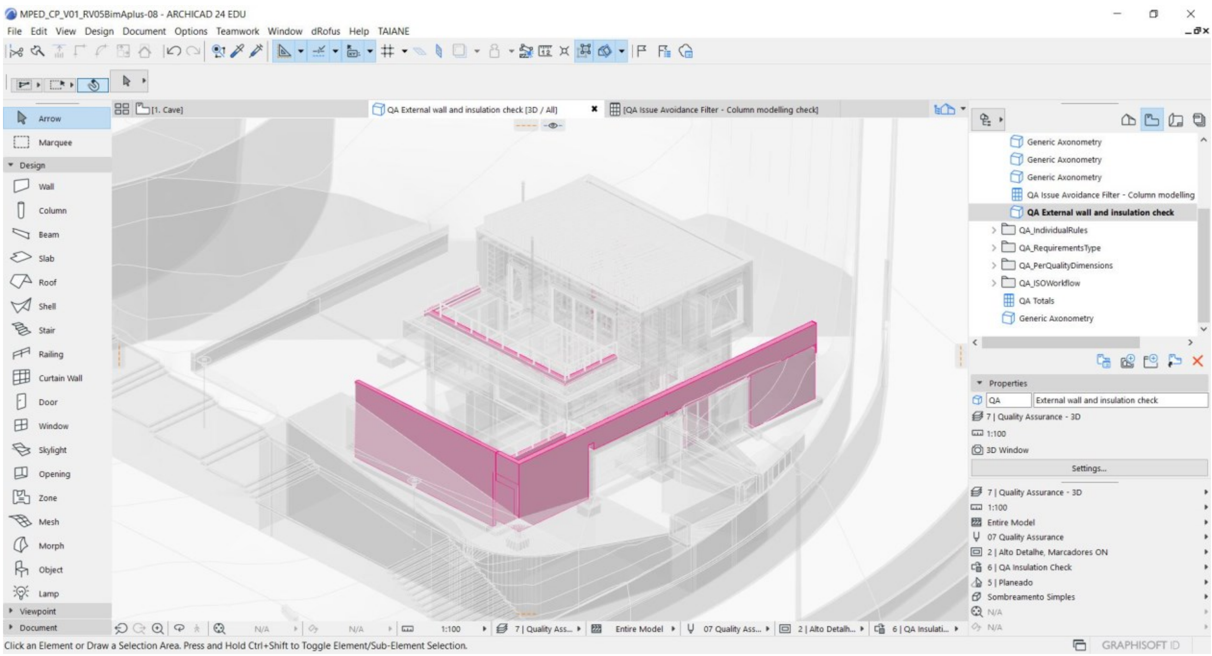

Figure 64: Issue avoidance example 03 – highlighted results

4.3 APPLICATION

4.3.1 Create the model

Since the case study was an existing model, this stage focused on modifying the existing model to adapt it for the framework. In a real case scenario, the model would be modelled according to the quality assurance plan. Therefore, it would not need to be prepared prior to checking. The main modifications can be summarized as follows:

(1) application of the new naming convention to composites, surfaces and building material.
(2) modification in the classification of objects.
(3) modification of elements ID.
(4) modification in layers naming
(5) creation of a new organization for the properties in the Property Manager

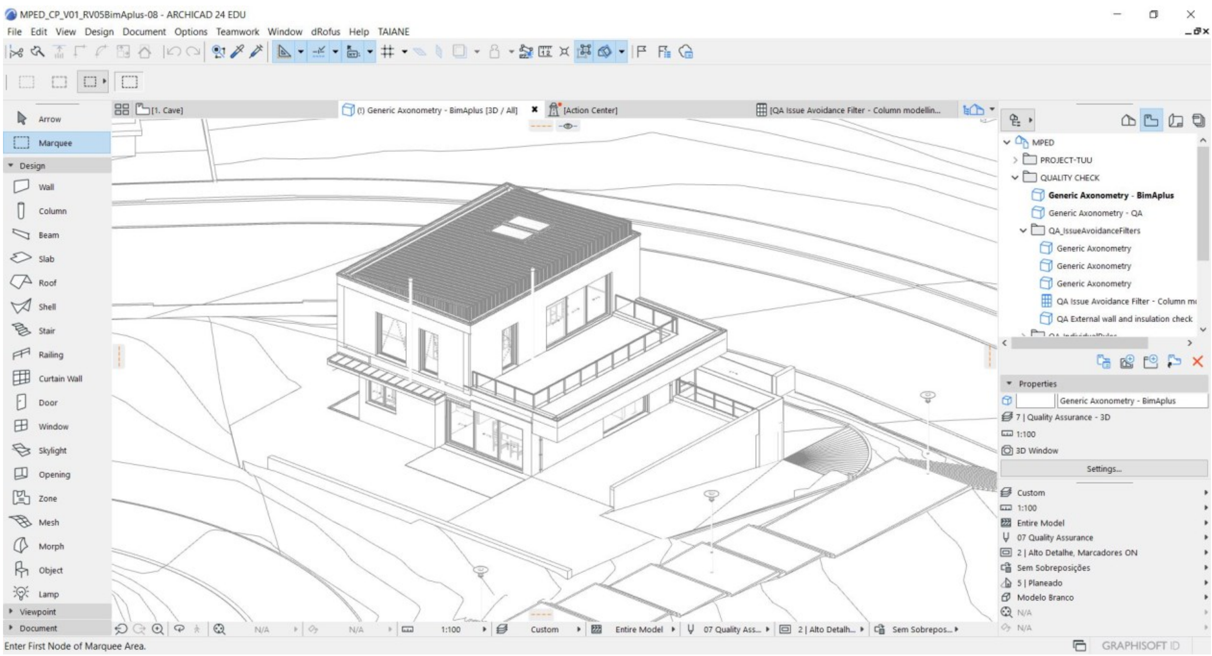

Figure 65: Case study model - produced by TUU Building Design Management

4.3.2 Apply BIM quality checks

In this stage, the rulesets in XML format were imported back into the model, and the results were filtered and organised for further analysis. The rules were imported through the property manager, and schedules with different criteria filtered the compliance results. The compliance feedbacks at this moment have two primary purposes:

- Warn the coordinator that some requirements are not compliant and feedback the elements that need to be modified.

· Provide data that is input for the quality measurement of the model

The same categorization applied for the rules in section 4.2.2 was also used here for filtering the results. The rules were filtered by:

(1) Per requirement type
(2) Per individual rules
(3) Per quality dimensions
(4) Per compliance results
(5) Per ISO 19650 workflow
(6) Per verification or validation

The one responsible for the checking must be aware of how the ruleset and template were structured to understand why the issues are being pointed and how to solve them. The schedules are compounded by element ID, rule results and the related parameters that are being checked by rule. The information presented in the schedule helps the user to understand the logic and take corrective actions.

The example below generated the schedule by filtering the rule that checks if external walls have correct insulation thickness. Also, the related parameters were placed so that the user could correct them.

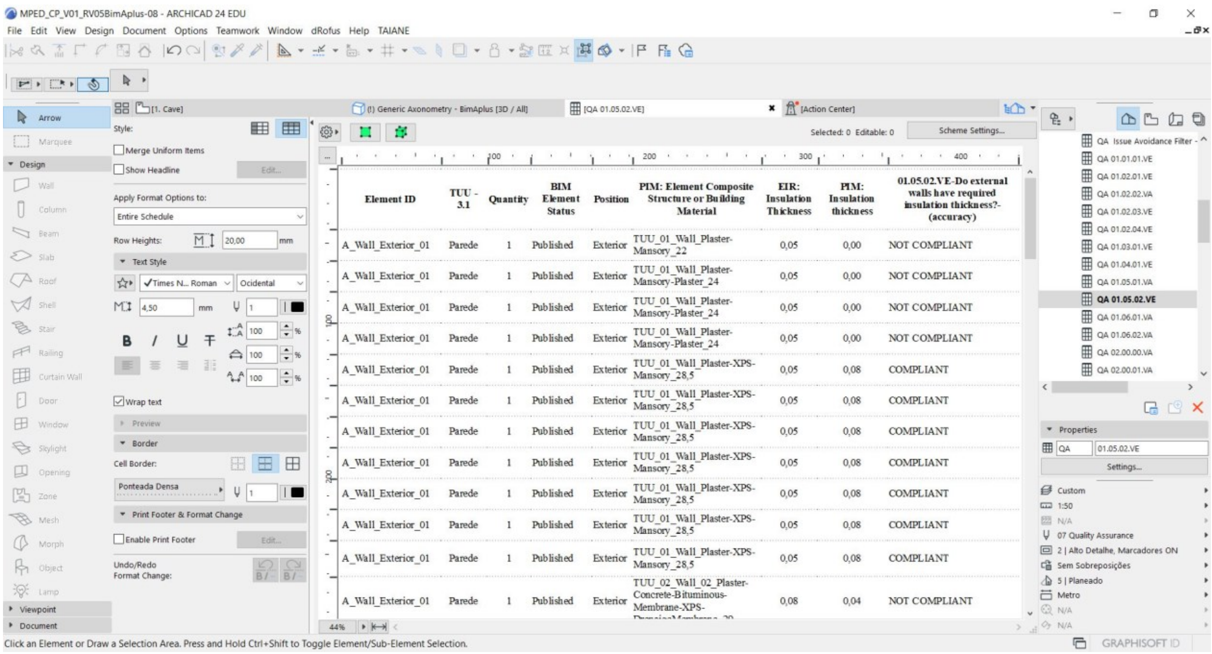

Figure 66: Rule QA.01.05.02.VE filtered in Archicad schedule

4.3.3 Analyse data

The data analysis was made in Power BI. After the schedules were generated in Archicad, they were exported to excel where the data was manipulated and imported to Power BI, where different data visualisations is possible. It generated diagrams that clearly represent the rules' status, the quality criteria, and their relationship to the project management.

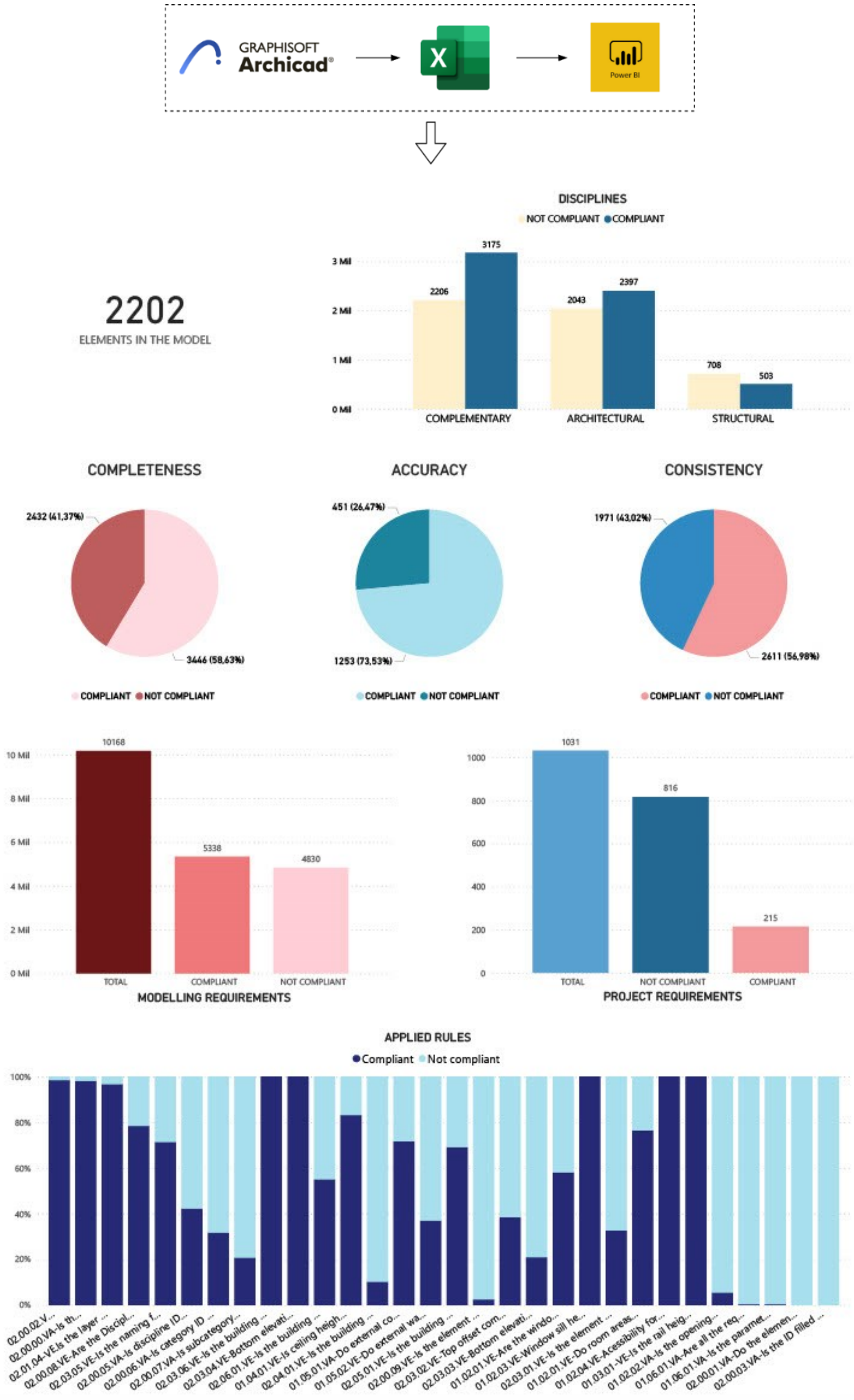

Figure 67: Data analysis on Power BI

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5 DISCUSSION

5.1.1 Framework review

This dissertation proposes a framework that addresses BIM quality checks not as isolated tasks to be performed prior to information delivery. Instead, in alignment with ISO 19650 [4], it presents a methodology that understands the quality checks as part of the management processes in a built asset life cycle. The framework sets a series of procedures that are integrated into the modelling stages, supporting the task teams with the model maintenance in the BIM authoring environment.

The framework's focus is to develop a quality assurance plan from the perspective of the lead appointed party that needs to deliver project information. By considering the requirements from appointing party and the lead appointed party, the framework is due to be applied in different projects under the lead appointed party' portfolio. When the appointed party own requirements are considered a set of standardised and continuous requirements across different clients and projects, the manipulation of the quality assurance plan is simplified. In other words, the clients' needs are changeable, while the company's requirements might remain similar regarding the project type and client. This differentiation brings the perspective that quality assurance can be organised at the organisational level of the lead appointed party and supports the production of standardised information within the company. The beneficial outcomes are the increased efficiency in project management and improvement in information consistency within the company. As the project information models are a database of knowledge acquired across the project, having proper management and consistency in the information contained within the model acquires strategic importance.

Within the procedures proposed by the framework, the automated checks can be highlighted. The quality checks are integrated into the modelling stages as embedded algorithms in the BIM elements properties that feedback with COMPLIANT and NOT COMPLIANT values. The functions provided by the authoring tools can be powerful for this purpose and enables the checks to be done internally, without extra tool. However, the need for human interpretation and visual checks is still necessary since the expressions proposed in this dissertation cannot cover all the project needs. Even with the need for visual checks, the possibility of replacing repetitive tasks, or checks to be done in large-scale models, represents a promising tool for time and cost reduction [36]. Still, it is important to highlight that the rules must be carefully structured according to the classification and model logic since feedbacks with false compliant or not compliant values may cause wrong data interpretations.

Limitations related to the language should be pointed. As the rules get the alphanumerical information contained in the BIM element as inputs for the checking, working with different languages is not feasible. If from one side the use of English would solve the collaborative processes in BIM workflow, from the other side is still needed to use native language for building permission, construction works, and other activities related to the country internal procedures in the construction field. It is understood that language is a limitation of the proposed framework, but it is present in any procedure developed collaboratively with teams of different nationalities.

Another limitation is that according to ISO 19650, the checks should be done prior to information exchange. However, the control of the information already checked and shared with another appointed party in connection with the BIM model still needs improvement. The framework proposes that metadata is attached to the objects relating to CDE workflow to filter the objects by their information status. However, how to control the status of the information in the BIM environment considering the project as an iterative and changeable process is still an aspect to be further studied.

Further aspects of the framework to highlight are the importance the requirements and quality criteria assume in the quality assurance plan. It is acknowledged that the quality assurance will be as efficient as these aspects are addressed from the start of the project, development of the BIM execution plan (BEP) and contractual stages. Therefore, procedures set by ISO 19650 regarding the structuring of the information requirements are advisable and should be taken before starting to create the project's quality assurance plan. In addition, it is necessary to point out that naming conventions and classification assume a vital role in the framework. Naming conventions and classifications are essential features for managing and checking the information. By applying appropriate naming conventions, the model can be organised and queried. Consequently, the quality plan can be largely applied in the project.

5.1.2 Software review

The software Graphisoft Archicad 24 shows up to be powerful for BIM checking focused on information management. The Property and Classification Managers are efficient and user-friendly tools to manipulate and manage the data of the model. As the properties can have different embedded values as well as embedded expressions, a variety of possibilities regarding the quality checks is opened. Easily the user can create algorithms that make use of existent parameters and functions provided by Graphisoft. The guidance for using the functions was helpful to the generation of rules presented in this dissertation. Besides the properties and expressions, Archicad has many features regarding model filtering and visualisation. Those features are essential for a quality check process as it supports the team in searching for non-compliant elements intuitively. In addition, the settings defined for the quality assurance plan are exchangeable with other projects in XML format. It allows those properties, rules, and visualisation settings to be imported to the model only when needed. The XML feature also enables that different models are checked by the same rules or filtered by the same conditions.

If Archicad showed to be powerful in quality check for quality management purposes from one side, it should also be pointed out its limitations. As it is an authoring tool and not a dedicated checking software, some types of checks cannot be performed. Unlike other checking tools, the rules created on expression-based properties cannot review the relationship between different elements or cannot compare properties of various components. Although properties can be manageable globally in the file, the properties are placed to instance BIM elements. It means that the embedded expressions in property manager can only be applied for the purpose of own element checking.

When it comes to property management inside of the authoring environment, Archicad also presents some limitations. As Archicad cannot connect to an external database through the user interface, the properties must be created inside the environment. As pointed before, transferring data through XML is powerful. However, XML showed usefulness for transferring information rather than producing a new one. Therefore, a connection to an external database would be helpful for the improvement of this proposed workflow.

Finally, not all building elements can be modelled by authoring related tools, resulting in incorrectly modelled objects. Even if they are classified and named correctly, they still need to follow software rules for some calculations. For example, a suspended ceiling that has horizontal and vertical plasterboard. There is no tool in Archicad dedicated to model suspended ceilings. In this scenario, it would be modelled through a slab and a wall tool. However, they have different parameters available as the vertical would be modelled by a wall and the horizontal, by a slab. Complex profiles or objects can be used. Yet, there will be even more limitations in the information take-off of these elements, as they are considered particular elements and not standardised ones. Those kinds of issues still need to be addressed, and if improved, it could result in better information and quality management.

5.1.3 Implementation proposal

A stepped approach should be considered to support design teams in implementing the framework as the modelling procedures currently applied may suffer meaningful changes. Therefore, the following steps are advised:

(1) Define generic model breakdown structure
(2) Start from defining a classification that is in alignment with international standards
(3) Adapt template naming convention
(4) Apply requirements-driven approach by each design stage
(5) Apply simple checks and analyse results
(6) Adapt the proposed framework
(7) Implement full plan

6 CONCLUSION

This dissertation addressed the need of assessing, managing and maintaining the quality of information generated in the BIM authoring software. Hence, it addressed the topic of model checking from a broader perspective, not as isolated tasks, and integrated QA/QC into the modelling process. This focus was chosen since it is acknowledged that the model reliability depends directly on how the data is structured beforehand.

In order to understand the status of quality assurance of information in BIM, the literature focused on four main parts. Initially, it focused on what information quality means and how it relates to the construction field. Then, quality management concepts were presented and connected to the BIM methodology. At this point, an overview regarding the current research efforts on BIM-QA/QC was covered. Moreover, an investigation on Model Checking concepts was performed, and rule-based checking processes were further investigated. Finally, the most relevant aspects of information management proposed in ISO 19650 were covered since it is understood that information quality results also from well-managed information.

By looking at model checking as integrated activities throughout the design process, a framework for quality assurance of BIM models was proposed. The framework englobes three main parts: (1) preparation, (2) structuring the modelling process and (3) application.

These steps are crucial for the entire workflow as it defines the goals that need to be achieved in each modelling stage. Still, the proper definition of goals and acceptance criteria's will support the team in keeping the focus on what information is needed to fulfil the requirements, reducing waste of resources. Next, the Structuring part refers to defining the main tools that will support the design team throughout the modelling stages. This stage intends to determine the properties, classifications, ruleset and template for the project. Finally, the Application relates to applying and controlling the tools created previously. Furthermore, this part intends to report and analyse the results of the applied rules. The reports are designed to be used to support decision making and improvement of the model.

From the proposed framework, there are some features to be highlighted. Some aspects were developed to enable the integration of model checking tasks into the design workflow. The first one is the application of rules in the format of expression-based properties. The expression-based property is a feature provided by Graphisoft Archicad. The applicability of it for the matter of quality checks was deeply studied in this dissertation. It resulted in the generation of six categories of computable rules, detailed in section 3.4.2, that feedback with COMPLIANT, NO COMPLIANT or NOT APPLICABLE values. This feature allowed the BIM objects to perform automated self checkings that can be easily integrated into the modelling stages.

Another feature deeply studied for this framework was the filtering methods provided by the authoring tool. The applicability of different filter methods was investigated to filter elements that do not comply with some conditions. It resulted in the concept of Issue Avoidance Filters that would support the team in keeping the quality of the produced data.

The Quality Assurance of BIM models was proposed to be applied in design companies that use authoring software to produce building information for different clients. The framework can be organised at the organisational level and support the production of standardised and consistent information within the company. The beneficial outcomes are the increased efficiency in project management and improvement in information consistency within the company. As the project information models are a database of knowledge acquired across the project, having proper control and consistency in the information acquires strategic importance.

Although the case study was focused on Graphisoft Archicad, the framework has the potential to be applied in any other tool. Nevertheless, the specificities of each software must be considered. Therefore, further studies on this topic would extend the applicability of the proposed framework to other authoring tools. In addition, applying the framework to other disciplines would also be a step forward in the current proposal. Furthermore, developing other expression-based properties in Archicad focused on model checking and studying advanced methods for the properties generation, such as plugins or XML generators, would significantly contribute to this research.

Finally, the author seeks to inspire further research and instigate discussion regarding information quality in building projects. As a result, the topic of data quality becomes a concern widely spread and moves the AEC industry towards better collaborative and integrated BIM processes.

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8 ANNEXES

RULE GLOSSARY				
CODE	**REQUIREMENT**	**QUALITY CRITERIA**	**CATEGORY**	**RULE EXPRESSION**
QA.01	**RULES TO CHECK EXCHANGE INFORMATION REQUIREMENTS:**			
01.01.01.VE	Room areas must meet the required area	Accuracy	Class 4	IF ({Property:PIM-Zone/Zone - Measured Area} >= {Property:EIR-Zone/EIR: Zones-AreaRequired}; "COMPLIANT"; "NOT COMPLIANT")
01.02.01.VE	Windows and Doors must be properly classified	Accuracy	Class 6	IF (STRCALCUNIT ({Property:Window\/Door/Sill\/Header Value}) = "0,00"; IF ({Property:ClassificationSystemPropertyDefinitionGroup/Uniclass} = "Doors and windows"; "COMPLIANT"; "NOT COMPLIANT"); IF ({Property:ClassificationSystemPropertyDefinitionGroup/TUU - 3.1} = "Janela"; "COMPLIANT"; "NOT COMPLIANT"))
01.02.02.VA	Opening type of door and windows must be defined	Accuracy	Class 1	IF ({Property:PIM-Openings (TUU)/PIM: Window openning type} <> "CHOOSE"; "COMPLIANT"; "NOT COMPLIANT")
01.02.03.VE	Windows sill height must have minimum dimension	Accuracy	Class 4	IF (OR ({Property:PIM-Openings (TUU)/PIM: Window openning type} = "Sliding"; {Property:PIM-Openings (TUU)/PIM: Window openning type} = "Horizontal Sash") = TRUE; IF ({Property:Window\/Door/Sill\/Header Value} >= {Property:EIR-Window/EIR: minimum sill height}; "COMPLIANT"; "NOT COMPLIANT"); "COMPLIANT")
01.02.04.VE	The public door must have a minimum width	Accuracy	Class 4	IF ({Property:PIM-Openings (TUU)/PIM: Is the door located in a public area?} = "Public"; IF ({Property:General Parameters/Width} >= {Property:EIR-Ceiling/EIR: Minimal dimension PNE door}; "COMPLIANT"; "NOT COMPLIANT"); "COMPLIANT")
01.03.01.VE	The rail height must comply with the local regulation	Accuracy	Class 4	IF ({Property:General Parameters/Height} >= 0,8 cm; "COMPLIANT"; "NOT COMPLIANT")
01.04.01.VE	Ceiling height must comply with the local regulation	Accuracy	Class 4	IF ({Property:PIM-Ceiling/Ceiling Height - OK} >= {Property:EIR-Ceiling/EIR: Zones-CeilingHeightRegulation}; "COMPLIANT"; "NOT COMPLIANT")
01.05.01.VA	External walls have insulation layer?	Completeness	Class 3	IF (AND ({Property:CategoryPropertyDefinitionGroup/Position} = "Exterior"; STR (CONTAINS ("XPS"; {Property:PIM-Wall/PIM: Element Composite Structure or Building Material}; FALSE)) = "True"); "COMPLIANT"; "NOT COMPLIANT")
01.05.02.VE	External walls have correct insulation thickness	Accuracy	Class 4	IF ({Property:CategoryPropertyDefinitionGroup/Position} = "Exterior"; IF ({Property:PIM-Wall/PIM: Insulation thickness} >= {Property:EIR-Wall/EIR: Insulation Thickness}; "COMPLIANT"; "NOT COMPLIANT"); "Not Applicable")
01.06.01.VA	All the furniture and equipment must have ProductModel defined	Completeness	Class 1	IF ({Property:PIM-Product Information (TUU)/ProductModel} = "Not defined"; "NOT COMPLIANT"; "COMPLIANT")
01.06.01.VA	All the furniture and equipments must have the specific property set defined	Completeness	Class 1	IF (AND ({Property:PIM-Product Information (TUU)/ProductModel} <> "Not defined"; {Property:PIM-Product Information (TUU)/ProductModelCode} <> "Not defined"; {Property:PIM-Product Information (TUU)/PurchaseDate} <> "Not defined"; {Property:PIM-Product Information (TUU)/PurchaseDate} <> "Not defined"; {Property:PIM-Product Information (TUU)/Price} <> "Not defined"; {Property:PIM-Product Information (TUU)/Manufacturer} <> "Not defined"; {Property:PIM-Product Information (TUU)/WarrantyDate} <> "Not defined"; {Property:PIM-Product Information (TUU)/MaintanancePeriod} <> "Not defined") = TRUE; "COMPLIANT"; "NOT COMPLIANT")
QA.02	**RULES TO CHECK MODELLING REQUIREMENTS:**			
02.00.00.VA	All elements must have position defined	Completeness	Class 1	IF ({Property:CategoryPropertyDefinitionGroup/Position} <> "Undefined"; "COMPLIANT"; "NOT COMPLIANT")
02.00.01.VA	Element type and classification must be consistent	Accuracy	Class 4	IF ({Property:ClassificationSystemPropertyDefinitionGroup/Uniclass} = {Property:General Parameters/Element Type}; "COMPLIANT"; "NOT COMPLIANT")
02.00.02.VA	The structural function must be defined	Completeness	Class 1	IF ({Property:CategoryPropertyDefinitionGroup/Structural Function} <> "Undefined"; "COMPLIANT"; "NOT COMPLIANT")
02.00.03.VE	Element ID must be consistent with the classification	Consistency	Class 5	IF (UPPER (MID ({Property:ClassificationSystemPropertyDefinitionGroup/Uniclass}; 1; 2)) = UPPER (MID ({Property:General Parameters/Element ID}; 1; 2)); "COMPLIANT"; "NOT COMPLIANT")
02.01.04.VE	Structural elements should be placed in layers that bellong to structural discipline	Consistency	Class 5	IF ({Property:CategoryPropertyDefinitionGroup/Structural Function} = "Load-Bearing Element"; IF (MID ({Property:General Parameters/Layer}; 1; 1) = "E"; "COMPLIANT"; "NOT COMPLIANT"); "COMPLIANT")
02.01.04.VA	Building material must follow naming convention	Accuracy	Class 2	IF (TRIM (SPLIT ({Property:General Parameters/Building Material}; "_"; 1)) = "TUU"; "COMPLIANT"; "NOT COMPLIANT")
02.00.05.VA	Dicipline ID must be defined	Completeness	Class 1	02.00.05.VA-Is discipline ID defined?-(completeness)
02.00.06.VA	Category ID must be defined	Completeness	Class 1	IF ({Property:PIM-Discipline, category, sub-category (TUU)/Categoria} = "NOT DEFINED"; "NOT COMPLIANT"; "COMPLIANT")
02.00.07.VA	Subcategory ID must be defined	Completeness	Class 1	IF ({Property:PIM-Discipline, category, sub-category (TUU)/Sub-Categoria} = "NOT DEFINED"; "NOT COMPLIANT"; "COMPLIANT")
02.00.08.VE	Discipline ID, Category ID, Sub-categories ID should relate to each other	Consistency	Class 4	IF (AND ({Property:QA.02.00-General/_Get ID from Discipline} = {Property:QA.02.00-General/_Get ID from Category}; {Property:QA.02.00-General/_Get ID from Discipline} = {Property:QA.02.00-General/_Get ID from sub-category}) = TRUE; "COMPLIANT"; "NOT COMPLIANT")
02.00.09.VE	The element classification and layer must be consistent	Consistency	Class 5	IF ({Property:ClassificationSystemPropertyDefinitionGroup/Uniclass} = TRIM (SPLIT (SPLIT ({Property:General Parameters/Layer}; "|"; 2); "."; 1)); "COMPLIANT"; "NOT COMPLIANT")
02.03.01.VE	The elements must be properly linked and placed to the level it belongs to. Example: wall of two floors height, should be splited by levels	Accuracy	Class 6	IF ({Property:General Parameters/Home Story Name} = "Cave"; IF ({Property:General Parameters/Top Link Story} = "Piso"; "COMPLIANT"; "NOT COMPLIANT"); "Not applicable")
02.03.02.VE	Façade walls placed in levels different than basement floor must have top offset = zero	Accuracy	Class 6	IF (AND ({Property:General Parameters/Home Story Name} <> "Cave"; {Property:CategoryPropertyDefinitionGroup/Position} = "Exterior") = TRUE; IF (STRCALCUNIT ({Property:General Parameters/Top Offset}) = "0,00"; "COMPLIANT"; "NOT COMPLIANT"); "Not applicable")
02.03.03.VE	Façade walls placed in the basement floor must have bottom elevation of -0.50m	Accuracy	Class 6	IF (AND ({Property:General Parameters/Home Story Name} = "Cave"; {Property:CategoryPropertyDefinitionGroup/Position} = "Exterior") = TRUE; IF (STRCALCUNIT ({Property:General Parameters/Bottom Elevation To Home Story}) = "-0,50"; "COMPLIANT"; "NOT COMPLIANT"); "Not applicable")
02.03.04.VE	Walls placed in level different then basement must have bottom elevation of -0.21m	Accuracy	Class 6	IF (AND ({Property:General Parameters/Home Story Name} <> "Cave"; {Property:CategoryPropertyDefinitionGroup/Position} = "Exterior") = TRUE; IF (STRCALCUNIT ({Property:General Parameters/Bottom Elevation To Home Story}) = "-0,21"; "COMPLIANT"; "NOT COMPLIANT"); "Not applicable")
02.03.05.VE	The composite ID must be related to the core building material of the composite structure	Accuracy	Class 5	IF (CONTAINS ({Property:QA.02.03-Wall/_Element Material Type B}; {Property:PIM-Wall/PIM: Element Composite Structure or Building Material}; FALSE) = TRUE; "COMPLIANT"; "NOT COMPLIANT")
02.03.06.VE	If the wall element is structural, the composite or building material must be compounded by structural material	Consistency	Class 5	IF ({Property:QA.02.03-Wall/_Is the material structural?} = {Property:QA.02.03-Wall/_Does the element have structural function?}; "COMPLIANT"; "NOT COMPLIANT")
02.04.01.VE	If the beam element is structural, the composite or building material must be compounded by structural material	Consistency	Class 5	IF ({Property:QA.02.07-Beam/_Is the material structural?} = {Property:QA.02.07-Beam/_Does the element have structural function?}; "COMPLIANT"; "NOT COMPLIANT")
02.05.01.VE	If the slab element is structural, the composite or building material must be compounded by structural material	Consistency	Class 5	IF ({Property:QA.02.05-Slab/_Is the material structural?} = {Property:QA.02.05-Slab/_Does the element have structural function?}; "COMPLIANT"; "NOT COMPLIANT")