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Lucas Lima Vieira **Coordinated specification and quantity take-off through digital modelling**

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Universidade do Minho
Escola de Engenharia

Lucas Lima Vieira

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BIM A+ European Master in Building Information Modelling

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Building Information Modelling

Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of:
Miguel Azenha
José Granja
Marta Campos (tutor in company)

Co-funded by the
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STATEMENT OF INTEGRITY

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RESUMO

Especificação e extração de quantidades coordenadas através de modelação digital

Embora os processos de especificação e extração de quantidades pautados em BIM sejam mais eficientes do que quando realizados por métodos tradicionais (Olsen and Taylor, 2017; Khosakitchalert, Yabuki e Fukuda, 2019), há ainda um longo caminho a ser percorrido para que eles atinjam altos níveis de digitalização. Tais processos não são completamente integrados e automatizados, demandando que a informação navegue por diferentes plataformas. Além disso, requerem intervenções manuais suscetíveis a erros e que podem consumir muito tempo. Não obstante, soluções para especificação e extração de quantidades baseadas em BIM são muitas vetestezes caras e não respondem às necessidades de customização para uma melhor adequação aos fluxos de trabalhos internos específicos de uma determinada empresa. Esta problematização levou o trabalho à seguinte questão: Como reestruturar os processos de especificação e extração de quantidades tornando-os mais automatizados, precisos, integrados, rápidos e baratos?

Esta dissertação lida com o problema colocado, desenvolvendo um add-in através da Interface de Programação de Aplicações de uma ferramenta de modelagem BIM. O add-in baseia-se na abordagem conceitual do trabalho que compreende questões relacionadas à padronização, modelagem da informação e gerenciamento de banco de dados. A ferramenta desenvolvida é uma solução digital fundamentada em BIM que permite a geração de um relatório coordenado de especificações e quantidades de forma automática, incorporando ainda uma estimativa de custo preliminar. Para além disso, extrai as informações do modelo BIM, combinando-as com a sua correspondência no banco de dados, baseada num sistema de classificação.

Paralelamente à revisão bibliográfica, a metodologia para a realização deste trabalho se estruturou a partir de um objeto de estudo, o escritório de arquitetura Marta Campos Atelier de Arquitectura, situado no Porto, Portugal. Primeiramente, foi feito o diagnóstico do fluxo de trabalho, mapeando todo o processo como ele é atualmente (AS-IS) para especificação e extração de quantidades. Em seguida, foi feita a avalição desse processo, culminando numa proposta para uma nova abordagem do trabalho que compreende o processo reestruturado (TO-BE), no qual se fundamentou a solução digital desenvolvida. Por fim, o add-in foi executado em casos reais, dois projetos em andamento no escritório de arquitetura, produzindo com sucesso o resultado esperado, o relatório coordenado de especificação e extração de quantidades (Mapa de Trabalhos e Quantidades).

O processo de especificação e extração de quantidades reestruturado que faz parte da abordagem de trabalho proposta, bem como a solução digital desenvolvida permitiram a geração do Mapa de Trabalhos e Quantidades, incorporando uma estimativa preliminar de custo, de forma mais integrada, automatizada e rápida. O processo redesenhado (TO-BE) levou 1/5 do tempo do processo como era executado atualmente (AS-IS) e contribuiu para limitar intervenções manuais às atividades de modelagem da informação. Este novo processo permitiu o aumento do valor agregado ao modelo de negócios do atelier de arquitetura, atingindo um nível maior de digitalização.

Palavras chave: (Especificação em BIM, extração de quantidades em BIM, modelação da Informação, add-in em BIM, Interface de Programação de Aplicações)

ABSTRACT

Even though BIM-based specification and quantity take-off are more efficient than traditional methods (Olsen and Taylor, 2017; Khosakitchalert, Yabuki and Fukuda, 2019), they still have a vast space for further developments which would enable them to reach higher degrees of digitalization. Both processes still lack integration and are not entirely automatized, requiring the information to flow within different BIM platforms, demanding some time-consuming and error-prone human interventions. Also, BIM-based solutions for specification and quantity take-off can be expensive and not compliant with some needs for customization to better adapt to companies internal workflows. This problematization led this work to the following question: How to re-engineer BIM-based specification and quantity take-off processes in order to make them more automatized, accurate, integrated, faster and cheaper?

This dissertation addressed the problem by developing an add-in through the API of a specific BIM authoring tool, found on a proposed framework that comprises standards, information modelling and database management issues. The developed tool is a BIM-based digital solution which automatically generates a coordinated report for specification and quantity take-off, setting up also a preliminary cost estimation. It extracts, matches and combines information from a BIM model and a database, based on a classification system.

Alongside the literature review, the work methodology leaned on a study object, the architectural office Marta Campos Atelier de Arquitectura based in Porto, Portugal. It diagnosed their current workflow, mapping the process AS-IS for specification and quantity take-off. Next, it performed its assessment and finally proposed the framework which comprises the re-engineered process TO-BE, embedded in the developed digital solution. In the end, the add-in was executed in real case scenarios, on two ongoing projects at the study object firm, and successfully produced the expected outcome, the coordinated specification and quantity take-off report (in Portugal commonly called “Mapa de Trabalhos e Quantidades”).

The re-engineered BIM-based specification and quantity take-off embedded by the proposed framework alongside the developed digital tool enabled a more integrated, automatized and faster generation of the coordinated specification, quantity take-off and preliminary cost estimation report. The whole re-engineered process (TO-BE) took 1/5 of the time than the AS-IS (performed in the current workflow) and was able to limit the manual interventions for the modelling activities. The TO-BE process added value to the firm business model, accomplishing a higher degree of digitalization.

Keywords: (BIM-based specification, BIM-based quantity take-off, information modelling, BIM add-in, authoring tool API)

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1. INTRODUCTION

Building Information Modelling (BIM) is amongst the leading digital innovations in the Architecture, Engineering and Construction (AEC) industry over the past decades, and its adoption has been growing all over the world with significant potential to expand even more (World Economic Forum, 2018). BIM has contributed to increasing the digitalization of the AEC processes addressing its low growth of productivity over time (Mihindu and Arayici, 2008), seeking for more efficiency and revenues for the industry. It stands against the fragmentation of information during the project lifecycle, towards a more effective collaboration among project stakeholders (Al-ashmori *et al.*, 2020). Since the earliest stages of a project, designers, clients, contractors, and manufacturers should have a shared understanding of what and how they are going to build, and how much the construction and operation will cost. Specification and quantity take-off processes and their outcomes play a significant role in creating this common ground and are essential to answer these questions (NBS, 2017). Besides what and how, they also determine which resources and materials should be used, keeping a straight relationship among each other and with the construction drawings (Utiome, 2015). However, although the importance of the specification information and precise quantities is widely recognized and considered as crucial to obtain accurate cost estimations and successful execution (NBS, 2017), the process to prepare them is still fragmented, lacking in automatization (Utiome, Drogemuller and Docherty, 2014). Specification and quantity take-off when BIM-based are considered BIM uses, which are the intended or expected outcomes/project deliverables from a BIM model (BIM Dictionary, 2019). These two BIM uses are still time-consuming and subordinate to repetitive routines, once BIM authoring tools and solutions focused on them do not allow a complete customized automated process, mostly due to interoperability issues. Manual procedures and checking are necessary to attend the real-life demands of some business and their specific workflows (Khosakitchalert, Yabuki and Fukuda, 2020). The high cost of the existing BIM tools for specification is also a limiting factor which prevents small and medium enterprises (SMEs) from using them. This context leads to the following question: How to re-engineer BIM-based specification and quantity-take processes in order to make them more automatized, accurate, integrated, faster and cheaper? This work approaches this problem through the development of a tailor-made digital solution for specification and quantity take-off, capable of integrating the BIM model to a specification database and providing automatic specification report and bill of quantities. The development of such a tool is a feasible way to achieve custom automatization and has been a goal of researchers and companies for a more integrated design process (Pereira and Correia, 2018).

1.1. Motivation

The study developed by Succar and Kassem (2015) about macro BIM-adoption around the world defines three stages of BIM capabilities ordered as following: 1.modelling, 2.collaboration and 3.integration. Once someone entirely domains one of them and jumps to the next capability, the performance and possibilities for innovation increases. Digital modelling is already performed globally in the AEC industry in higher levels of maturity in comparison to other BIM capabilities (Talamo and Bonanomi, 2020). However, when it comes to BIM uses such as specification and quantity take-offs, which demand more collaboration and integration capabilities from the BIM systems, lower levels of maturity predominate (Succar and Kassem, 2015). It is still necessary, and consequently, there are many opportunities for advancements in BIM processes oriented to these uses for improving their collaboration, integration, and degree of digitalization. Even though BIM-based specification and quantity take-off have already proved to be more efficient than traditional methods (Olsen and Taylor, 2017; Khosakitchalert, Yabuki and Fukuda, 2019), they still lack integration among each other, with related processes, and within internal subprocesses. Existing digital solutions for these two BIM uses usually require expensive software solutions that are not affordable for SMEs (Vidalakis, Abanda and Oti, 2020), which are the vast majority of companies in the AEC industry (Designing Building Wiki, 2020). They also do not comply for some customization needs to attend specific commitments of these companies workflows. Re-engineering specification and quantity take-offs through digital technologies towards more integrated, digitalized, and accessible processes would bring a positive impact for all project stakeholders. It would take the AEC industry more steps closer to the level of digitalization of other sectors, in the search for more productivity and efficiency.

Besides the reasons mentioned above, the BIM A+ partner, Marta Campos Atelier de Arquitectura, inspired by a tool developed by the Portuguese company Groud Motion (Pereira and Correia, 2018), proposed this work theme found on real demand. The office is an architectural design firm, based in Porto, which already has been using BIM in a high level of maturity, mastering modelling processes. However, aiming more productivity, they have faced the need for re-engineering their workflow for specification and quantity take-off. The thinking of a real problem is also a motivation to develop this work.

The acronym MC henceforward will be used as a replacement of Marta Campos de Arquitectura (MC).

1.2. Objectives

This work aims the establishment of a framework for BIM-based specification and quantity take-off. Its development leads to a digital solution as an add-in for a BIM authoring platform through programming that enables intelligent automated extraction of information from a digital model, coordinating this data with an already implemented Classification System and an existing database (DB).

The proposed framework has as a study object Marta Campos Atelier de Arquitectura and its practice. It considers the AS-IS processes for specification and quantity take-off at the company, its evaluation, and defines new strategies to re-engineer these processes to be more integrated and digitalized. It addresses issues regarding standards compliance, information modelling, and DB management that once overcome, will enable a workflow with a higher level of digitalization. The new framework intends, through a digital solution, to establish a more accurate, faster and cheaper way of producing coordinated specification and quantity take-off, adding business value to the company. The framework works as an enabler for the intended add-in once it provides guidelines and milestones for it.

The add-in will extract from the BIM model whether data incorporated in its objects natively or specific parameters/attributes created for the purpose (mostly to represent non-modelled objects/activities), their quantities measurements, and classification indexes. The data incorporated in the objects and in the created attributes will be related to a construction specification database matching their classification keys. The add-in would automatically produce specification documentation which coordinates the data from the BIM objects/created attributes with their respective match in the specification database.

1.3. Dissertation structure

Besides the introduction, other five chapters structure this work. Chapter 2, *"Digital specification and quantity take-off processes"*, clarifies the concepts digitization, digitalization, and digital transformation in business processes. Additionally, it illustrates how BIM takes part in these three concepts, as the leading digital innovation in the AEC industry, going through digital modelling driven for specification and quantity take-offs. It also briefly surveys and examines existing works and tools developed for these BIM uses. Finally, it highlights the importance of applying and complying to standards to deal with digital data and to establish digitalized processes.

The following chapter *"Designing a framework for digitalized specification and Quantity take-off "* is divided into three sections. The first one, section 3.1 (Diagnosis of the specification and quantity take-off existing workflow), describes the development of an as-is process for specification at Marta Campos Atelier de Arquitetura, mapping all the subprocesses, their inputs, outputs, resources, and controls (standards and best practices). This development has as primary sources the analysis of the current workflow outcomes and the information gathered conducting work meetings with the Head of the company and its collaborators. Based on the literature review, section 3.2 (Assessment of the existing workflow) compares best practices with the status quo for specification through digital modelling at Marta Campos Atelier de Arquitectura. It also documents the expectations regarding the new add-in obtained from the mentioned meetings with MC team. The last section 3.3 (Framework for a digital solution) ends chapter 3 and focuses on the development of a to-be process based on the previous steps and establishes a flowchart for the add-in. Besides, it narrows down the technical means to reach the proposal goal, defining, tools, software, and database architecture.

Chapter 4 (Framework programming) registers the development of the proposed digital solution (add-in) using Python language with pyRevit support. This tool allows integration with Revit (the BIM authoring software used at Marta Campos Atelier de Arquitetura) and Python language script. Programming and testing were based in samples provided by the company of the BIM objects library, specification database, and template of the coordinated specification and bill of quantities report (designated in Portuguese as "*Mapa de Trabalhos e Quantidades*").

Chapter 5 (Testing in real case scenarios) dedicates on documenting the use of the add-in two ongoing projects: a new single-family house and a renovation. It assesses the add-in performance in a real scenario, evidencing its efficiency at providing automatized specification reports and quantity take-offs and describe the process of promoting a user evaluation by the company as feedback to make adjustments and improvements.

Lastly, the conclusion, embedded in chapter 6, states the results of the developed work and indicates further developments for the specification and quantity take-off processes to reach a higher level of digitalization, the same for the add-in itself.

2. DIGITAL SPECIFICATION AND QUANTITY TAKE-OFF PROCESSES

2.1. Digitalization, BIM and their possibilities

Digitalization is a conceptual term which authors have frequently been using to head the discussion of how businesses are applying and managing data in their business models (Ritter and Pedersen, 2020). Its definition very often interchanges meaning with two other strongly associated concepts: digitization and digital transformation. However, many researchers (e.g. Brennen and Kreiss, 2014) stand for clearly differentiating them once this approach allows inferring some analytical values to understand digital businesses transformations (Ritter and Pedersen, 2020).

Digitization consists in transforming analogic data into a digital representation and precedes digitalization. ((Ritter and Pedersen, 2020) based on Brennen and Kreiss, 2014). Gupta (2020) has an aligned definition for digitization as the *"creation of a digital representation of physical objects"*. The scanning of some paper documents into a PDF file (a digital representation) is an example of digitization. It enables data-based processes to use digital data as inputs.

On the other hand, digitalization refers to the enablement or improvement of business processes through digital technologies and digitized data. It allows re-engineering business model processes to be more efficient, adding new revenues to them. However, it does not change the processes core.

Succeeding Digitization, Digitalization is an enabler for Digital Transformation. The last of the three mentioned concepts represents the transformation of the business into a completely digital business model, changing the essence of the processes.

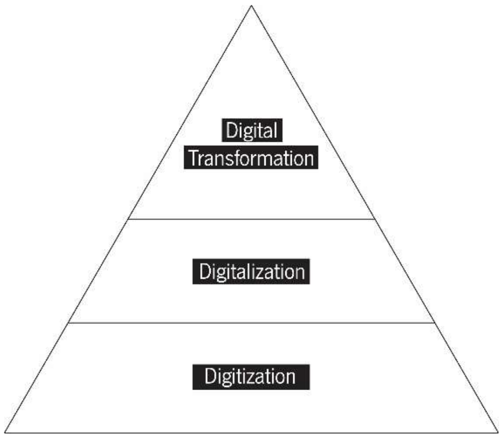


Figure 1 –Digital Transformation Pyramid adapted from (Gupta, 2020)

The Architecture, Engineering and Construction (AEC) Industry digitalization have gradually changed the processes of designing, constructing, and operating a building. Also, how the different stakeholders in a project lifecycle work and interact with each other. However, in comparison with other industries, AEC is still one of the less digitized, therefore with one of the lowest levels of digitalization embedded in its business model (Talamo and Bonanomi, 2020). A McKinsey report (2018) illustrates this statement establishing a correlation between productivity growth and the degree of digitization for different industries in Europe in the decade of 2004-2014. See Figure 2:

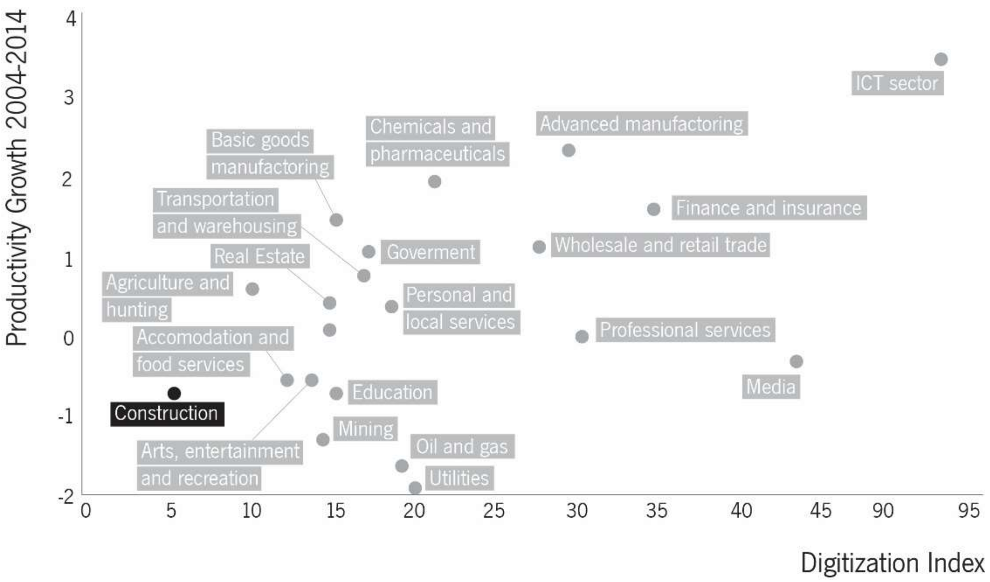


Figure 2 – Correlation between productivity growth and digitization in the European AEC industry (McKinsey Global Institute, 2018 cited in Talamo and Bonanomi, 2020)

Although there is still a long way to achieve the digital transformation of the AEC fully, BIM is considered the most promising approach towards digitalization in the sector (Eastman *et al.*, 2011; World Economic Forum, 2018). Its adoption has been growing over the past decades (NBS, 2019), and there are many private and public initiatives supporting it (Succar and Kassem, 2015).

The formal definitions of BIM vary, but many of them embed the concept of processes digitalization in the AEC industry, allowing stakeholders to create, share and manage structured data during a project lifecycle. It is a set of technologies, digital processes and policies (standardizations) for digital representation of the built environment (Succar, 2009). According to NBS (2016), BIM is *"a process for creating and managing information on a construction project across the project lifecycle"*. The BIM Dictionary, curated by the BIM Excellence Initiative, defines BIM as *"a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space"* (2019). ISO 19650 standard and PAS:1192 framework also provide a similar definition of BIM.

BIM enables a digital representation of the built environment (BIM model), which can be used during all project lifecycle, from planning, over construction and the building operation, enabling *"an optimized collaboration and information exchange between all participants and disciplines in building industry"* (Krämer and Besenyoi, 2018).

2.2. Digital modelling and specifications

Digital modelling consists of creating a digital representation of a real word element or system of elements. Digital models try to simulate reality. However, usually, they represent simplifications of it. According to George E.P. Box cited from M. Dumas, M. La Rosa, J. Mendling, H. A. Reijers,(Dumas *et al.*, 2013) "*Essentially, all models are wrong, but some are useful*". This statement is observable when someone exams a BIM object placed in a BIM model. A digital representation, depending on the purpose of the BIM model, has different data granularity (Utiome, Drogemuller and Docherty, 2014) represented by different Level of Information Need (LoIN) for a model and its objects. The geometrical data could be a simplification of the real geometry. Still, even so, this representation could be useful once it could carry non-geometrical information embedded in the object itself through its attributes/parameters or linked to other sources of information that refers to the same object, such as a database. Specifications, for instance, can be fully expressed or complemented by non-geometrical data as long the object has an identification code assigned to establish the link with an external specification source (Stutzman, 2013).

For this reason, besides the geometrical data, for the production of specification documents, it is crucial the use of an classification code to label each BIM object in a model. This procedure indexes the objects being able to express its specification data directly in the model (views, schedules, etc.) or linking them to an external source, such as a specification database. (Stutzman, 2015).

The Oxford dictionary defines specification as *"A detailed description of the dimensions, construction, workmanship, materials, etc., of work done or to be done, prepared by an architect, engineer, etc."* and according to the UK´s National Building Specification - NBS Specification Report 2017 in the context of AEC industry *"A specification is the document that describes, in words, what cannot be visualized or explained on a drawing or in a model."* It is a description of products, materials and work required by the construction contract. They do not contain cost, quantities or construction drawings, but they must be read in conjunction with these other documents to provide accurate information for tendering and executing the construction. Among a wide range of aspects, It determines "*the establishment of the […]quality of the systems and products, which standards are applicable and how they should be executed, and even the products to be used"*(NBS, 2017). Detailed specification documentation will assure the client certainty of what is going to be executed and delivered.

The construction specification process relies on some standards to structure and manage digital specification information. The classification systems are crucial for standardizing and structuring construction elements information, allowing this, once digitized, to serve as input for digitalized specification processes. One example of one of these digitalized construction specification solutions is NBS Chorus for writing construction documentation by NBS (NBS, 2020). This cloud-based software helps specifiers to collate specification from a specification database of elements classified according to Uniclass 2015, combining this information with the BIM model, generating specification documentation. Running on the cloud is the main advantage of Chorus, once it makes the specification data aways up to date for all different project team members, making the process of specifying more collaborative and integrated (Day, 2018). The Spanish company CYPE has the platform Arquimedes (CYPE, 2020). Besides the BIM-based specification itself, it also coordinates this specification information with extracted quantities from the BIM model and cost estimation, having a broader scope. This tool also counts with a database on the cloud. Even though both are robust solutions developed by big players in the market, both are not tailor-made solutions and do not adapt so easily to attend specific demands of a business model. Furthermore, in the case of Chorus, the price to purchase or subscribe it is not affordable for the vast majority of AEC companies, which is composed mostly for Small and Medium Enterprises (SMEs).

Another example of a tool that provides a comparable digital solution is the add-in developed by the Portuguese company Ground Motion (Pereira and Correia, 2018). This ultimate tool inspired this work proposal, once it faced the cost and customization issues. Using the Application Programming Interface – API of the BIM authoring tool Autodesk Revit®, they developed an add-in written in C# that enables automatized quantities extraction from the BIM model, generating a report that consists on a bill of quantities associated to specifications. In Portugal, this report is known as "*Mapa de Trabalhos e Quantidades*" (MTQ). In this case, the specifications are extracted only from the BIM model, and the add-in does not go through an external specification database.

Regarding BIM-based solutions for specification, the dissertation research has shown that there are less academic works available about this theme in comparison to quantity take-off and cost estimation.

2.3. Digital driven information for quantity take-offs

As introduced in the previous section, aiming to be efficient and accurate, the BIM model drives its geometrical and non-geometrical information to pre-defined finalities/outcomes. The granularity of data, expressed in the level of information need (LoIN) of the model and its objects, in conjunction with other aspects, address these purposes. They are commonly named as BIM uses. A model can claim to originate construction drawings, perform energy efficiency analysis, 4D simulations, among many other scopes. Quantity take-off is one of these BIM uses.

BIM-based quantity take-off is faster and more reliable than traditional methods to measure quantities from building designs. In comparison to pre-BIM processes, it saves time, it is less error-prone, and it is more independent of human interpretation (Bečvarovská and Matějka, 2014; Khosakitchalert, Yabuki and Fukuda, 2020; Olsen and Taylor, 2017).

Besides the compliance with object standards, the development of the BIM model aiming precise and accurate quantity take-off has to structure its data specifically for this BIM use. The way someone develops a BIM model (quality of the model) and the chosen LoIN for each object impact the accuracy of the Bill of Quantities (Zima, 2017). One of the main issues that lead to inaccuracies at getting quantities is the use of compound elements (Khosakitchalert, Yabuki and Fukuda, 2020). Despite behaving as a unique object, these elements are composed of several layers with different materials. Walls, floors, ceilings, and roofs are commonly modelled as compound objects. The inaccuracies come from the fact that in real life, each layer occupies different surfaces areas. The masonry and cementitious grout layers go until the bottom of the slab; meanwhile, the layer of the ceramic tiles stops at the ceiling (Figure 3 exemplifies the described situation). Another source for inaccuracies is the elements that usually do not have a graphical expression in the model, such as paintings, primers, jointing grout. They typically are obtained using manually inputted formulas in quantity take-off tools with lower levels of digitalization. To overcome these issues, and achieve more accurate quantities, some authors recommend the development of BIM models avoiding compound materials (Khosakitchalert, Yabuki and Fukuda, 2019 and 2020). Each material layer is an independent element, in compliance with higher levels of development, at least LoD 300 or 350 depending on the element, as shown in Table 1 (BIM Forum, 2019).

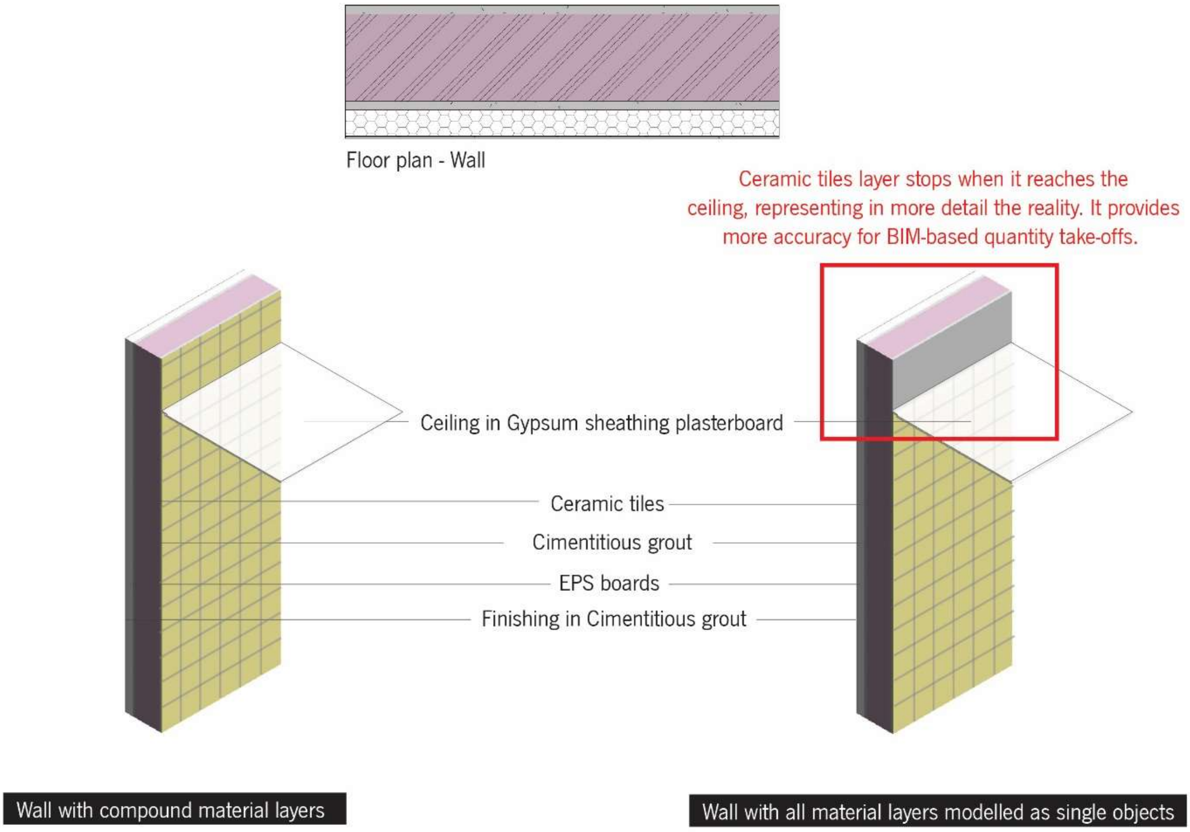
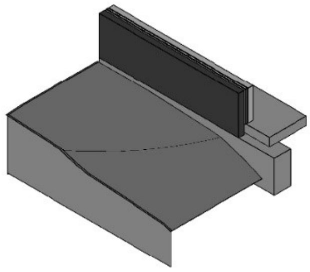
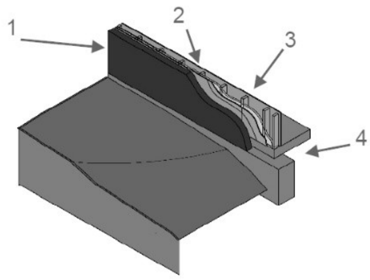


Figure 3 – Example of layered elements: a wall with compound material layers X a wall with all materials layers modelled as single objects

Table 1 – LODs that require elements material layers to be modelled as single objects/separated elements (Adapted from BIM Forum, 2019)

LOD 300	Exterior wall veneer modelled as a separate element; Specific wall modelled to actual dimensions; Penetrations are modelled to nominal dimensions for major wall openings such as windows, doors, and large mechanical elements.	 65 B2010.10-LOD-300 Exterior Wall Veneer
LOD 350	Exterior wall veneer modelled as a separate element; All penetrations are modelled at actual rough-opening dimensions; Precast concrete panels are individually modelled. Connection points are specified; Connection to interfacing systems. *Images notes:* *1.Wall veneer element* *2.Skin layers including but not limited to waterproofing membrane* 3.*Core framing* 4. *Concrete slab edge*	 66 B2010.10-LOD-350 Exterior Wall Veneer

In the case of non-geometrical data, some solutions for quantity-take-off such as Autodesk Navisworks® allow the user to associate non-modelled elements to an existing object and base its measurement in formulas which use attributes of the later one. Activities such as repairs, interventions, and cleaning applied to some objects also do not have graphical expression. They can be associated with existing objects through formulas, allowing them to be measured. One reference to measure those activities and assign them to modelled objects is the solution proposed by the Portuguese Company Build Gest, part of the engineering company A400 (BUILDGEST, 2018). They executed a structural inspection and diagnosis for the pavilion Rosa Mota (Palácio de Cristal) in Porto, Portugal. The BIM model contained host-based objects with simplified geometry representing the structural interventions that must be done. These objects were positioned in the host, precisely where those actions were required. By using this solution, quantity take-off could consider these intervention activities without the need for using complex arrangements.

2.4. The importance of standardization to digitalize processes

Digital specification and quantity take-off, like any other digitalized process, are hardly achieved if not based on standards. They demand data sharing among project stakeholders during its lifecycle, and this exchange faces several interoperability issues among different digital tools involved in those processes. Standardization is considered a critical factor to enable the digitalization of processes and its evolution, overcoming these issues. It allows for better management of digital representations (Cerovsek, 2011). In the AEC industry, specifically in BIM oriented process, it is not different. Digital innovations and standardization are firmly connected, being the standards able to confer interoperability, trust, and comparability to digital solutions (Cerovsek, 2011). This perspective is valid for construction specification and quantity take-off through digital modelling. Products, activities, and systems data must share the three mentioned features to perform those BIM uses successfully.

Classification systems, for instance, structure data in an agreed way allowing different stakeholders to obtain and understand the information they need. They create a common ground for establishing communication among humans, machines, and software, assuring them to use Building Information efficiently and accurately (Aksomitas, 2020). Due to the complexity of the projects and the network of team collaboration, project parties generate more and more data, and this data relies on standardize and structured digital solutions to serve as a source for decision making and project development. Classification systems benefit different actors in the industry according to their necessities and associated BIM uses. Generally, architects and engineers use them to generate project specifications, contractors for scheduling and cost estimations, and owners for facilities and assets management (Autodesk, 2017). Different classification systems have been developed by distinct agents in the AEC industry, approaching different ways of structuring data and taking into consideration different regional contexts. Some of them are Uniclass2015 (UK), OmniClass (North America) and CoClass (Sweeden) (Aksomitas, 2020).

Besides the classification systems, information modelling procedures and BIM objects standards are also enablers of digital processes. As described in section 2.3, there are some recommended practices to develop BIM models for quantity take-offs. The most recollected one is to avoid the use of layered elements, as a single object. It requires consistency to model the objects, following the same criteria for all of them. The modelling procedures will define the input used for BIM-based quantity take-offs. Because of that, the data contained in the BIM model must be structured (standardized) accordingly to the digital solution to perform the referred BIM use. Regarding the BIM objects, NBS says: *"By standardizing the information recorded within objects, we can compare them and make an appropriate selection for the project"* (2014). They also support the idea of using standardized properties, which facilitates their use as input for digital processes, once it mitigates exceptions and human interpretations at dealing/treating objects data.

3. DESIGNING A FRAMEWORK FOR DIGITALIZED SPECIFICATION AND QUANTITY TAKE-OFF

3.1. Diagnosis of the specification and quantity take-off existing workflow

BIM-based specification and quantity take-off, as described in the previous chapters, are crucial for tendering a construction and, alongside the construction drawings, to enable its successful execution. These two BIM uses takes part in the work scope of the object of study firm, Marta Campos Atelier the Arquitectura, setting up an architectural estimation cost when designing a project. This practice is not typical for other design-oriented architectural firms, which usually focus on producing the specification documentation and schedules for windows, doors and plumbing fixtures as deliverables alongside the construction drawings. Quantity take-off and preliminary architectural cost estimations are performed by other stakeholders involved in the project, such as surveyors or contractors. It is essential to highlight that the coordinated specification and quantity take-off report (MTQ), as well as, cost estimation is required as mandatory project deliverables by the Portuguese regulation *"Portaria n.º 701-H/2008"* (Ministérios, 2008). As an architectural office with a consistent background at using BIM, MC saw the possibility of adding value to its business model by incorporating BIM-based quantity take-off to their project scope, besides leaving this activity to be performed by another project stakeholder.

The methodology applied to diagnose the existing workflow was based on weekly working meetings (usually video-calls) with the Head of the company and its associates. Besides, a place for discussing the dissertation development, they were an opportunity to understand the office practice once the ongoing projects were also discussed, providing subsidies for this work. A communication channel on Microsoft Teams platform was established since the very beginning of the dissertation development, enabling information exchange through messages in a daily-base. Furthermore, a Common Data Environment (CDE) was also set up on Dropbox, allowing data sharing between the MC team and the author of the dissertation. It is worth to highlight that the full availability and commitment of the MC team were crucial for this work achievements.

The existing workflow at MC has as a primary outcome a single report, which coordinates specification and quantity take-off data, the MTQ. Figure 4 illustrates their understanding of the current workflow for generating the mentioned report.

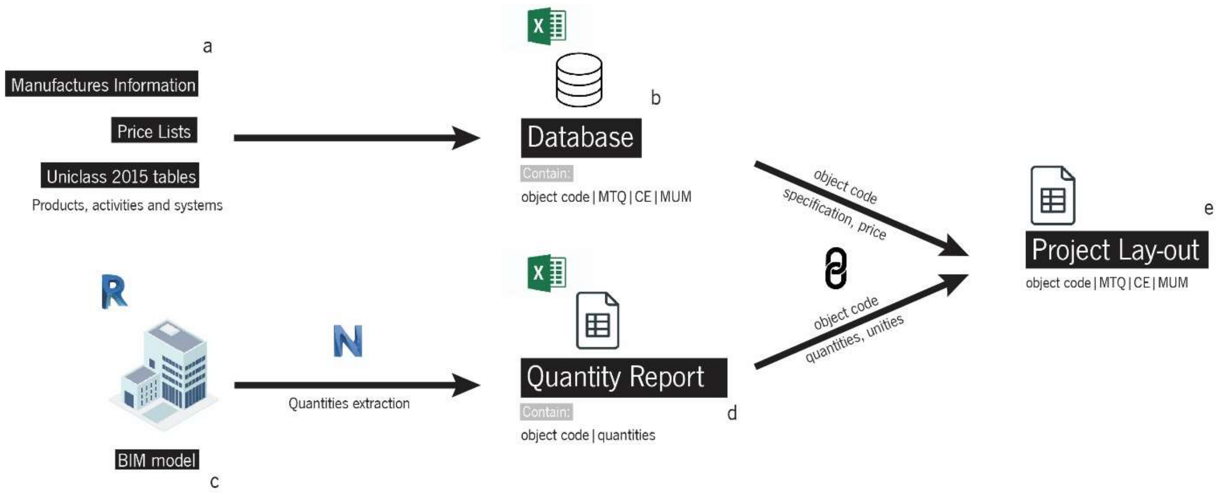


Figure 4 – Perceived current workflow for generating coordinated specification and bill of quantities report by Marta Campos.

MC has been developing a BIM object library in compliance with NBS Object Standards and also specification database for these objects. The atelier classifies the objects using an internal classification based on the Uniclass2015 system, having the same classification code/index in both, object library and specification database, which confers the possibility of linking them. The choice for Uniclass relies on the coverage of this classification system, comprising products, system, activities, among other categories, and the fact it is developed by the leading BIM specification institution in the UK, one of the countries with highest levels of BIM adoption in the world (Kassem and Succar, 2017). Moreover, as mentioned by the head of the company, an internal movement in Portugal to establish a national classification system based on Uniclass has directed the firm to stick to NBS standards.

The Uniclass 2015 code composes the classification code of the objects used by MC, which is complemented by an internal suffix. This suffix provides deeper classification levels for the objects, such as manufacturer, model, thickness, suffered interventions, element function (exterior or interior), depending on the object class. The authoring tool Autodesk Revit® 2020, which is the one used by MC, provides native file-based attributes (arguments of the attributes loaded from an external tabulated .txt file) to secure the classification index/code, the Keynote, Assembly Code and OminiClass. Respectively, the last two are structured to store the following classification systems: Uniformat (based on the functionality of the elements) and OmniClass (based on listing components or assemblies of components) (Gómez, 2015). Among these three, MC uses the Keynote attribute to insert the custom classification code once it can be assigned independently of Revit categories. The Keynote attribute has as source an external .txt file created by MC team and managed in conjunction with the database, the called Keynote Table Source. The central server of the company houses this file, and all associates have access to the most up to date version of it. *"Keynotes assigned in a project are linked to their source keynote table. When the keynote table is changed, keynotes in the project will reflect the changes when the project is closed and reopened."*(AUTODESK, 2018).

It was selected from its object library a wall composed by aggregate concrete blocks to understand the custom classification code used by the atelier. Following NBS Object Standards, the object name is

"MC_Artebel_AlvBlo280_BlocoBetaoBBE28_E280" and the Uniclass 2015 code "Pr_20_93_52_01" is the one that corresponds for aggregate concrete blocks generically. In order to go further in the classification, as mentioned before, MC adds the suffix ARTEBEL_BBE28, and the classification code stored in the Keynote parameter (originally from the Keynote Table Source created and managed by the office) and the primary key of the object register in the database keep the value "Pr_20_93_52_01_ARTEBEL_BBE28". The suffix added to the Uniclass2015 classification code creates other levels of classification, specifying in detail the object, once the aggregate concrete blocks could have different specification information to be built/assembled, depending on its manufacturer, thickness, among other attributes (Figure 5).

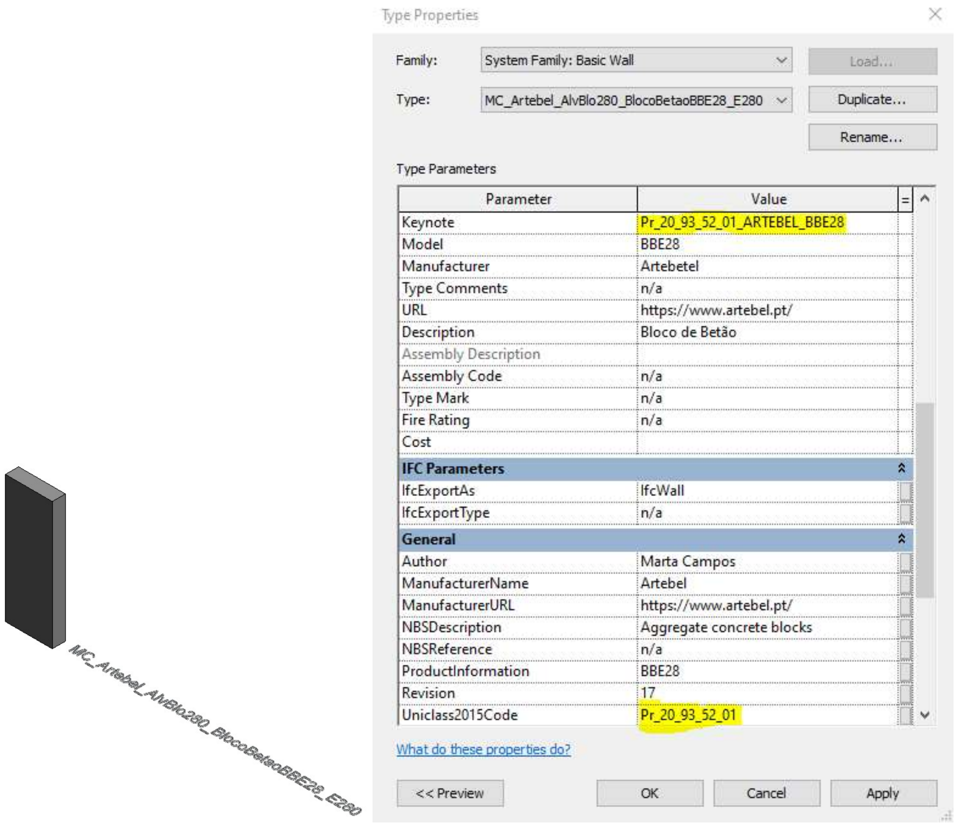


Figure 5 – Example of an object from MC object library which the classification code formed by Uniclass 2015 code, plus a suffix to provide more detailed specification information.

MC uses Autodesk Navisworks to perform the quantity take-off itself (See Figure 4, entities c and d). Even though the BIM-based process is faster than traditional 2D methods, it has some limiting factors (Olsen and Taylor, 2017), that goes beyond the quality of the model and the level of development of its objects. Navisworks runs the quantity take-off by using many-sided filtering and mapping based on the classification codes (Uniclass + suffix) applied to the elements in the authoring tool. Even though different projects can use a template for the filtering and mapping rules, these procedures can be time-consuming. In the end, it exports a quantity report spreadsheet.

The quantity report generated by Navisworks is coordinated and linked to the specification database trough formulas on MS Excel, based on the classification code of the elements. Each element listed in the quantity spreadsheet goes to the MTQ template, and there they are coordinated with their correspondent data from the specification database (also an excel spreadsheet). This linking process even though with some degree of automatization, due to the excel formulas, requires manual structuring for the report, validation and checking to assure the input data is usable, if the link was correctly established and if the outcomes are accurate (See Figure 6, processes 3 and 4).

The whole process of creating the coordinated specification and quantity take-off report, therefore, is composed by subprocess which, through the use of digital tools, consume outputs from the previous ones and provide, as outcomes, inputs for the next ones. It is necessary to assure that a particular information output is structured in a way it can be used as input for the next subprocess. This is achieved by using integration subprocess, also called glue process, that treats and adequates the data to be used as input again (Turk, 2006). They find the output information, retrieve it in a different location and convert it to be useful in the following step.

After being developed in the authoring tool, the BIM model is exported to a Navisworks readable format. The quantities extraction in Navisworks, far from being generated automatically, need the input of a Work Breakdown Structure (WBS), which can be imported from a project management tool such as MS Project, or inserted manually. In both cases, the WBS ideally is based on an available template or in a classification system. Each object must be linked with one activity/product listed on the WBS. If the WBS matches the classification system used to classify the objects in the authoring tool and database, the link can be done automatically; otherwise, it must be done manually. The whole process of creating the coordinated specification and quantity take-off report needs some glue subprocess based on manual intervention, in order to integrate each step of the chain. Treating and making BIM model data usable in Navisworks, and after, matching the data from Navisworks with the specification information, are examples of these glue subprocess.

In the end, the checking and validation of the obtained MTQ are performed manually by the user. The process of generating it, even though using digitized inputs, is not entirely digitalized; some subprocesses still need manual, error-prone, and time-consuming work.

The AS-IS process to produce the coordinated specification and quantity take-off report requires continuous management of the specification database. Some of the subprocesses or activities to make the MTQ request updates or the inclusion of new elements in the specification database (see Figure 6, process 2, subprocess p2.a). The specification database is kept and managed in an MS Excel spreadsheet. The diagram in the following page (Figure 6) represents the process AS-IS to generate the MTQ (coordinated specification and quantity take-off) at Marta Campos Atelier de Arquitectura:

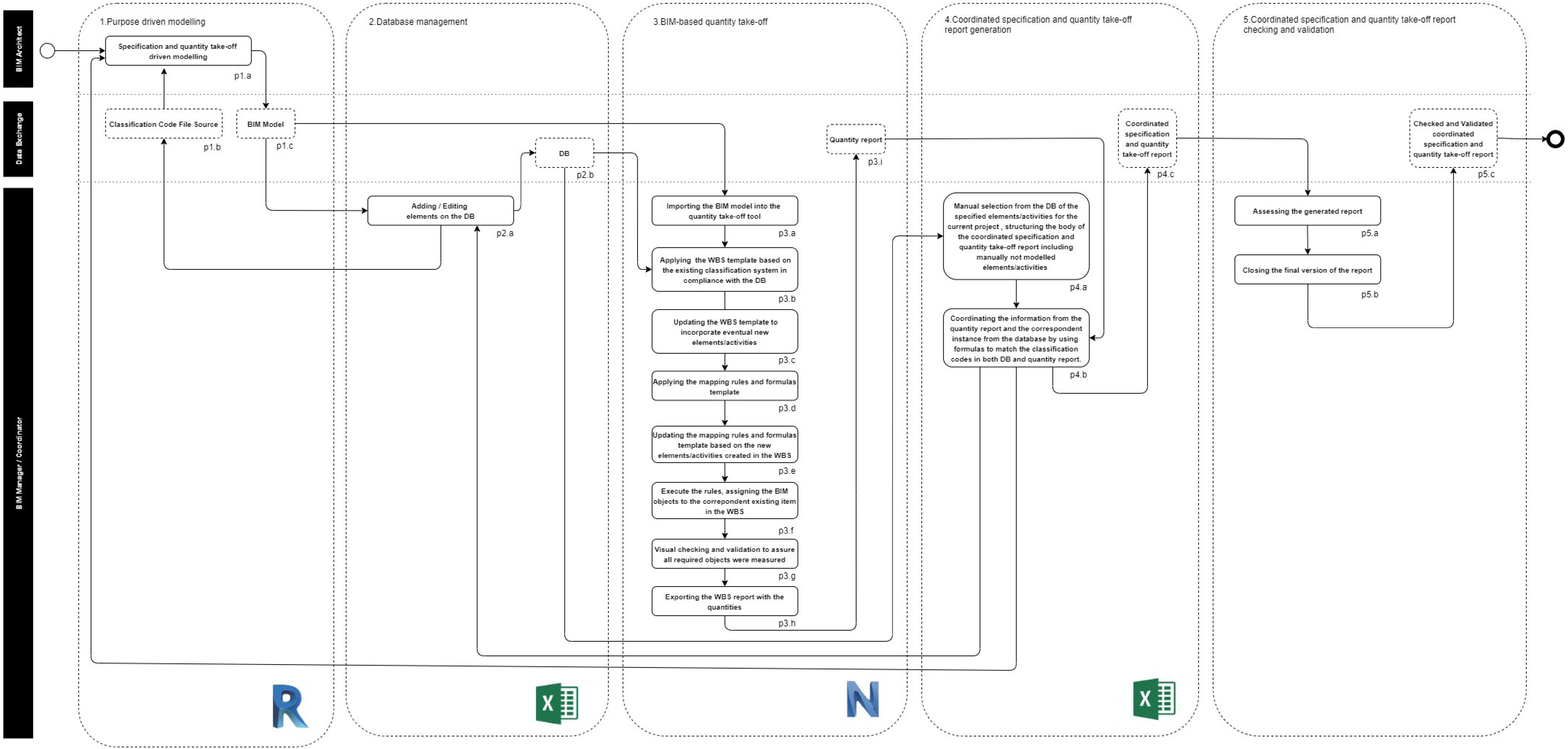


Figure 6 – AS-IS process to generate a coordinated specification and quantity take-off report.

3.2. Assessment of the existing workflow

Marta Campos has already a BIM-based workflow for coordinated specification and quantity take-off documentation, which has benefits in terms of time and accuracy in comparison to traditional methods. The company is aware of the impact of the modelling activity to produce MTQ. Thus, the BIM models are driven to match this purpose, besides exploring design solutions and production of construction drawings. The office also manages its BIM objects library and specification database in compliance with the classification system Uniclass 2015 and the NBS object standards. Both classification system and standards are indispensable for the intended increase of automatization, allowing the link between different sources of construction data and assuring its interoperability among distinct digital tools.

However, the whole process lacks integration, is broken down into several steps, and some of them require repetitive, time-consuming and error-prone manual work. There is an opportunity to add value to their business by increasing the level of digitalization for producing coordinated specification and quantity take-off. It is possible to achieve a more efficient and digitalized workflow by re-engineering the way these two BIM uses are performed.

The primary demands for manual intervention within the AS-IS process concern the elements and tasks not graphically expressed in the BIM model and the elements that the authoring tool can not calculate and, consequently, does not allow the reading of a specific attribute value, such as the area for the stair landing. However, it can be obtained by reading their volume and thickness parameter, expressing the area in the quantity report resulted from a mathematical expression assigned on Navisworks. Another example is the roof ridge which usually is not modelled, though an item should represent it on the quantity report generated by Navisworks. Its information is computed and inputted manually by the modeller/surveyor in the MTQ. Hence, the current workflow presupposes that the user surveys and assess all the non-modelled objects that should be part of the MTQ, once it does not recognize automatically which non-modelled elements/activities are related to a modelled object. Besides, if the project differs significantly from the ones the office commonly designs, it could require the reviewing and adjusting of the filtering and mapping rules on Navisworks.

An automatized way of identifying non-modelled elements and activities expected in the coordinated specification and quantity report would represent a substantial improvement. They could be expressed in the BIM model through some custom attributes set in modelled objects which relates with the expected element/activity, or through simplified geometrical representations. Regarding custom attributes, for instance, if there is a wooden floor, the finishing material could be secured in one of them, enabling it to be expressed in the MTQ automatically. Similarly, the use of simplified geometrical representations to embody activities with no modelled expression, as the mentioned strategy adopted by BuildGest (2018), would also help to automatize the process once it stores the information in the BIM model enabling the reading of the activity by a digital solution for the purpose. These elements only need to store the classification code, allowing to query its specification information in the database.

In the "AS-IS" the reading of the quantities implies setting the units both in Navisworks and in the Database. The units in the Navisworks are those considered for the reading of the model; if the units in the database are different, they should be corrected manually, which can lead to errors. By enabling automatic reading of the expected parameters/formulas and their related units directly from one single source, the database, manual intervention is dismissed, permitting automatic according to the classification code of the object.

The user generates the quantity report on Navisworks comprising the results from the mapping rules and formulas in an Excel spreadsheet. This report presents the information in raw format, without being treated and organized by any template. By applying some Excel formulas, the data is structured following a final template and a report classification system. The use of the same classification system for the report structure, keeping consistency in terms of standards, would facilitate this step and further developments through digital platforms. MC adopts a template for the report structure that organizes the elements/activities by disciplines and groups of materials or correlated type of work, such as steel or wood. For this reason, it is necessary to map the classification code to the correspondent index of the discipline and materiality/type of workgroup. The coordination with the Excel specification database is also made possible through Excel formulas, which links the element/activity listed in the raw quantity report to the information in the database querying and matching their classification codes. For every new project, this procedure must be redone or reviewed and adjusted, at different levels of intervention, depending on the project. Even though with some degree of automatization, this task also relies on manual, repetitive and error-prone work.

Besides the core of the process already assessed above, it is primordial to check and validate the BIM model driven for specification and quantity take-off. All modelled elements and activities must have the classification code assigned, and the assigned codes need their correspondence in the specification database. At MC, they manage to identify the elements missing the classification code by scheduling lists in the authoring tool. However, they can not act similarly to check those who do not have correspondence in the database. The user performs this task manually, querying the code on Excel. A proposed digital solution could perform checking and validation automatically, just informing the user what adjustments are necessary.

The classification system based on Uniclass 2015 shared by the object library and specification database it is consistent enough to enable the degree of automatization already implemented to generate the MTQ. However, aiming to digitalize the process entirely, the rules of the suffixes added to the Uniclass 2015 code and its format are not stable; they vary in datatype and structure. It is desirable to promote some constrains and standards to conceive the suffixes that will detail an object/activity, providing more levels of classification for it.

Regarding the existing specification database, even though Excel is a powerful tool for data analysis, it is not a complete functional Relational Database Management System (RDMS) for structuring data, its integrity, and establishing relationships among different data fields. The data type controls and data validation lack some functionalities in comparison to other RDMS such as Microsoft Access or MySQL. On Excel, the information does not relate appropriately among different tables (Microsoft, 2019a). The existing specification database on Excel also presents some problems at filtering the inputs provided by the user, independently how careful the user is. There were duplicated registers, data placed in the wrong field, and data not following the constraints or validation rules required for the field. For these reasons, a more robust RDMS would match better the needs to keep and manage the specification database and connect with other BIM-based tools.

The structure of the existing specification database composed by only one table is represented by the diagram in Figure 7, which also demonstrates the arguments secured in each field of the table for a specific element. The current structure has some data issues. For example, the instances placed in the field *"KeynoteA",* which represents the classification code, and the primary key of the table (database concept for the unique identifier in a table), do not follow the same rules for the suffixes that compose their codes. It creates subjective interpretation to read and understand the levels of classification that go beyond the Uniclass 2015. Also, Some of the instances in the field *"KeynoteC"*, which secures the closest parent in the classification tree the element belongs, were wrong in some cases in which the instance above was in the same classification level.

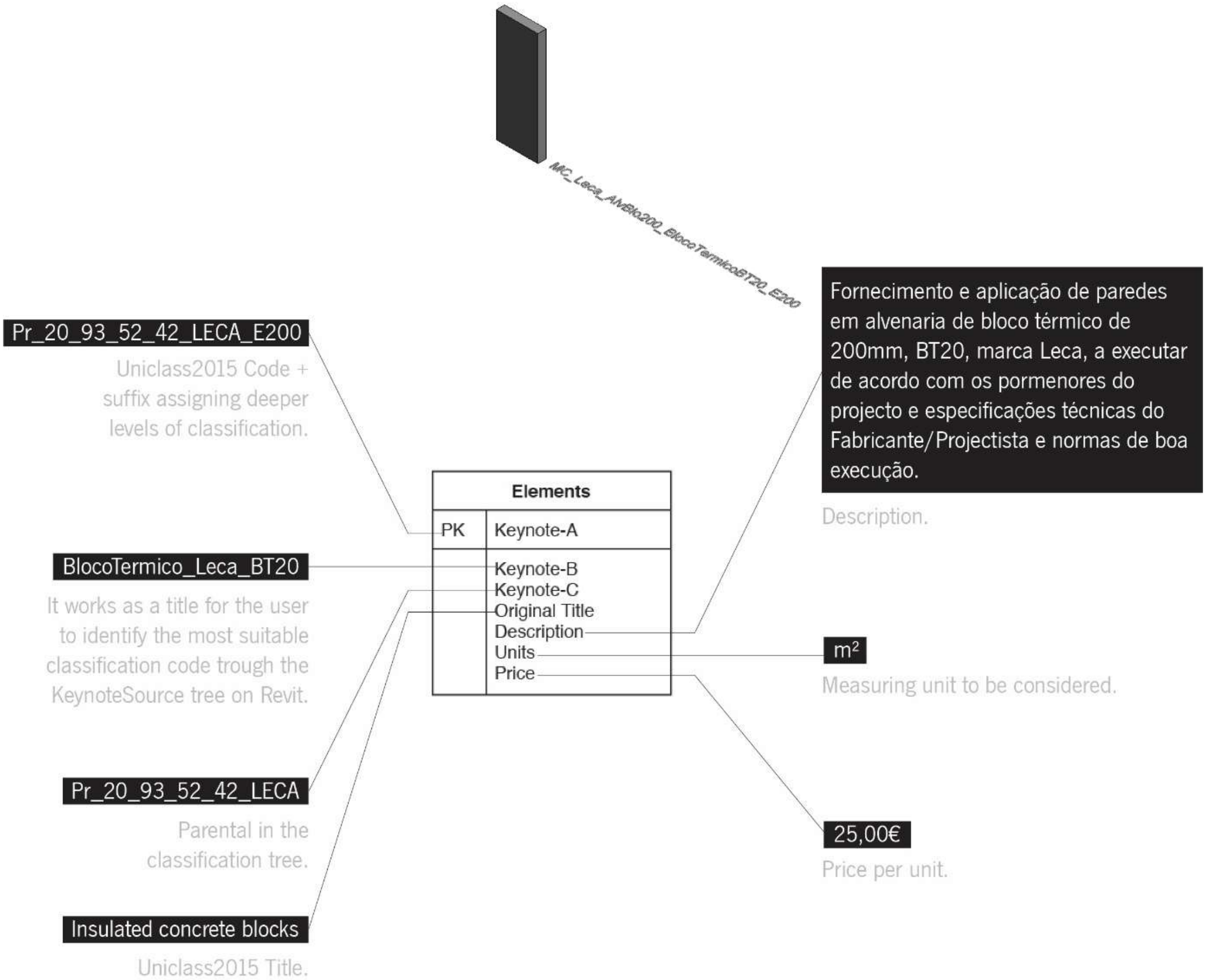


Figure 7 – Representation of the existing specification database exemplifying the content of each field.

Last but not least, this work assessed the modelling practices at MC in collaboration with the head of the company and its associates. The outcome was a table which relates the architectural elements/systems/activities to the categories defined in the authoring tool, and the measuring units to quantify them. This analysis was relevant once it exposed modelling issues and indicated how the digital solution would deal with different categories inside the authoring tool in order to extract data. The table exemplifies how the AS-IS process handled the different classes of objects considering whether there is or not a graphical representation of the required element/system/activities to extract information from them. This procedure provided a better understanding of how the firm currently drives its models to perform the BIM uses approached by this work. A sample of the table with four examples of construction elements is shown below (Table 2).

Table 2 - Driven modelling activity mapped: architectural elements x measurement units for quantity take-off x authoring tool categories

Element / Activity	**Unit**	**Authoring tool categories and observations**
Cement sand mortars	m²	Walls; Floors; Roofs; Ceilings.
Paving jointing mortars	vg (unit of a tailor-made item, such as steel or wood work)	Not graphically expressed in the model. Parameter MC_Matajuntas used for the purpose.
Clay interlocking tiles	m²/un/m	Roofs. Clay interlocking tiles: m² Roof slope ventilator tiles: m² (% of the area of the roof | Measurement input manually in the quantity report); Roof ridge tiles: m (usually it is not modelled. Measurement input manually in the quantity report); Cover stripes: un (usually it is not modelled. Measurement input manually in the quantity report).
Skirtings	ml	Wall; Wall-sweeps.

3.3. Framework for a digital solution

3.3.1. General structure

Based on the diagnosis and assessment of the current workflow, this section proposes a framework to increase the degree of digitalization for generating coordinated specification and quantity take-off report, re-engineering this business process "AS-IS" to the called "TO-BE". As observed, there were many steps in the process chain that require analogic intervention in the current workflow. The new framework cuts out those interventions and extinguishes manual intervention to perform the process as a whole, integrated, decreasing the number of steps in order to achieve the expected outcome.

A reduced number of tools required to perform a process would make it more integrated and interoperable, once it requires less glue subprocess. The framework proposes only two digital platforms to support BIM-based specification and quantity take-off: the BIM model and the database. Respectively, primary source and a complementary source of construction information (see Figure 8 – Diagram of the proposed framework for generating coordinated specification and quantity take-off report and Figure 16 – TO-BE (re-engineered) process representation). Within this work, the database stores the specification information and the estimated unit costs of each component/activity; however, it could be expanded to embed data needed for other processes, such as facility management. The generation of the MTQ will happen directly from the authoring tool.

The proposed general framework of the digital solution starts by reading an object in the digital model, communicates with the database matching the object classification code with its correspondent instance in the DB. From the DB, it gets the needed data, such as specification information, properties to be read, measurement unit, and unit estimated price. Based on the information obtained in the database, it searches for the properties which will express directly the measurement or that compose the formula to express it. Lastly, it coordinates the data obtained from the BIM model and DB into a project deliverable, the MTQ.

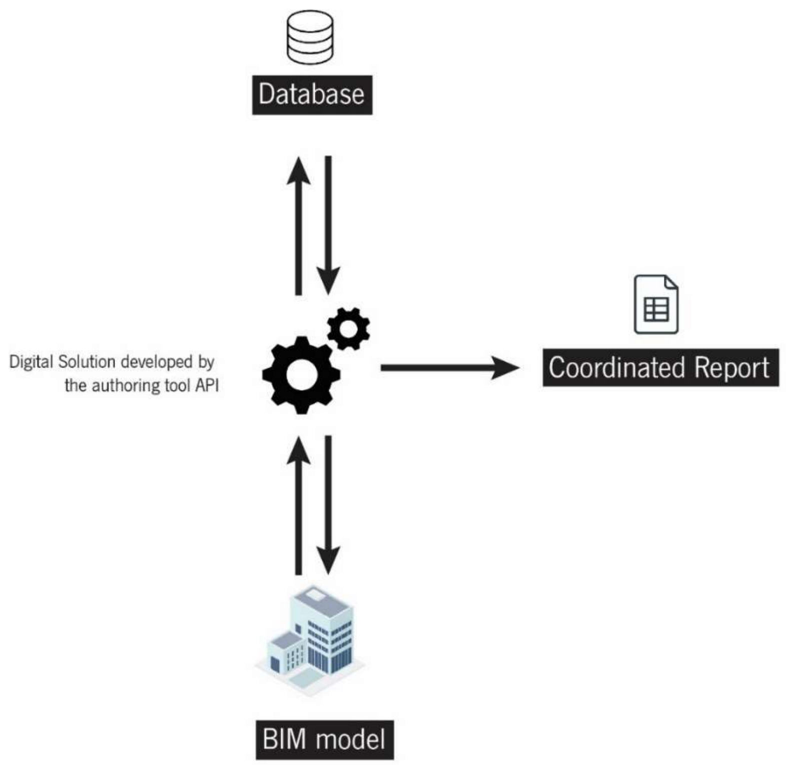


Figure 8 – Diagram of the proposed framework for generating coordinated specification and quantity take-off report

3.3.2. Information modelling issues

The proposed framework addresses the modelling issues identified in the current workflow at MC for producing BIM models driven for specification and quantity take-off.

Most of the issues have to do with elements/activities that usually do not have a graphical expression in the model, which comes to a question: how to represent them in the BIM model without spending lots of resources, such as time and money, assuring the minimal information, in the right format to be used as input for a specification and quantity take-off digital solution? Addressing those issues is the critical factor for generating useful and accurate BIM-based coordinated specification and quantity take-off reports. Usually, to deal with them, these elements/activities are handled not in the modelling stage, but within further steps in the process, meanwhile using external quantity take-off tools, such as Navisworks, or added manually during the checking and validating procedures for the final report. The intention here was to frame the data in such a way that will attend the demands of an automatized digital solution.

After assessing the modelling activities "AS-IS" and structuring the analysis results in Table 2, the author and MC team developed new strategies to address the mapped modelling issues of the surveyed architectural elements. A table was produced describing the chosen proposals to deal with each one of the construction elements. is a cut-out of the complete table, with some examples of elements, describing the chosen strategy (a sample of the complete table is shown in Table 3). For the record, 1651 construction elements were analyzed, comprising 20 model categories of the authoring tool. Depending on the element/activity, the literature review alongside the assessment led us to two leading solutions: the use of custom attributes and simplified geometrical representations.

Table 3 - Addressing modelling issues of construction elements.

Element Activity	**Unit**	**Authoring tool categories**	**Purpose-driven modelling recommendations**
Cement sand mortars	m²	Walls; Floors; Roofs; Ceilings.	Classification code applied directly to the object.
Paving jointing mortars	m²	Not graphically expressed in the model.	Create a custom material property. Choose a material from the material library assigned with a classification code.
Cement sand mortars repair	vg (unit of a tailor-made item, such as steel or	Not graphically expressed in the model.	Create a face-based simplified object with an assigned classification code, whose type will indicate what kind of intervention the host will suffer. The digital

	wood work)		solution will read the object and include the activity in the MTQ.
Filling Cabinets	vg (unit of a tailor-made item, such as steel or wood work)	Caseworks and Generic Models.	Create an assembly grouping all elements the objects that compose the desired element into one. The assembly object can be assigned with a classification code in the authoring tool.

3.3.3. Use of custom properties

For any reason, a digital modeller can choose for not modelling the paintings for a specific project (considering it would not affect the accuracy of the quantity take-off for this products) even though primer and painting must be considered in the MTQ. In these situations, the framework proposes the creation of custom attributes to secure the material applied to a surface. A classification code indexes the material in the authoring tool. This procedure allows a digital solution based on this framework to identify the correspondent instance on the database to obtain specific information for it. The quantity will show the area of the host surface. A gypsum ceiling object in the BIM model would be expressed in three elements in the MTQ, the first the ceiling itself, followed by the primer, and the finishing product (such as painting). If the painting or the primer has a geometrical expression in the BIM model, that tool will read it as a modelled object, checking its classification code directly, not being necessary for the user to assign a material to the custom parameters finishing and primer. In this case, the quantity would be precisely the area of both finishing and primer. On the other hand, if the painting or the primer are not modelled, they could be assigned through the custom material attribute created in the object that host one or both of them. The material instance correspondence in the DB would be identified and its information obtained. The host surfaces area would express the quantities for them.

Another example of using custom attributes to deal with elements with no graphical expression in the BIM model comprises the complementary accessories to execute a roof with clay interlocking tiles. These roofs, besides the interlocking tiles itself, need slope ventilator tiles, ridge tiles and cover stripes. For most BIM uses, modelling all these objects is not useful and not economically viable. Custom parameters will represent these objects. The interlocking tiles are the roof object itself, which will be read by the proposed digital solution, matching its classification code with its correspondence in the database. The ventilator tiles, which at MC are not usually modelled, therefore do not have geometrical expression, should be represented by a group of custom attributes on the roof object. The first one, *"VentilatorTiles",* is a yes or no attribute to indicate whether the ventilator tiles will be used or not in the roof. The second, *"VentilatorTiles_ClassificationCode"*, will secure the classification code for this non-modelled element, to allow the digital tool to get correspondent specification information from the DB. Lastly, the third *"VentilatorTiles_Percentual"* stores the percentual of the roof area that will be applied to quantify this element. The ridge tiles and cover stripes of the roof are count in the MTQ in a similar way.

The creation of these custom properties in the objects concentrates the information in the BIM model, avoiding the step of creating them in an external platform, which would keep the BIM model unsynchronized with the further subprocess. Due to the high level of maturity at modelling in Marta Campos Atelier de Arquitectura, some of the custom properties already existed for some classes of objects, such as MC_Acabamento1, MC_Acabamento2, MC_Primario1 and MC_Primario2 (respectively Finishing 1, Finishing 2, Primer 1 and Primer 2). However, without driving it to be used as this framework proposes, assigning classification codes at the materials. The following table shows all the proposed custom attributes to address the surveyed modelling issues, highlighting the ones that already existed in the architectural firm.

Table 4 – Existing and proposed custom attributes for the framework

Element / Activity	**Proposed Parameter to secure the non-modelled elements**	**Authoring tool categories and observations**
Finishing 1	MC_Acabamento1 Finishing1	Assemblies, Ceilings, Doors, Floors, Generic Models, Railings, Roofs, Stairs and Walls.
Finishing 2	MC_Acabamento2 Finishing2	
Primer 1	MC_Primario1 Primer1	
Primer 2	MC_Primario2 Primer2	
Jointing Mortars	MC_MataJuntas JointingMortars	Ceilings, Floors and Walls.
Ventilator roof tiles	MC_TelhasVentiladas VentilatorTiles	Roofs.
	MC_TelhasVentiladas_Keynote VentilatorTiles_ClassificationCode	
	MC_TelhasVentiladas_Percentagem VentilatorTiles_Percentual	
	MC_TelhaPassadeira VentilatorTiles	
	MC_TelhaPassadeira_Keynote VentilatorTiles_ClassificationCode	
	MC_ TelhaPassadeira_Quantidade VentilatorTiles_Quantity	
Ridge roof tiles	MC_Telhao RidgeTiles	
	MC_Telhao_Keynote RidgeTiles_ClassificationCode	
	MC_ Telhao_Quantidade RidgeTiles_Quantity	
	MC_TelhaoInicio RidgeTiles_Begininng	
	MC_TelhaoInicio_Keynote RidgeTiles_Begininng _ClassificationCode	
	MC_TelhaoInicio_Quantidade RidgeTiles_Begininng_Quantity	
	MC_Telhao3Hastes RidgeTiles_3Stems	
	MC_ Telhao3Hastes_Keynote RidgeTiles_3Stems _ClassificationCode	
	MC_Telhao3Hastes_Quantidade RidgeTiles_3Stems _Quantity	

Element / Activity	Proposed Parameter to secure the non-modelled elements	Authoring tool categories and observations
	MC_Telhao4Hastes RidgeTiles_4Stems	
	MC_ Telhao4Hastes_Keynote RidgeTiles_4Stems_ClassificationCode	
	MC_Telhao4Hastes_Quantidade RidgeTiles_4Stems_Quantity	
Restoration and reusing	MC_IntervençãoGeral GeneralIntervention	Assemblies, Doors, Floors, Plumbing Fixtures, Railings, Stairs and Walls.
Stair landings	MC_StairLanding StairLanding	Stairs.
	MC_StairLanding_Keynote StairLanding_ClassificationCode	
	MC_StairLandingArea StairLanding_Area	
Glass in panels, doors or windows frames.	MC_Material_Painel/Caixilho_Vidro GlassMaterial_PanelWindowsDoors	Curtain Panels, Doors and Windows.
Insulation	MC_Isolamento GlassMaterial_Insulation	Ceilings, Floors, Roofs and Walls.
Sloped roofs and glazing.	MC_SlopedGlazing_Area SlopedGlazingArea	Roofs.

3.3.4. Project Phases of an object

The project phases assigned to an object also comprises some issues to drive the BIM model to be used as input to generate the coordinated report. Even though the BIM model holds all the project phases, the MTQ will list just the elements/activities that belong to the phases the user wants to consider. For example, in an existing building renovation project, many elements belong to the initial construction phase and some new elements were created according to the proposed design, which makes them part of the project phase. Indeed, The MTQ will list this project phase. However, some elements assigned as initial construction, depending on some design decisions, can figure in the MTQ as well. A door from the initial construction phase could require restoration, which means that this action would belong to the project phase, even though the door itself not. The same door could be moved and installed in a different place; the activity of reusing it in a different place also counts for an accurate MTQ. To filter the objects whose phases will not be measured, but result in activities that would affect the measured phases, such as the project phase, the framework proposes to use a custom property named *"MC_intervençãoGeral"* (general intervention). This property keeps the argument that indicates whether the element is going to be restored or reused. In the figure below (Figure 9), the selected window belongs to the initial construction phase (Assigned in Portuguese as *"CONSTRUÇÃO INICIAL")*; however, it was moved from its original position and installed in a different place. For this reason, the attribute *"MC_intervençãoGeral"* (general intervention), stores the argument *"Reused"* (assigned in the example below in Portuguese as *"Aproveitamento")*.

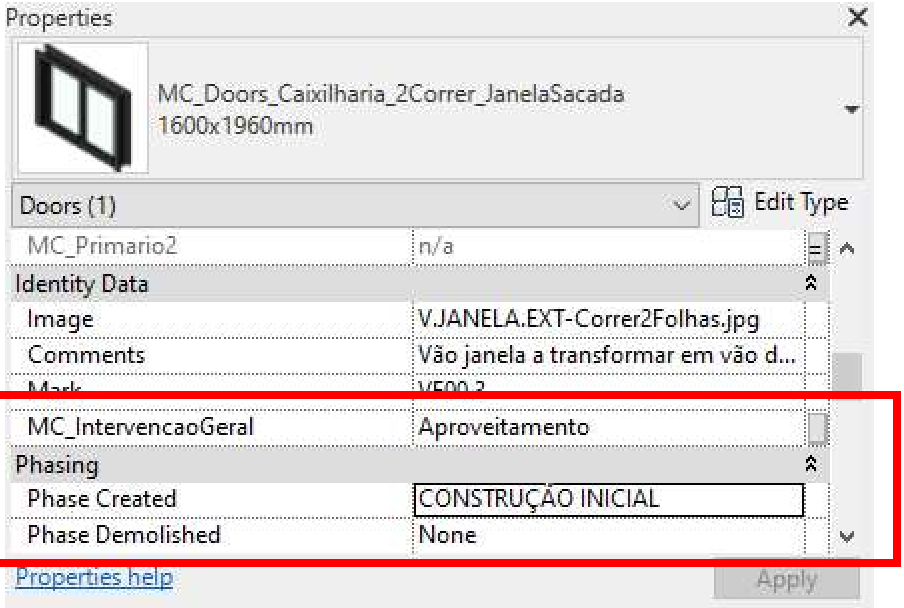


Figure 9 – MC_IntervencaoGeral (general intervention) property to indicate whether an element will be restored or installed in a different place.

The demolishment has a similar approach, playing with the phases. A wall assigned as initial construction intended to be demolished in the project phase, would generate a demolishment activity that must appear in the coordinated report. Therefore, the objects in the BIM model must indicate in the Phase demolished if there is in planned demolition for it or not. Based on this native property, a digital tool can identify a demolition activity assigned for a particular object.

3.3.5. Simplified digital representations of activities

Activities are challenging to represent once they are not objects but actions. Based on the solution mentioned in chapter 2 used by Buildgest (2018) to identify and locate interventions in a building, this framework also proposes the use of simplified objects to map the following activities: restoration, cleaning, construction site preparation, among others (the list can increase according to the demand). The objects created to represent these activities are surface-based, with a simplified geometry (a cube), named Magic Cubes, which needs a host to be placed in the BIM model. The host consists of the objects that will suffer the intervention, and the Magic Cubes type represents the intervention itself. Once they have a classification code, it is possible to determine which kind of activity they represent and establish a connection with the DB in order to get detailed information about them. This information will be exhibited in the coordinated specification and quantity take-off report. The example below (Figure 10) shows the application of the Magic Cubes for indicating the repair of steelwork fences during the modelling stage. These objects, even though geometrically expressed in the BIM model, should not be visible in the views that originate the drawings documentation. The authoring tool allows to easily set visibility filters for the views they must be hidden, individually or as a view template, assuring the produced drawings will not represent them.

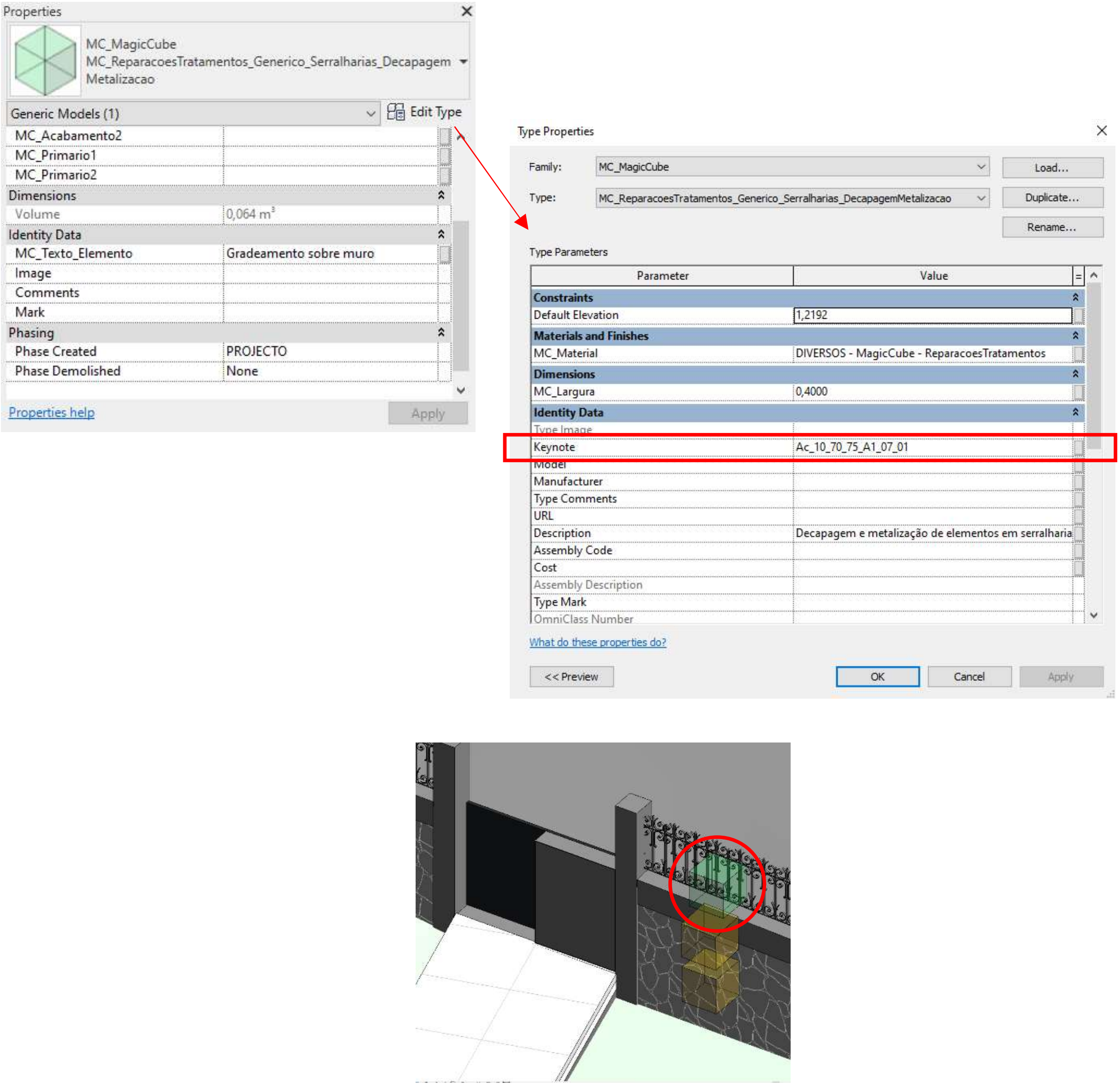


Figure 10 – Use of simplified objects to represent activities; the *"Magic Cubes"*.

3.3.6. A new structure for the classification code suffix

The existing classification system developed and used by MC, which adds a suffix to a Uniclass 2015 code, as assessed in the previous section of this chapter, lacks consistency in the suffix structure. The new framework, discussed and built during work meetings, proposes a suffix that follows the same structure as its core, the Uniclass 2015 code. Whatever classification levels that come after the Uniclass 2015 code should be expressed in two characters, and for each increased level, there will be an underscore character stating that the classification level went further. This procedure complies with Uniclass 2015, keeping the same structure. It also keeps the classification codes short enough to be readable in classification code lists. It eliminates the duplicity of information with the classification title, which is the property that informs the user what is this classification code for. The proposed format impacts in the visualization of construction drawings as well. Short classification codes tagging the elements in the drawings make them clearer and easier to read. The example below illustrates a cementitious grout object which composes a wall:

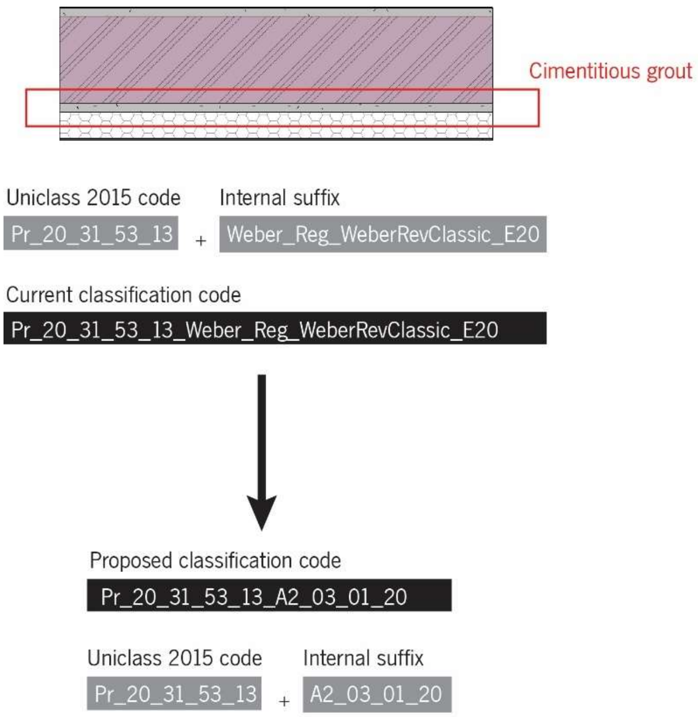


Figure 11 – Current classification code X Proposed classification code

The new classification generally has a number coding the levels. For the elements that belong to the same parent level, this number increases or expresses a dimension that different them such as the thickness. For example, similar sink taps but only with different finishings, one polish and the other satin, would have similar codes except for the last level which represents the finishing, respectively 01 and 02 ("Pr_40_20_87_84_A3_02_02_01" and "Pr_40_20_87_84_A3_02_02_02"). As the second example, the last level could also express the thickness of an element numerically. For instance, a gypsum sheathing plasterboard with 12.5mm and other with 15mm are indexed as "Pr_25_71_52_40_A1_13" and "Pr_25_71_52_40_A1_15" respectively. However, during the work meetings and from the current workflow assessment, there are three exceptions for the general use of numbers to assign a level. If an element/activity can be differentiated as generic or one that will present more classification levels, the first level (position) of the suffix will express that information by using A1 for generic elements or A2 for elements which will go further into more granularity of information. The second level will determine, whether it is necessary, if an element/activity function is exterior or interior, expressed by the codes F1 for exterior or F2 for the interior. The third and last exception places in the last classification level the corresponding code to identify if the element by any chance is reused or restored, claiming for those respective actions on it.

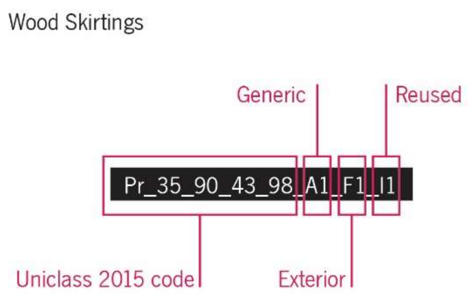


Figure 12 – Proposed classification code decomposition

3.3.7. Proposed database architecture

The Database for complementary objects information should be established in a Relational Database Management System, which is based in the Entity-relationship model. The chosen one was Microsoft Access, for being the most user- friendly database RDMS once all MC associates are familiar with other Microsoft Office software. The framework proposes a new architecture for the database structure, creating new tables and queries, with relationships among each other, according to the Entity-Relationship (ER) diagram in Figure 13. The proposed ER database structure is more complex than the existing one, which is composed of only one table. This complexity allows better management of the data, once information stored in a table can be related to another by using foreigner keys. The new database architecture comprises independent tables and on primary dependent one, the table Elements. Due to this new structure and the use of a relational model, every time they need to change or add an instance in the independent tables, elements/activities assigned with the correspondent foreigner key will have access to the updated information automatically (Watt and Eng, 2012). This organization allows, for instance, the MC team to update the Uniclass 2015 codes easily and securely every time NBS releases a new version of it. Also, The report classification system has the flexibility to align with the Uniclass 2015 system or to follow a different system according to the firm´s necessity.

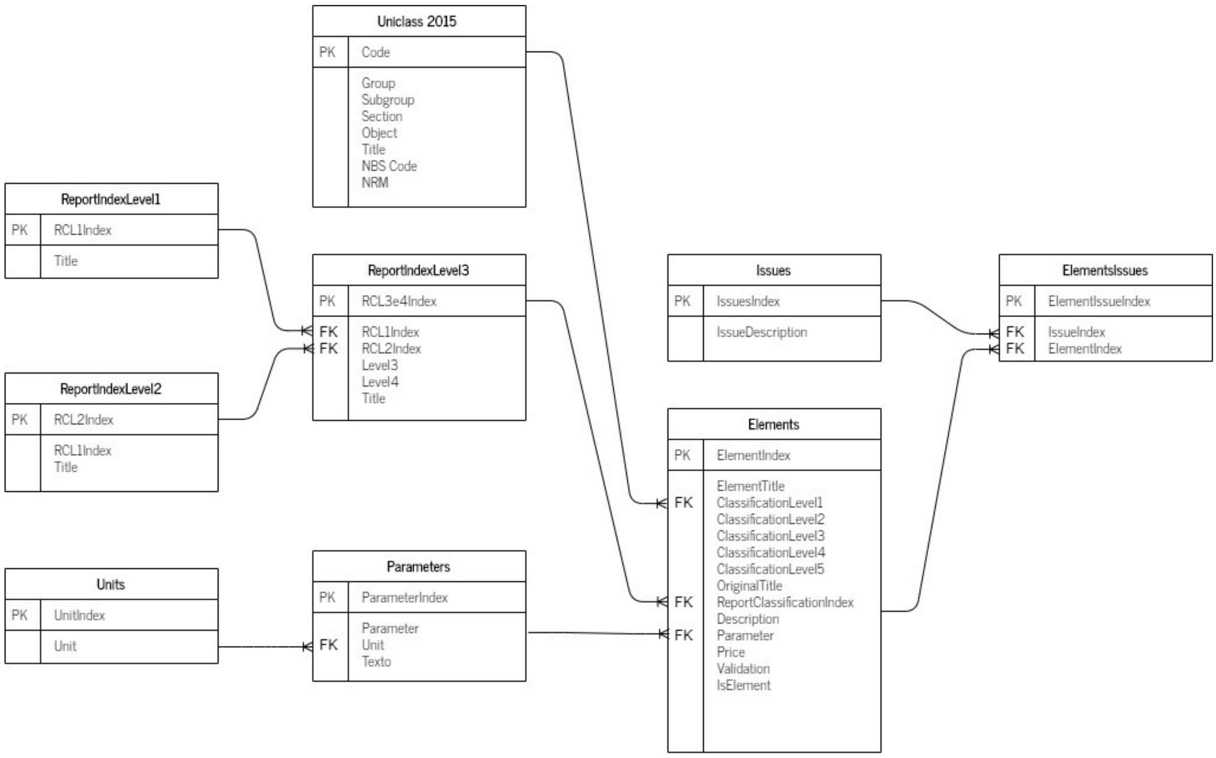


Figure 13 – Proposed database architecture represented in an Entity-Relationship diagram.

A Graphic User Interface (GUI) provides a more straightforward way of managing the data in the DB. The chosen RDMS, MS Access, has the functionality to create forms in order to manage the database, its tables and queries. The table elements, which represents the entity “elements”, is the core of the DB, depending on almost every other table in the DB, comprising this dependence into the foreign keys from other entities. For this reason, it was created a GUI in MS Access form to manage the information in this table. Besides, a second form was developed to search and navigate through the instances of the elements on the database. The idea was to provide a friendly interface that allows MC team to work simultaneously in the authoring tool, developing the BIM model, and managing the database, as a cyclical process. Modelling activities, for instance, require to query the instances in the database to assign the correct classification code in a particular object in the BIM Model; Also, sometimes it is necessary to include a new instance in the database that matches appropriately with a BIM object. During the development of the GUI and work meetings, several enhancements were tested and discussed in order to make this contemporary work practical and efficient. The achieved results are show in the figures 14 and 15.

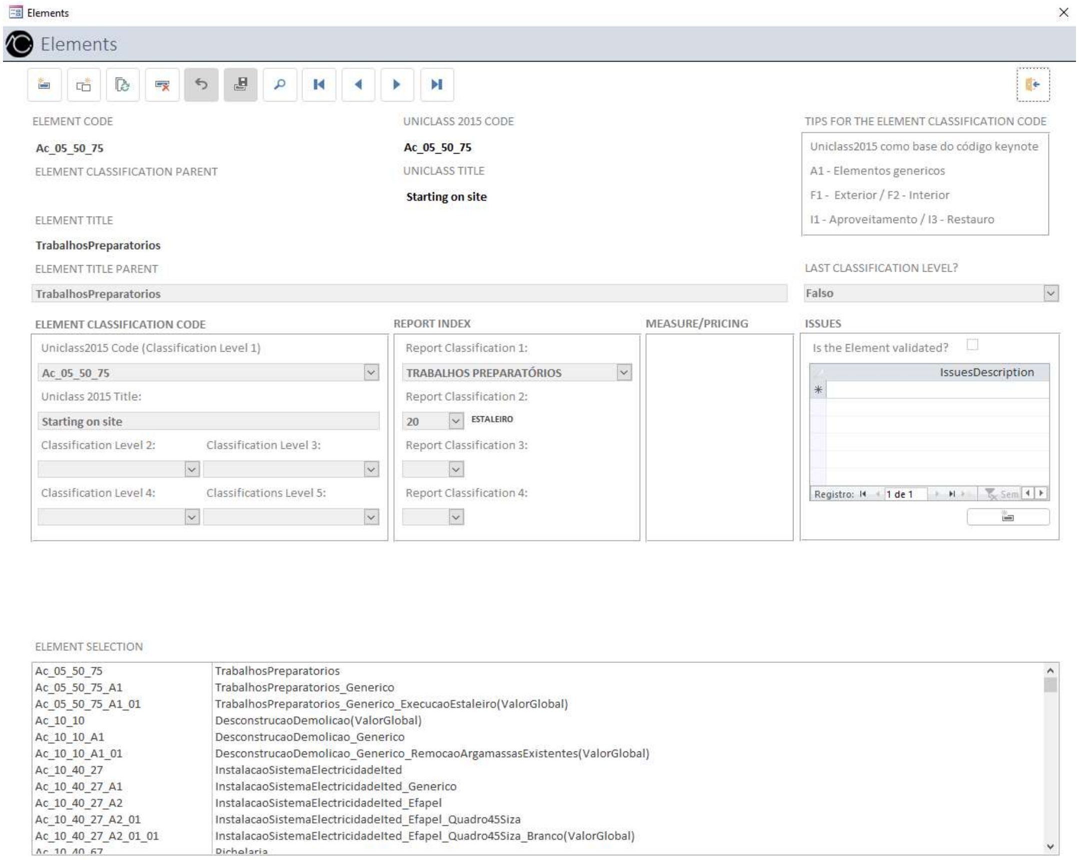


Figure 14 – Elements Form: GUI for managing elements/activities in the database

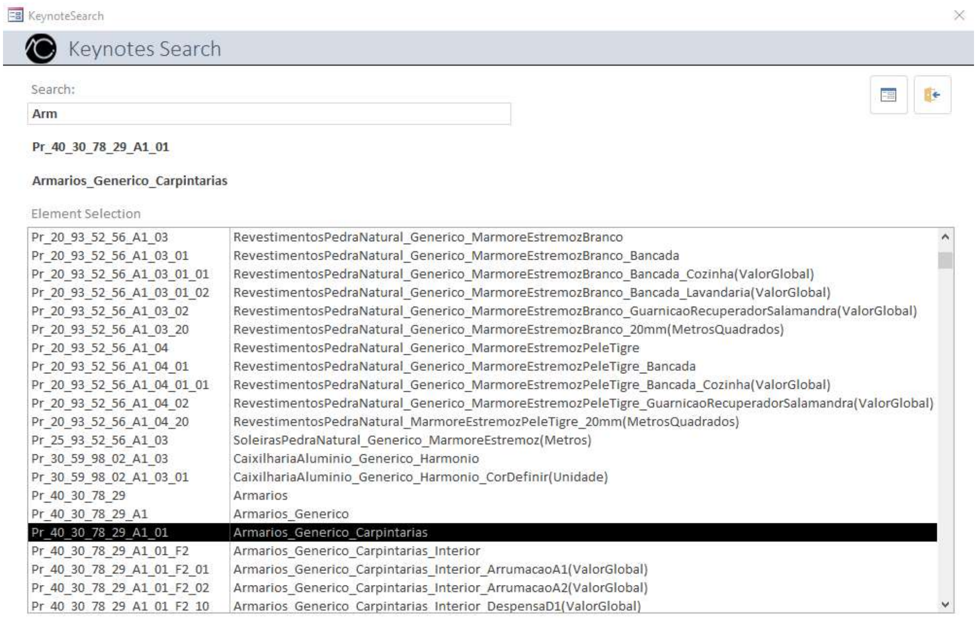


Figure 15 – Classification Code Search Form: GUI to easily query and search for a specific element instance in the database.

3.4. To-Be process (re-engineered) for generating coordinated specification and quantity take-off report

The re-engineered process for generating a coordinated specification and quantity take-off report comprises the current workflow diagnosis, its assessment, and the proposed framework addressing the identified issues to perform it in a higher degree of digitalization. The process diagram in the following page expresses the process as to-be as described in the previous sections.

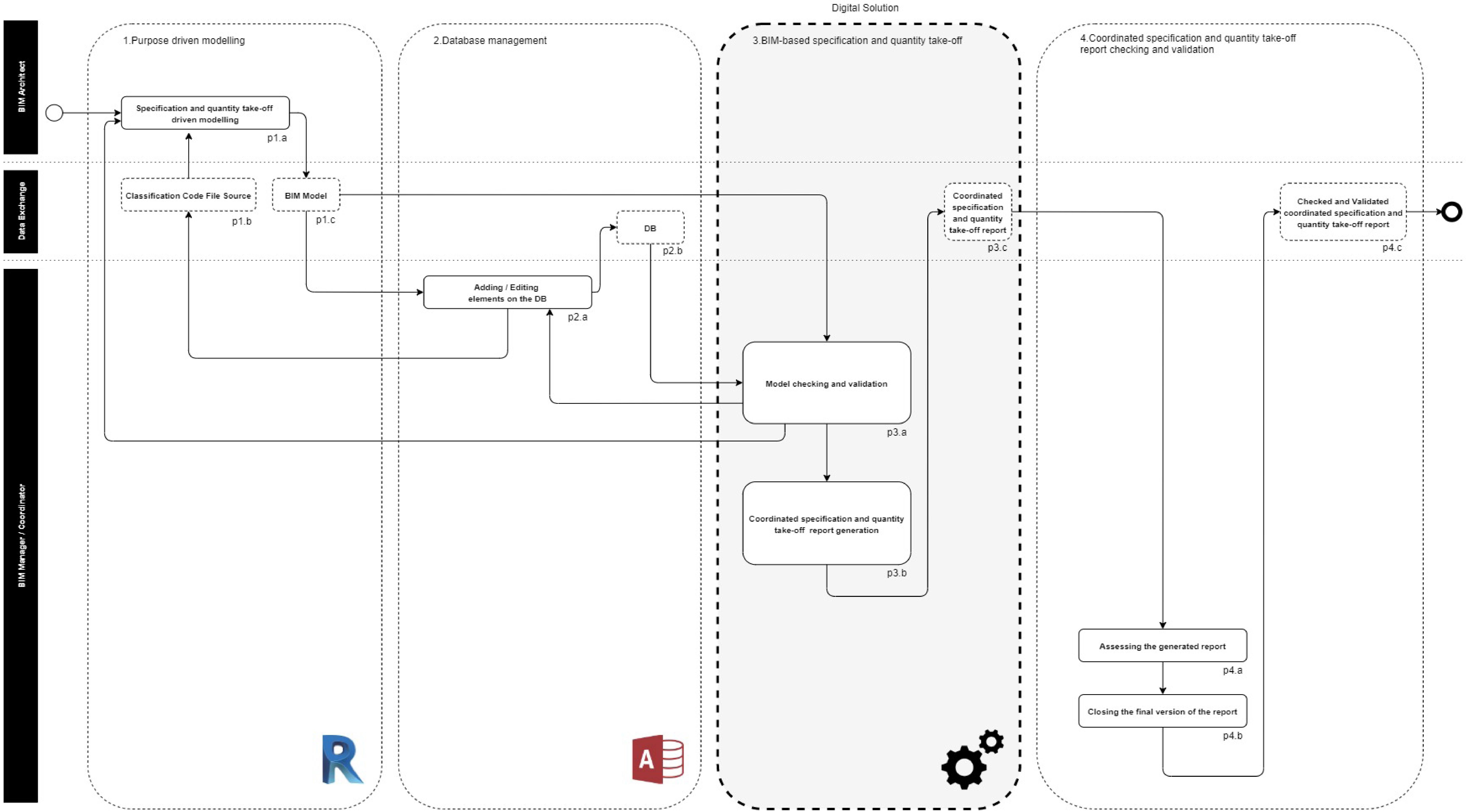


Figure 16 – TO-BE (re-engineered) process representation

4. FRAMEWORK PROGRAMMING: DEVELOPMENT OF AN ADD-IN

The digital tool for the automatized and coordinated specification and quantity take-off (enabling preliminary architectural cost estimation) report relies on the Application Programming Interface (API) of the authoring tool used by Marta Campos Atelier the Arquitectura, Autodesk Revit 2020 ®. The Autodesk Revit 2020 API is an intermediary software that enables information exchange between two different applications (Jalaei and Jrade, 2014). It is a powerful resource for users and developers to create applications aiming to the extent the core functionalities of the authoring tool. For this reason, these applications are referred to as Add-ins and Plug-ins. Their modules of algorithms communicate with the authoring tool through its API. (Jalaei and Jrade, 2014). Revit API works with applications developed in .NET compliant programming languages such as VB.NET, C# and C++/CLI (Carvalho, Bragança and Mateus, 2019).

The development of an add-in trough different programming languages than the ones mentioned above is possible and expands the possibilities for users and developers; however, it depends on using an interpreter. Python programming language, for instance, has an open-source implementation, the IronPython (NET Foundation, 2020), that interprets Python into the .NET framework. Even though Revit API does not communicate with scripts written in Python natively, some free and open-source add-ins, such as pyRevit© (Iran-Nejad, 2020), enable the exchange of information between them working as an IronPython interpreter. Once this tool has considerable documentation available, and due to some basic background of this author at programming in Python acquired during the BIM A+ Master Program, this was the language chosen to develop the Add-in.

At the beginning of the programming activities, three milestones were established as critical to the feasibility of the development of the add-in, considering the proposed framework for generating coordinated specification, quantity take-off and cost estimation report, the time available, and the thesis author´s previous background at programming. The dissertation milestones were (i) the extraction of information from the BIM model, (ii) the establishment of a connection with the database, querying and obtaining information from it, and lastly (iii) the coordination of this information into an external file report. The author focused on achieving these milestones once they were considered as the most challenging aspects for conceiving the digital tool in terms of coding. The programming stage started by researching the documentation available about ways of achieving the mentioned milestones, coding and testing possible solutions for them.

During the first stages of the add-in development, most of coding and testing were performed simultaneously by using some simplified BIM models containing just a few objects from the MC object library. The whole process started focusing on only one object class, the walls; however, new object classes were step by step added to attain growing complexity, in the end, all the object classes of the authoring tool assessed in Table 2 were covered. The database migration from MS Excel to MS Access also happened in parallel, growing according to the demands for testing the digital solution. In these first stages expected errors were simulated, to drive how the developed digital solution would deal with them (objects not classified, without correspondence in the DB, attribute assigned to read the quantities not found in the object). Once the scripts from both modules were able to process all the assessed object classes, performing the expected workflow, the tests with real case scenarios started.

As the programming stage was progressing, the need for naming the add-in came-up. The name TIE was the chosen one. TIE stands for something that connects and unites, which is an allegory for what it performs: ties information from the BIM model and a DB. It also fits as an anacronym for Technical Information Exchange.

TIE has two modules. The first one (module 1) for checking and validating the BIM model and the second (module 2) generates the coordinated report for specification and quantity take-off, the MTQ. As mentioned, the core of the two modules was written in Phyton. However, during the add-in development the necessity of using a GUI was noticed, once some user inputs were needed. For this reason, the add-in also relied on Windows Presentation Foundation (WPF) which is user interface (UI) framework to develop desktop client applications for Windows (the same Operational System that the authoring tool runs) (Microsoft, 2019). The WPF employes Extensible Application Markup Language (XAML) to define and link the user interface, dealing with the appearance of the application. The Python scripts perform the code-behind the UI.

PyRevit allowed the creation of personalized tab, panel and buttons inside the authoring tool. The last ones, when pressed by the user, execute the scripts.

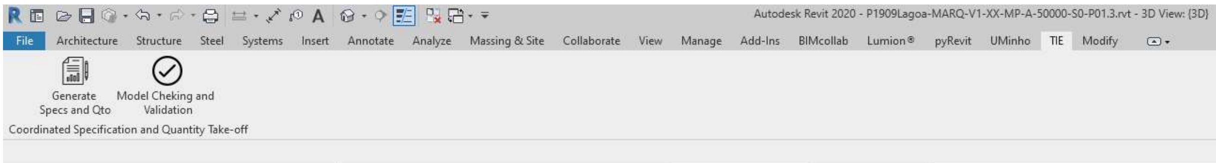


Figure 17 – TIE tab, panel and buttons.

4.1. Module 1: checking and validation

Module 1 *"Checking and Validation"* runs four main verifications that identify informational modelling and database management issues that will affect the accuracy of the MTQ. It gets all the model objects from the BIM model, allowing the user to filter them by the project phases. The filtered list of objects goes through the routines of checking and validation. The add-in places the issued objects in four specific lists, three of them representing found problems and the fourth providing an extra verification for information modelling. They are respectively (i) objects not classified by classification code, (ii) objects without correspondence in the database, (iii) objects without the attribute assigned in the DB for reading the quantities and (iv) object assigned as demolished. In the end, TIE module 1 also provides to the user a visual confirmation of the issues, once as the script runs, it hides the elements without issues temporally, leaving on the screen just the ones that need some information input. The general flowchart of TIE module 1 is illustrated below (Figure 18).

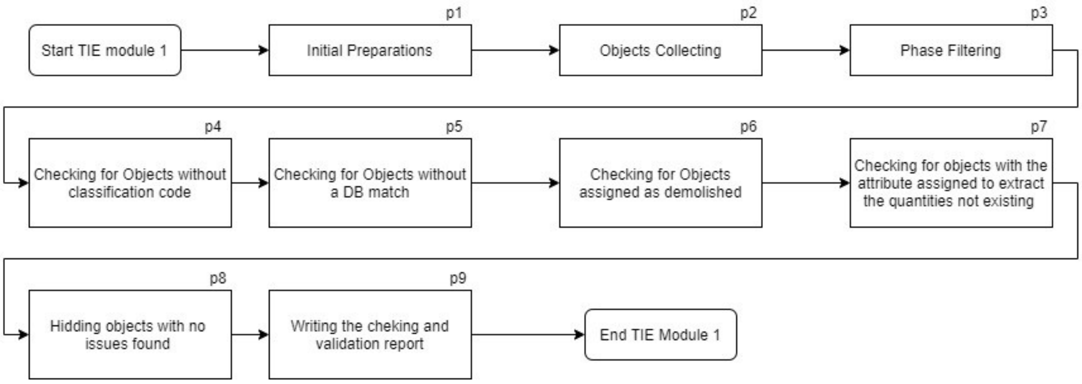


Figure 18 - General flowchart of TIE module 1

The first lines of code set libraries and modules needed to establish the information exchange with the authoring tool and get the active document (project file that corresponds to a BIM model), which is the one TIE will process (Figure 19, p1 and p2). The script collects a list of objects from the BIM model following filters previously defined. During the weekly work meetings, as described in chapter 3, section 3.2, a vast amount of architectural construction elements specified by MC team was assessed and classified into the authoring tool native categories (See Table 2, section 3.2). The first filter collects only the objects from model categories comprised in the inventoried architectural construction elements according to the developed assessment. At the moment, the code allows the add-in to process the following categories: Assemblies, Ceilings, Curtain Wall Mullions, Curtain Wall Panels, Doors, Fascias, Floors, Generic Models, Gutters, Plumbing fixtures, Railings, Roofs, Roof Soffit, Specialty Equipment, Stacked Walls, Stairs, Stair Railings, Walls, Wall Sweeps and Windows. This filter narrows downs the number of elements analysed by the script, collaborating to its performance, once it avoids unnecessary processing of elements not contemplated by the architectural discipline, or elements from annotation native categories, such as levels, sections, and elevations(Figure 19, p3).However, the list of native categories can incorporate new items by quickly adjusting the script, matching other disciplines needs, such as MEP or structural engineering, without interfering in the core of the code.

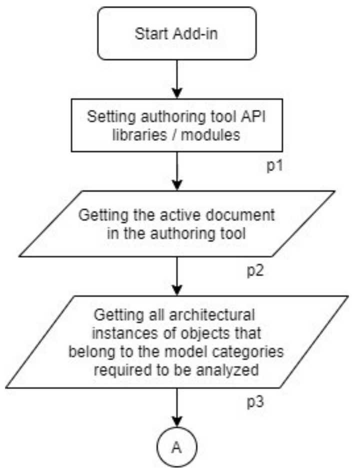


Figure 19 – TIE Module 1 flowchart: first steps of the script

In the next step, the script pops up a window (a UI developed in WPF/XAML) which requests the user to select the project phases he wants to include in the checking and validation (Figure 20). The script reunites all the project phases attributed to the project in the authoring tool (Figure 21), lists them, allowing the selection through checkboxes. When the selection by the user is complete, he gives the command that will start the core processing of the script. Only the elements that belong to the selected project phases will compose the list of elements that will be analyzed by the code.

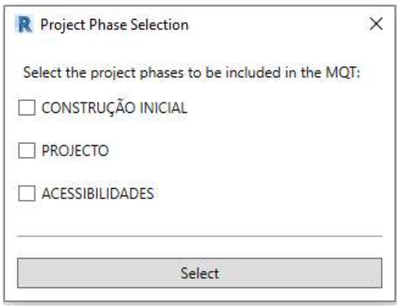


Figure 20 – Pop-up window allowing the user to select the project phases he wants to analyse.

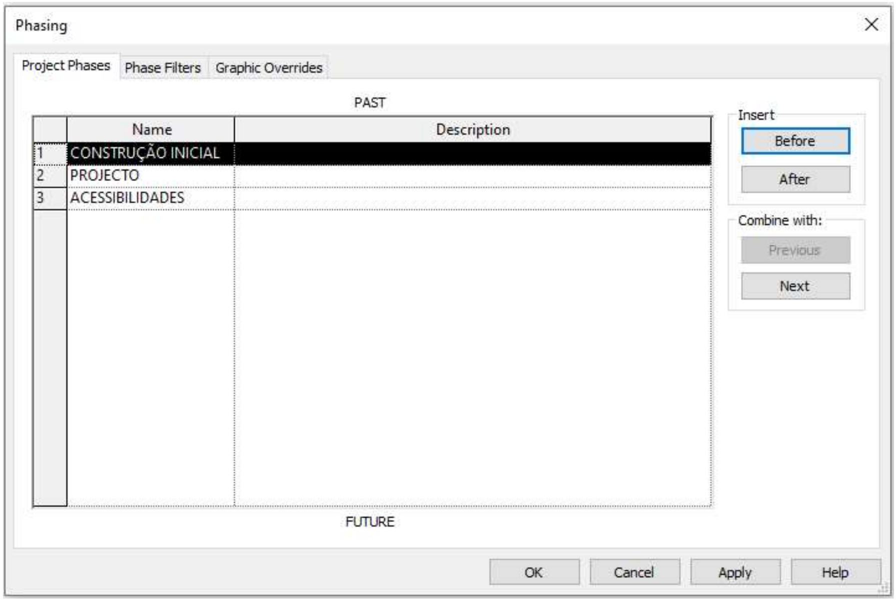


Figure 21 – Project phases manager in the authoring tool.

The following image (Figure 22) illustrates the flowchart for the phase filtering inside the script code:

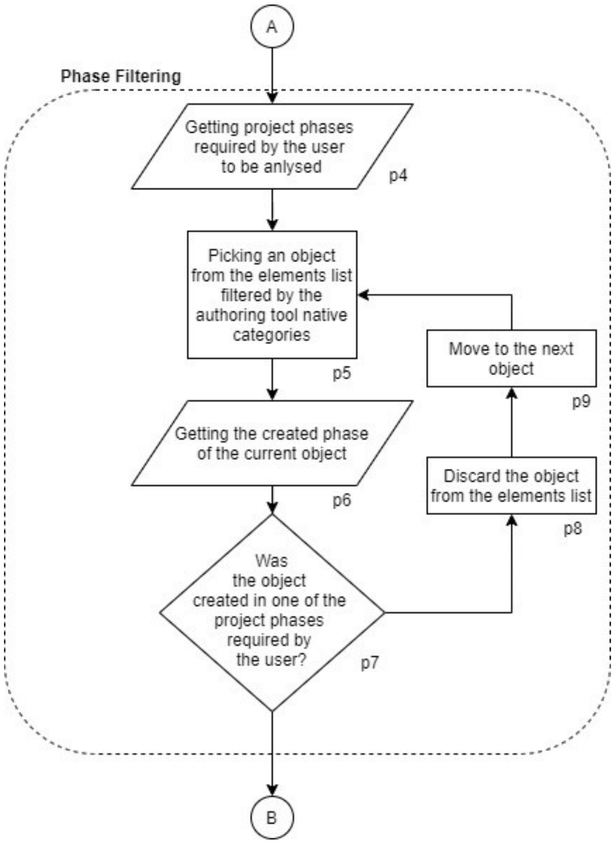


Figure 22 - TIE Module 1 flowchart: phase filtering

The first main routine (Figure 22) separates in a list all the objects from the filtered elements list assigned as demolished in the native attribute *"Phase Demolished"*. This function provides in the "*Checking and Validation*" report a panorama of all demolished elements, allowing the user to assess if any object was assigned as demolished by mistake or if some demolitions assignments are missing (Figure 23, processes from 10 to 12). Further in the script, the elements discarded by process "p8" in Figure 22 have also their native attribute *"Phase Demolished"* checked. This procedure is necessary once even if an object was created in project phase not required by the user, being discarded by the phase filtering, this object could be assigned as demolished in one of the required phases. If this is the case, the script will move the object from the discarded elements list to the list of demolished ones.

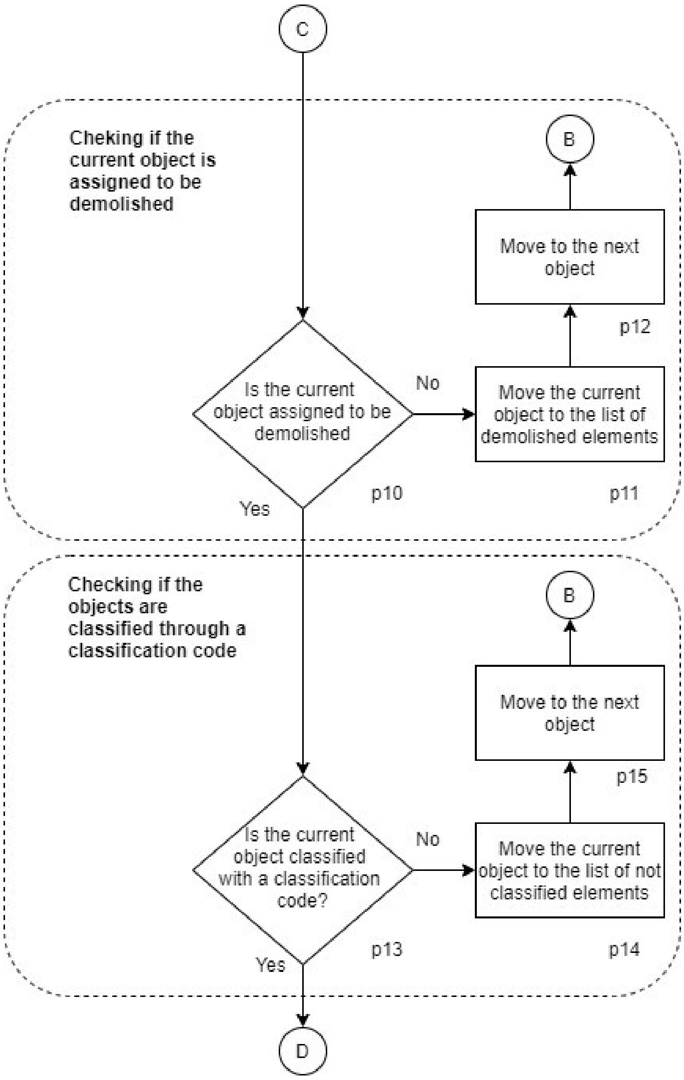


Figure 23 - TIE Module 1 flowchart: checking elements assigned to be demolished and elements not classified through a classification code

The following step, the second main verification routine of the script, verifies if all objects of the filtered elements list have a classification code assigned in the authoring tool native parameter "*Keynote*" (Figure 23, processes 13 to 15). This verification is necessary once the module 2, responsible for generating the report, will not be able to find a correspondence for the object in the database without reading the classification code. The script identifies the objects without a classification code, and store them in a list of not classified elements.

The third verification goes through the elements that have a classification code assigned and looks for their correspondence in the database. The script filters the objects whose assigned classification code does not match with any instance in the database, moving them to the list of elements without correspondence in the DB (Figure 24). It would require from the user the inclusion of a new element item in the DB, or it would indicate that the object has an incorrect classification code assigned

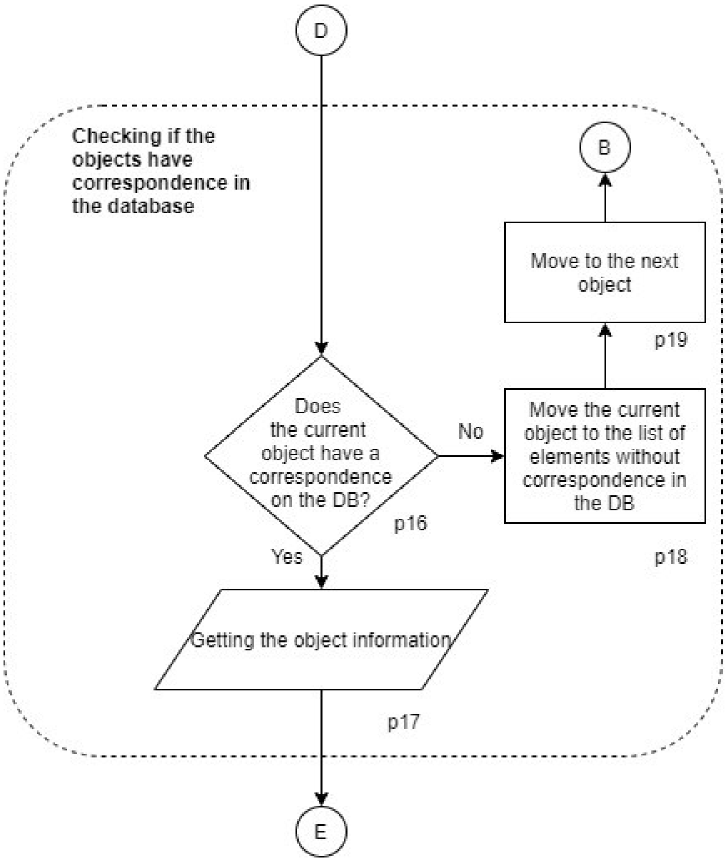


Figure 24 - TIE Module 1 flowchart: checking if the objects have a correspondence in the database

The fourth and last main function of the script handles the objects that have a classification code assigned and the proper correspondence in the database (Figure 13, subsection 3.3.7). From the DB, the script gets the attribute that should be considered for the quantities extraction. TIE Module 2 will not measure the expected quantity if the attribute assigned in the database does not exist in the object. For example, if the database indicates the property thickness to be read for an assembly of cabinets, the script will look for this property in the object and will not find it, once this attribute does not apply for assemblies. The quantity will appear in the final coordinated report highlighted to inform the user that there is an error. This function verifies if the property expressed by the database exists in the object. If not, the issued objects are grouped in a list to inform the user about the problem in the checking and validation report (Figure 25, process p22). At the end of this function, the script hides temporally from the screen all objects processed correctly by TIE module 2 with no issues found. On the other hand, the objects that presented some issue are kept on the screen for visual identification (Figure 25, process p21).

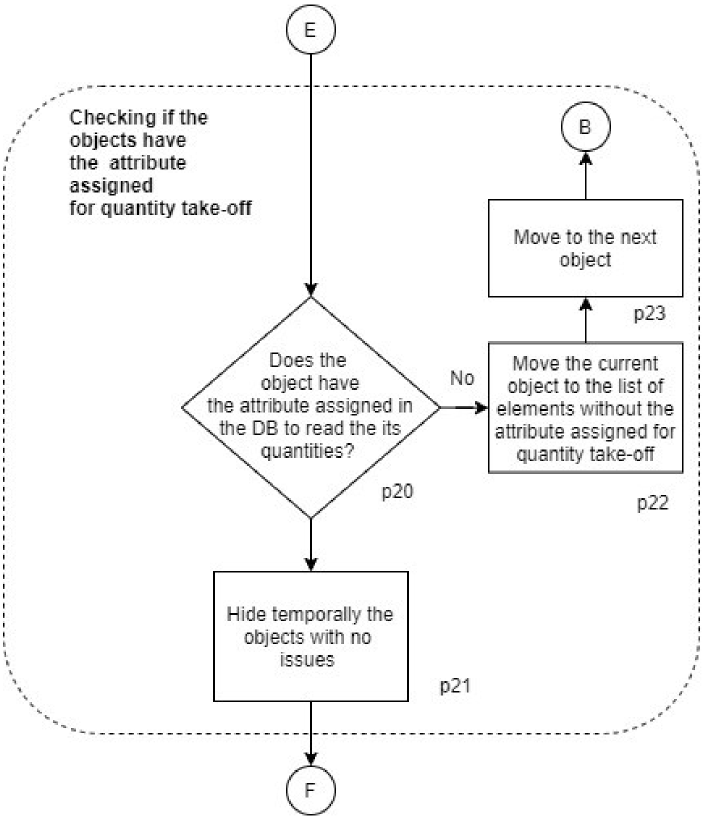
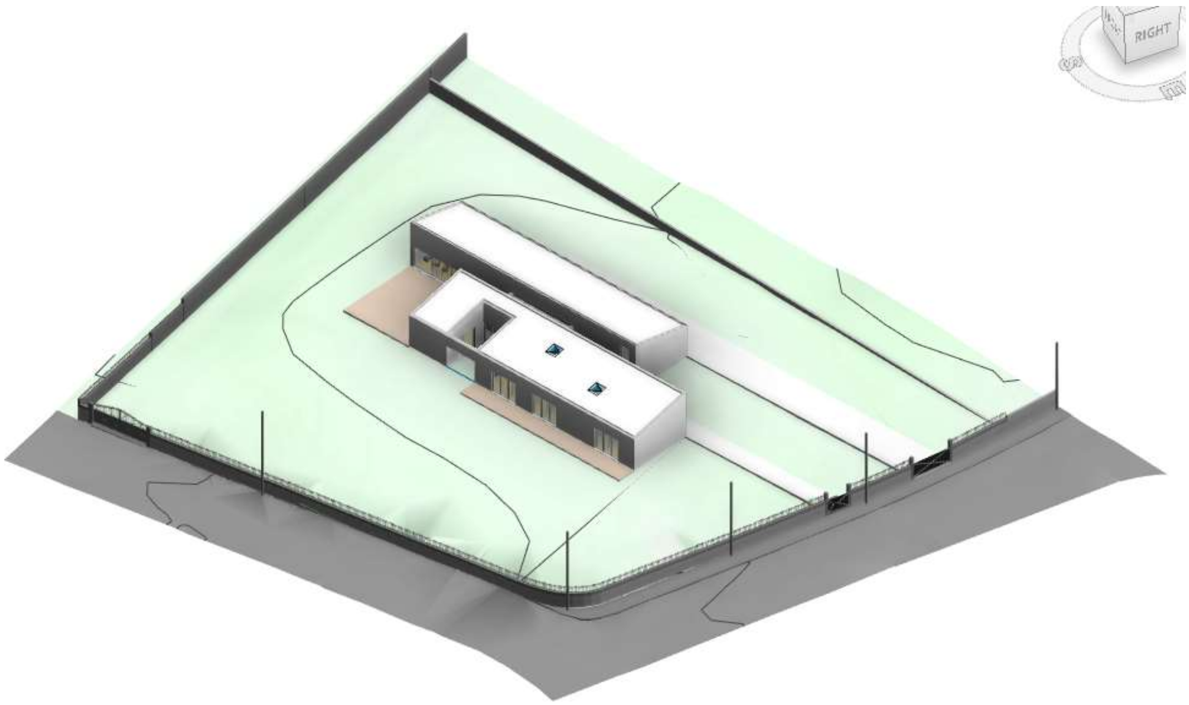


Figure 25 - TIE Module 1 flowchart: checking if the objects have the attribute assigned for quantity take-off.

After running the four main routines, the script of TIE module 1 generates a checking and validation report listing all the found problems. Four sections structure the report, one for each dealt issue: elements with no classification code, elements with no correspondence in the database, elements assigned as demolished in the selected project phases, and elements whose property intend to express the quantities indicated in the database does not exist. The report lists the elements, showing their id, category, family name, and type name, which makes more practical for the user to identify and find them in the BIM model (Table 5). On the screen, all elements with no issues are temporally hidden by the script, resting only the ones that needed to be adjusted



(Figure 26 – Visualization before running the Checking and Validate module).

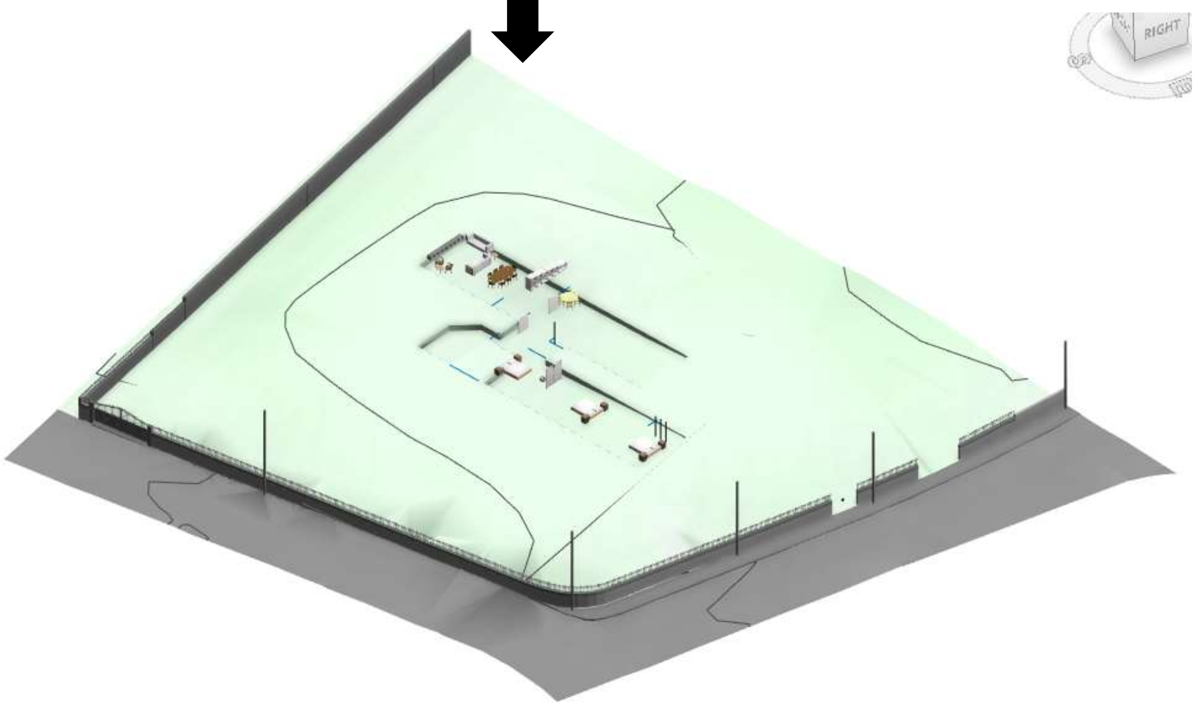


Figure 27 – Visualization after running the Checking and Validate module.

Table 5 - Checking and Validation report informing the users about the found issues

Id	Category	Family Name	Type Name
Elements not classified			
1846885	Ceilings	Compound Ceiling	MC_ALev48_EstruturaMontanteLaRocha30k48_E48
2270375	Curtain Panels	Painel de sistema	MDF_RAL9010_40mm
2678276	Curtain Panels	Painel vazio	Vazio
2678279	Curtain Wall Mullions	Rectangular Mullion	MC_Zinco camarinha_500x30mm
2439914	Doors	MC_CwDoors_PainelLiso_PuxadorHorizontalVertical_OffsetExterior	Metal_PretoRAL9011_E35
2439739	Doors	MC_Doors_CaixaCorreio_CaixaSerralheiro	CaixaCorreioVertical_260x350x170
2437236	Doors	MC_Doors_CaixaCorreio_FrenteSerralheiro	único
1814076	Doors	MC_Doors_Vao_Rectangular	1000x2000
1805479	Doors	MC_Doors_Vao_Rectangular	1000x2085
2698270	Doors	MC_Doors_Vao_Rectangular	1140x2085
1806096	Doors	MC_Doors_Vao_Rectangular	1800x2000
1806126	Doors	MC_Doors_Vao_Rectangular	1800x2085
2709646	Doors	MC_Doors_Vao_Rectangular	2000x2000
2629921	Doors	MC_Doors_Vao_Rectangular	2000x2085
2706129	Doors	MC_Doors_Vao_Rectangular	2500x2085
1807653	Doors	MC_Doors_Vao_Rectangular	3000x2000
1807404	Doors	MC_Doors_Vao_Rectangular	3000x2085
2709644	Doors	MC_Doors_Vao_Rectangular	6293x2000
2709659	Doors	MC_Doors_Vao_Rectangular	6293x2085
1798461	Doors	MC_Doors_Vao_Rectangular	7893x2000
1798210	Doors	MC_Doors_Vao_Rectangular	7893x2085
2709647	Doors	MC_Doors_Vao_Rectangular	900x2000
2709661	Doors	MC_Doors_Vao_Rectangular	900x2085
1805092	Doors	MC_Doors_Vao_Rectangular	900x3545.7
1805159	Doors	MC_Doors_Vao_Rectangular	900x3630.7
1804884	Doors	MC_Doors_Vao_Rectangular	9960x800
2441849	Doors	MC_PortaoHomem_CaixaTecnica	Unico

2440332	Generic Models	Model Text	80mm Arial
2282332	Roofs	Basic Roof	MC_Gen_E250
2413641	Walls	Curtain Wall	Parede cortina base
2682707	Walls	MC_VoidPala	MC_VoidPala
Elements without correspondence in the database			
2122077	Roofs	Basic Roof	MC_ALev48_EstruturaMontanteLaRocha30k48_E48
Demolished elements			
2361822	Railings	Railing	MC_Lagoa_ PostesVerticaisCornucopias
2361849	Railings	Railing	MC_Lagoa_ PostesVerticaisCornucopias
2361864	Railings	Railing	MC_Lagoa_ PostesVerticaisCornucopias
2410467	Railings	Railing	MC_Lagoa_ PostesVerticaisCornucopias
2412427	Railings	Railing	MC_Lagoa_ PostesVerticaisCornucopias
2347353	Walls	Basic Wall	MC_AlvPed_AlvenariaGranito220_E220
2347357	Walls	Basic Wall	MC_AlvPed_AlvenariaGranito220_E220
2347365	Walls	Basic Wall	MC_AlvPed_AlvenariaGranito220_E220
2347369	Walls	Basic Wall	MC_AlvPed_AlvenariaGranito220_E220
2411428	Walls	Basic Wall	MC_AlvPed_AlvenariaGranito220_E220
2410265	Walls	MC_Muro2	Unico
2411837	Walls	MC_Muro3	Unico
Attribute for extracting quantities assigned in the database not found in the object			
2226153	Doors	MC_Doors_SoleiraPingadeira_EncaixeExt-RecorteInt-RecortePingadeira	Estremoz_2000x330

4.2. Coordinated specification and quantity take-off generation module

The module 2 is responsible for generating the coordinated specification, quantity take-off and cost estimation report. For the execution of this module, even though recommendable, it is not mandatory to run first the checking and validation module. This option provides flexibility for the user, once it is possible to generate preliminary versions of the report, while designing/modelling/cost estimating. For this reason, the coordinated report also deals with the issues managed in the checking and validation module, informing the user of the problems found by highlighting them in yellow.

The general process of TIE module 2 (Figure 28) is described next. It collects the model objects from the BIM model, filtered by their types and project phases. The script gets their classification codes and looks for their correspondence in DB, obtaining their correspondent information. After, it extracts the quantities from the BIM model. The matched information obtained from both the BIM model and DB is coordinated and combined into a list. TIE module 2 reorders and organizes this list based on the classification codes and the MTQ template used by MC, generating, in the end, the coordinated report for specification, quantity take-off and preliminary estimation cost.

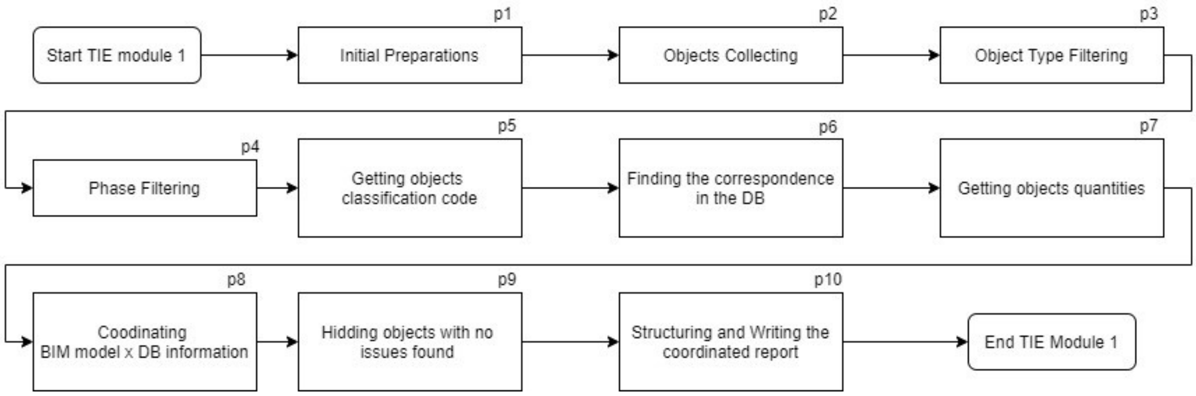


Figure 28 – General flowchart for TIE module 2

The script of the report generation starts by setting the libraries and modules to establish communication with the authoring tool (

Figure 19). It collects the elements in the BIM model, similarly to module 1, filtering them by the model categories required by the user through the UI (Figure 20) to be included in the final report (as referred in section 4.1). The phase filtering can be represented by the same flowchart used do illustrate this routine on module 1 (Figure 22).

From this point, the script of module 2 differs and gets more complex in comparison with module 1. A second UI window based on WPF and written in XAML pops up on screen requiring the user to select the object types he wants to include in the MTQ. The window presents a list of elements in which each one of them can be checked/unchecked (Figure 29). The selection made by the user filters the list of elements, based on the object types according to the user´s convenience. Besides the flexibility for filtering, this step proved necessary to deal with the called nested families and the assemblies objects in the context of the used authoring tool. A nested family consists of an object included inside another object (here called "parent object"). For instance, A door which is composed of the door leaf, the door frame, the door handle as single objects is a parent object. In this case, the add-in would read four elements, the parent object (door with nested objects), the door itself, the frame and the door handle. However, through the object type filtering window, the user has the choice to consider only the parent object to be computed or the individual elements. It would result respectively in 1 or 3 elements in the MTQ. For the assemblies, the add-in behaves similarly. In the authoring tool, the assemblies combine different objects into an assembly which can be identified, classified, quantified and documented as a single object (Autodesk, 2020). After the user input, the resulting elements list will contain only the object instances that belong to the selected object types. The script flowchart for filtering the objects by their types is shown below (Figure 30).

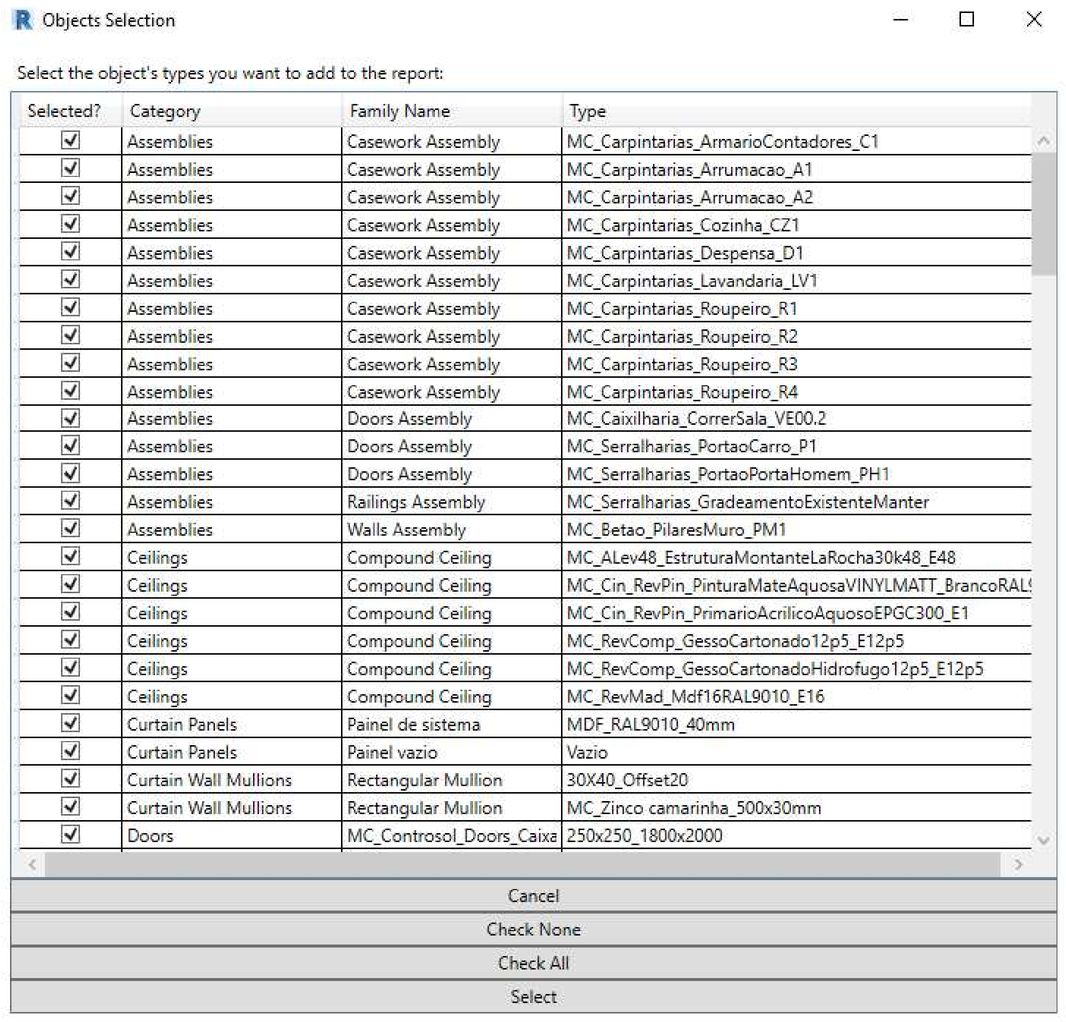


Figure 29 – Object´s type selection UI window.

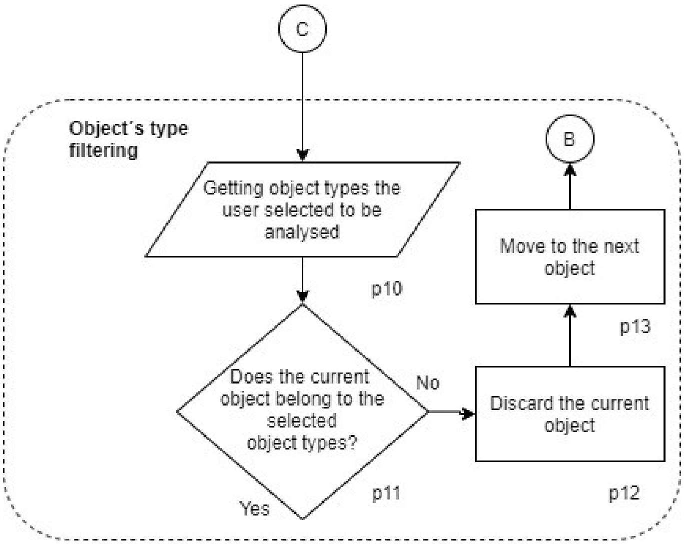


Figure 30 – TIE Module 2 flowchart: Object type filtering

The third step is a phase filtering similar to the one described for module 1; the user filters the elements from the resulting list of the previous step by their project phases. Through the UI already mentioned in section 4.1 (Figure 20), the user selects from the existing phases for that specific project the ones he wants to include in the coordinated report, the MTQ. After pressing the button Select, the resulting elements list starts being processed by the core routine of the script (see flowchart in Figure 22).

The core routine of TIE module 2 script is structured in a looping which processes each one of the elements/activities in the filtered list. The looping starts by filtering and separating in a specific list the objects that are assigned to be demolished in one of the project phases selected by the user (Figure 23, processes p10 to p12). Next, it looks for the object classification code. If the object is not classified, it goes to the list of not classified objects, and the script moves the next one (Figure 23, process p13 to p 15). On the other hand, if the classification code is assigned, the script connects to the DB and query for a correspondent instance. A new conditional verification is performed to verify if the correspondence was found or not. The elements without correspondence go to the list of elements without database correspondence. If the classification code matches a correspondent instance in the DB the script collects a set of information that comprises the report classification levels of the element, the specification description, the attribute assigned to read the quantities in the BIM model, the measurement unit and its unitary price. The information obtained from the DB is attached to the element item in the list, coordinating the data extracted from both BIM model e DB. The processes of getting the correspondent information and incrementing it to the element list, matching BIM model and DB information, are illustrated in the flowchart below (Figure 31):

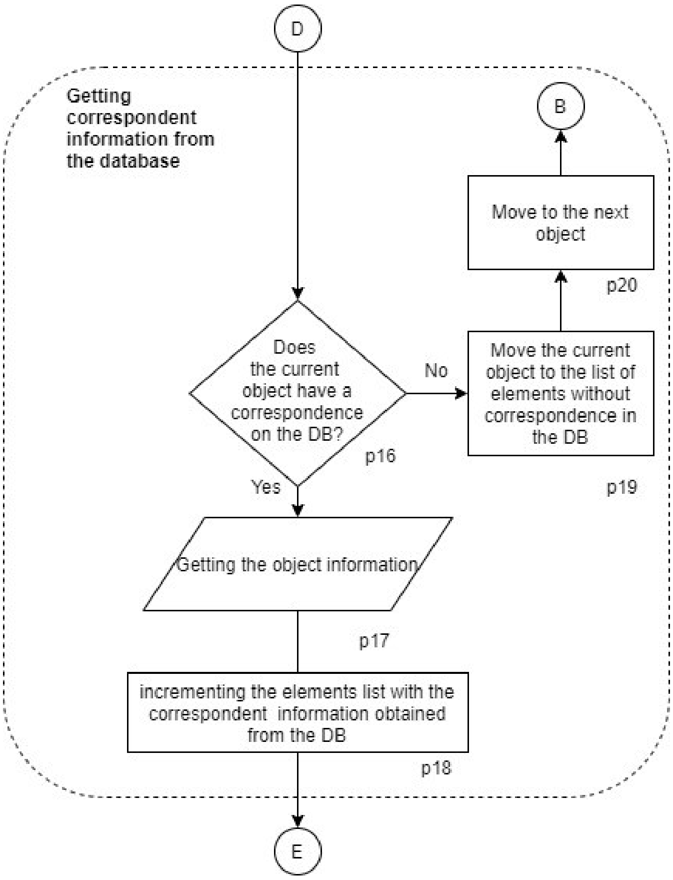


Figure 31 – TIE Module 2 flowchart: Getting and matching the information from the DB.

The script looks for the attribute assigned in the DB in the BIM model object, obtaining its value/argument, such as area, width, volume, unit, vg (in Portuguese *"valor global"*, represents a unit of a tailor-made item, such as steel or wood work) among others. If the attribute specified in the DB does not exist, the script will treat it as an error. If the value of the assigned attribute is "unit" or "vg" the quantity is 1 (one). However, for the other arguments, the quantity is expressed by the precise value obtained from the object. Instances of elements that have the same classification code must have their quantities summed once they will be presented in the MTQ as one element. Hence, the script verifies if instances that share the same classification code were already analyzed just one of them is kept in the element list, however summing the current quantity with the previous instance quantity. In the end, all instances that share the same classification code will represent an element classification code in the MTQ report, expressing the total of their quantities. The next flowchart, in Figure 32, exemplifies what was described above.

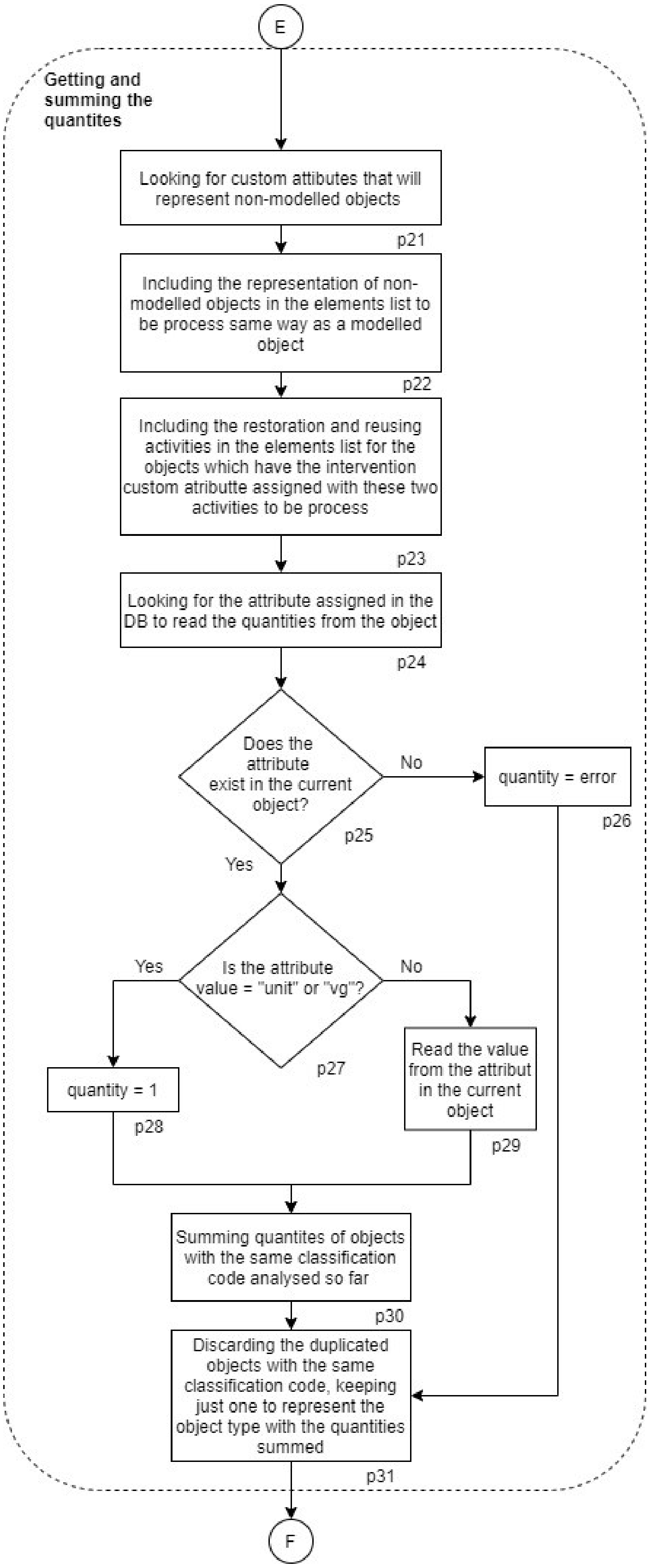


Figure 32 - TIE Module 2 flowchart: Getting and summing the quantities.

Just before the routine described above, the script looks for all the custom attributes (Table 4) created to represent an element/activity without graphical expression for each one of the analyzed objects inside the looping (Figure 32, process p21 and p22). For instance, if the current object in the looping is a floor, the script will look for the custom attributes designated to this class of object (Table 4), Finishing 1, Finishing 2, Primer 1, Primer 2, Jointing Mortar and Insulation. They secure a material class as their arguments. If a material is assigned for one of them, the script will proceed the same way it does when dealing with a modelled element. It will look for the classification code of the material, moving it to the list of not classified elements in case no classification code is assigned. It will look for the material correspondence in the database based on the classification code, discarding it to the elements without correspondence in the database list if no correspondence is found. The difference is that in these cases, the quantities are obtained based on the objects that host the material custom properties once they do not have their own geometrical expression in the BIM model. Continuing with the example of the floor, if the custom attributes Finishing 1 and Primer 1 are assigned, one element will be broken down into 3 (three) elements in the MTQ, the floor itself, the Finishing 1 and Primer 1. Each one of them with their classification code and with their total quantities (quantity resulted from the summing of all instances quantities).

As established in the framework proposal, module 2 of TIE handles the identified project phasing issues in elements that require some intervention as described in section 3.3.4. Even though an object was created in a project phase not selected by the user to be incorporated in the coordinated report, if the custom parameter for intervention assigns restoration or reuse, the script will include the intervention in that element in the MTQ (Figure 32, process p23). The demolishments are also considered by module 2 of TIE. If any object is assigned to be demolished in a project phase selected by the user, the script will express the demolishment activity in the MTQ.

Once the core looping analysed all the elements in the elements list filtered by object type and project phases, the script outcomes a final list of elements/activities/materials graphically expressed in the model and also the ones represented and processed through custom attributes. Each item represents one classification code. The quantities of all instances of objects classified with the same classification code are computed into a total quantity for the item.

Finally, the script generates the coordinated report for specification, quantity take-off and cost estimation (Figure 33 illustrates the report layout and Table 6 shows a sample of the information obtained by generating the report). It reorders the final list of elements/activities/materials according to the mapping assigned and obtained from the DB, in compliance with the report template for the MTQ used by Marta Campos Atelier de Arquitectura, grouping the items by discipline and materiality/type of work. The script writes the coordinated information in an MS Excel spreadsheet. All issues that prevented the script from processing an element/activity correctly, such as classification code missing in the BIM model object or object without correspondence in the database are listed at the end of the report and highlighted in yellow. Besides, if the attribute assigned in the DB does not exist in the BIM object model, the quantity will not be obtained. However, the field quantity with the error in the spreadsheet is highlighted em yellow informing the user that right attribute needs to be assigned in the DB. The same happens to unitary prices equal to zero or null extracted from the DB. The fields for unit price and total price are shown highlighted informing the user that it is necessary to assign a valid unitary price for the object in the DB.

NORTE MAGNETICO

MARTA CAMPOS

PROJETO REMODELAÇÃO DE HABITAÇÃO UNIFAMILIAR, RUA QUINTA DE CALVELHE, LAVRA

ARQUITECTURA - MAPA DE TRABALHOS E QUANTIDADES

	DESCRIÇÃO	UN	QUANTIDADES	PREÇO UNITÁRIO	PREÇO TOTAL
A	ARQUITECTURA				
A 1	DEMOLIÇÕES				
A 1 1	Demolição de elementos indicados no Projeto, incluindo reparação de eventuais danos em elementos contíguos, desmonte, numeração e armazenamento de elementos passíveis de reaproveitamento associados aos elementos a demolir, nomeadamente, vãos, guarnições de vãos, rodapés, azulejos, etc. para posterior reintrodução na obra, conforme assinalado nas peças desenhadas "Plantas - Demolições". Nota 1: Deve ser assegurado o transporte dos produtos sobrantes a vazadouro autorizado ou local a indicar pelo Dono de Obra e todos os trabalhos necessários, de acordo com as especificações técnicas do projetista e normas de boa execução.	vg	1,00	2.500,00 €	2.500,00 €
A 2	ALVENARIAS				
A 2 1	ALVENARIA DE TIJOLO				
A 2 1 1	Fornecimento e aplicação de paredes em alvenaria de tijolo de 15cm, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	8,40	20,00 €	187,84 €
A 3	ARGAMASSAS E REBOCOS				
A 3 1	ARGAMASSAS CIMENTÍCIAS				
A 3 1 2	Fornecimento e aplicação de betonilha de regularização para envolvimento do sistema de piso radiante, com 60mm de espessura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	83,47	20,00 €	1.669,39 €
A 3 2	ARGAMASSAS MATA JUNTAS				
A 3 2 1	Fornecimento e aplicação de argamassa mata juntas da Weber premium, cor branco sujo, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	96,48	11,00 €	1.064,34 €
A 4	COMPOSITOS				
A 4 1	GESSO CARTONADO				
A 4 1 1	Fornecimento e aplicação de placas de gesso cartonado de 12,5mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	122,69	7,00 €	858,80 €
A 4 1 2	Fornecimento e aplicação de placas de gesso cartonado de 15mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	37,29	8,00 €	298,33 €
A 4 2	GESSO CARTONADO HIDRÓFUGO				
A 4 2 1	Fornecimento e aplicação de placas de gesso cartonado hidrófugo de 12,5mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	69,67	10,00 €	696,75 €
A 4 2 2	Fornecimento e aplicação de placas de gesso cartonado hidrófugo de 15mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	70,29	12,00 €	843,42 €
A 5	CERÂMICOS, LAJETAS CIMENTÍCIAS E GRELHAS DE PAVIMENTO				
A 5 1	CERÂMICOS				
A 5 1 1	Fornecimento e aplicação de revestimento cerâmico 60x120cm, ARKETY GREY, acabamento mate, cor cinza, REF PRO13L, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	99,46	45,00 €	4.475,83 €
A 5 1 2	Fornecimento e aplicação de revestimento cerâmico 10x30cm, Cinca Arquitectos, acabamento brilhante, cor branca, REF.2200, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	20,42	30,00 €	612,59 €
A 6	CANTARIAS				
A 6 1	MARMORE ESTREMOZ				
A 6 1 1	REVESTIMENTOS				
A 6 1 1 1	Fornecimento e aplicação de bancada de cozinha, em Mármore de Estremoz, cor branca, a executar de acordo com os pormenores do projecto e as especificações do Fabricante/Projectista e normas de boa execução.	vg	1,00	1.750,00 €	1.750,00 €
A 6 1 1 2	Fornecimento e aplicação de bancada de lavandaria, em Mármore de Estremoz, cor branca, a executar de acordo com os pormenores do projecto e as especificações do Fabricante/Projectista e normas de boa execução.	vg	1,00	1.500,00 €	1.500,00 €
A 7	CARPINTARIAS				
A 7 1	CARPINTARIAS EXTERIORES				
A 7 1 1	PORTAS				

Figure 33 – MTQ | Coordinated specification, quantity take-off and preliminary cost estimation report lay-out generated by TIE.

Table 6 – Sample of the information obtained by generating the coordinated report for specification, quantity take-off and preliminary cost estimation, MTQ.

A	3			**ARGAMASSAS E REBOCOS**				
A	3	1		**ARGAMASSAS CIMENTÍCIAS**				
A	3	1	2	Fornecimento e aplicação de betonilha de regularização para envolvimento do sistema de piso radiante, com 60mm de espessura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	93,47	20,00 €	1.869,36 €
A	3	2		**ARGAMASSAS MATA JUNTAS**				
A	3	2	1	Fornecimento e aplicação de argamassa mata juntas da Weber.premium, cor branco sujo, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	99,46	11,00 €	1.094,04 €
A	4			**COMPÓSITOS**				
A	4	1		**GESSO CARTONADO**				
A	4	1	1	Fornecimento e aplicação de placas de gesso cartonado de 12,5mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	122,69	7,00 €	858,86 €
A	4	1	2	Fornecimento e aplicação de placas de gesso cartonado de 15mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	37,29	8,00 €	298,33 €
A	4	2		**GESSO CARTONADO HIDRÓFUGO**				
A	4	2	1	Fornecimento e aplicação de placas de gesso cartonado hidrófugo de 12,5mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior	m²	69,67	10,00 €	696,75 €

					pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.				
A	4	2	2		Fornecimento e aplicação de placas de gesso cartonado hidrófugo de 15mm de espessura a aplicar sobre as estruturas montantes ou sobre paredes com barramento geral, incluindo tapamento de juntas e acabamento para posterior pintura, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	70,29	12,00 €	843,42 €
A	5				**CERÂMICOS, LAJETAS CIMENTÍCIAS E GRELHAS DE PAVIMENTO**				
A	5	1			**CERÂMICOS**				
A	5	1	1		Fornecimento e aplicação de revestimento cerâmico 60x120cm, ARKETY GREY, acabamento mate, cor cinza, REF:P6012L, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	99,46	45,00 €	4.475,63 €
A	5	1	2		Fornecimento e aplicação de revestimento cerâmico 10x30cm, Cinca Arquitectos, acabamento brilhante, cor branca, REF:2200, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	20,42	30,00 €	612,69 €
A	6				**CANTARIAS**				
A	6	1			**MÁRMORE ESTREMOZ**				
A	6	1	1		REVESTIMENTOS				
A	6	1	1	1	Fornecimento e aplicação de bancada de cozinha, em Mármore de Estremoz, cor branca, a executar de acordo com os pormenores do projecto e as especificações do Fabricante/Projectista e normas de boa execução.	vg	1,00	1.750,00 €	1.750,00 €
A	6	1	1	2	Fornecimento e aplicação de bancada de lavandaria, em Mármore de Estremoz, cor branca, a executar de acordo com os pormenores do projecto e as especificações do Fabricante/Projectista e normas de boa execução.	vg	1,00	1.500,00 €	1.500,00 €
A	7				**CARPINTARIAS**				

A	7	1			**CARPINTARIAS EXTERIORES**				
A	7	1	1		PORTAS				
A	7	1	1	1	Aplicação de portas exteriores em madeira adequada ao ambiente exterior afornecer pelo Dono de Obra, e respectivos aros, guarnições, mata-juntas, travessas da bandeira, pingadeiras, se existentes, incluindo acabamento, ferragens, acessórios, todas as fixações, vedações, afinações e todos os trabalhos necessários ao seu bom funcionamento, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	un	1,00	100,00 €	100,00 €
A	7	1	2		REVESTIMENTO DE PAVIMENTOS				
A	7	1	2	1	Fornecimento e aplicação de réguas de deck, Lunadeck2 com 9,2cm de largura e 0,26cm de espessura, marca Lunawood, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	20,87	85,00 €	1.773,91 €
A	7	1	3		REVESTIMENTO DE PAREDES E TECTOS				
A	7	1	3	1	Fornecimento e aplicação de revestimento em réguas de pinho tratado em autoclave, 10/12cm de largura e respectivas guarnições, se existentes, incluindo acabamento, e todas as fixações, a executar de acordo com os pormenores do projecto e especificações técnicas do Fabricante/Projectista e normas de boa execução.	m²	26,60	75,00 €	1.995,37 €

5. TESTING IN REAL CASE SCENARIOS

5.1. Overview

Testing TIE in real case scenarios was essential to identify errors, prove the applicability of the tool, and evaluate its performance. Two ongoing projects at MC were chosen to be tested. The first, a new single house project, was in an earlier stage of development (design development), and as new construction, framed the testing to the main routines of the add-in, without dealing with different project phases and non-modelled interventions activities such as restoration and reuse. On the other hand, the second project, house renovation, was in an advanced project stage. Therefore it was expected to demand more adjustments to drive the BIM model for the intended uses once it started being developed without following the framework requirements. This second case involved different project phases assigned for the objects and implied several intervention activities that, even though not graphically expressed, were required to be computed and listed in the final coordinated report, increasing the complexities handled by the add-in. The choice for both cases firstly provided the consolidation of the core of the script, followed by an amplification of the spectrum of information modelling issues TIE would have to deal, allowing its refinement in terms of object project phases and interventions.

Also, the code development activities would tend to shape the data in the BIM model and in the database to be used as inputs for TIE, masking occasional programming issues. By using real case scenarios, the add-in would face these issues out of a controlled context dealing with data produced by others, that eventually the code was not expecting and prepared to handle, resulting in errors or impaired functioning of the tool.

During the testing procedures for both cases, the database structure and forms for its management were constantly adjusted based on the feedback provided by MC team, which would reflect in the framework as well. Some of the proposed tables, queries and fields were created based on these feedbacks aiming more agility at managing the DB, but also a better interaction between the BIM model and DB. For instance, it was established a query to structure data to be easily exported into a classification code Source file to be used in the authoring tool, the already mentioned Revit Keynote Source (section 3.1). Testing in a real case scenario also demanded layout adjustments in the DB forms, aiming more agility at searching and editing an instance in the database that was informed with an error by TIE. After running the validation and checking module, the elements without correspondence needed to be included in the DB. The ones that report showed the unitary price as null or zero needed to have a value assigned to produce a correct cost estimation; or the elements in which the attribute assigned to be read by the script in the DB does not exist in the BIM model object. These last two cases require an agile search mechanism to locate the correspondent instance in the DB, and this necessity guided the development of the search form that by typing a content, which makes the form starts filtering and listing at the same time the results that match this specific content as already shown in Figure 15.

Even though presented as different topics, the proposed framework development, the database re-structuring, the add-in programming, and the testing in real cases scenarios were cross-referenced and demanded adjustments from each other during all the dissertation development. Some of the custom attributes demanded by the framework were perceived as needed after testing with the real cases scenarios. For instance, the fact that the authoring tool does not calculate areas for Sloped Glazing objects was noticed during testing with the real case scenario. Based on the framework guidelines for centring the data in the BIM model and in the DB, the custom attribute to secure the area for this object class was proposed, the framework tables requiring its creation were updated, as well as the scripts (Figure 34 illustrates the creation of an attribute to store the area of Sloped Glazing objects).

Figure 34 –Custom attribute MC_SlopedGlazingArea demanded during the testing stage to store the area of Sloped Glazing objects.

Running and testing TIE in real cases exhaustively was useful to refine the scripts, to catch and adjust coding errors, considering the proposed framework aiming to achieve the highest level of automatization.

5.2. Architectural project for a new single-family house: The Lagoa House

Initially, the Head of MC suggested as a real case scenario an ongoing project for a new single-family house, the Lagoa house (Figure 27). This project was a good match for this work once all project stakeholders are BIM oriented, and have agreed to conceive it as a BIM study case, based on the best practices for using digitalized processes in the AEC industry (including MC as the architectural designer). Moreover, the current project stage, Design Development (DD) or in Portuguese *"Anteprojeto"*, allowed this work, alongside MC team, to explore and address the modelling issues in parallel to the development of the script.

The Lagoa House presented the opportunity of dealing with a project for new construction, in a stage that all modelling issues assessed in the framework could be addressed without compromising the project workflow inside the office and among the other stakeholders. As new construction, it matched perfectly for a first real case testing, once the complexity of dealing with project phases and interventions such as restoration and reusing would not be preponderant for the case. It provided the opportunity to refine the core functionalities of the two modules of digital solution, preparing it to be tested in more complex situations, involving the mentioned reusing and restoration interventions.

After the necessary improvements in the code, the scripts performed as expected for both checking and validation and generating the coordinated report for specification, quantity take-off and preliminary architectural cost estimation. For this first real case testing, the results of the model checking and validation were presented in Table 5. An overview of the outcome of TIE Module 2, the coordinated report, is presented below (Figure 35). As explained and expected, the report presents the coordinated information and points out for the user the modelling/database issues found during the processing. Lagoa project demanded from TIE the processing of 917 objects instances, representing 142 object types, from 14 native authoring tool categories. In the end, The coordinated report presented 88 items, identified by their unique classification code, taking around 2 minutes to run the script and release the report. The following image provides an overview of the outcome after running the add-in (Figure 35). The fields and lines in yellow (Figure 35) represent issues found by the add-in during the report generation. The highlighted fields in the columns on the right are the unitary prices assigned as null or zero in the DB. Consequently, the total prices values calculated based on the obtained quantities by the scrip are also zero and highlighted. The user must go to the DB and input/import valid values. The lines in the last page represent the objects not classified and without correspondence in the DB. For this case, the number of found issues was high once Lagoa project model was still in development, and many of the found issues were about to be addressed. The objects that were not processed or that present an issue are left on the screen for visual confirmation (Figure 36).

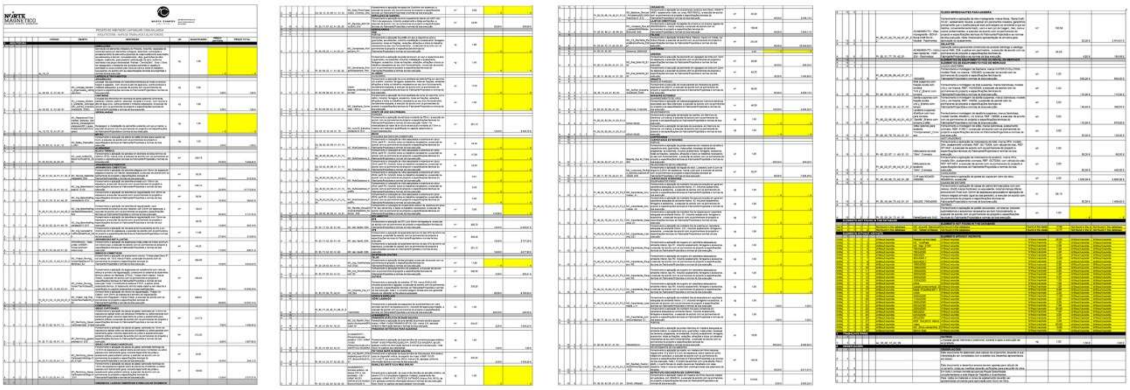


Figure 35 – Overview of the coordinated specification, quantity take-off and preliminary cost estimation for the Lagoa project (reported generated during the project development)

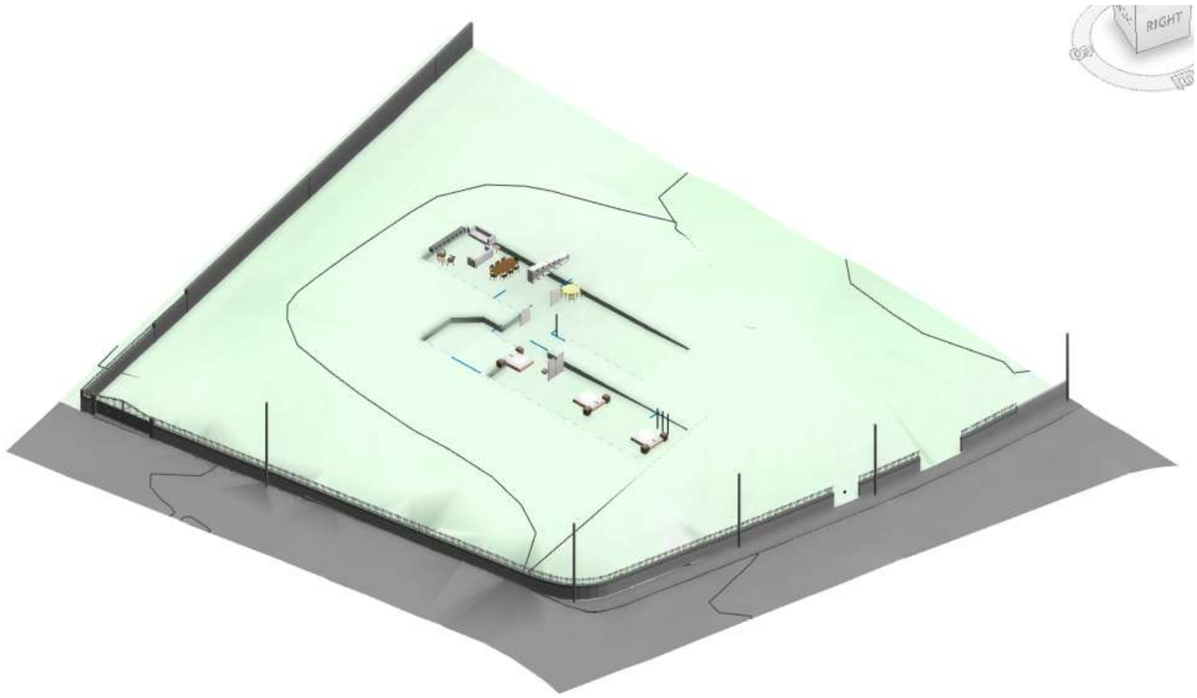


Figure 36 – Outcomes of running TIE module 2: The MQT and the BIM model visualization keeping on the screen only the elements with issues or not processed by the add-in.

5.3. House Renovation: Calvelhe

After succeeding at using TIE for the first real case scenario, and making all the code and database adjustments needed to achieve the expected results, TIE was put into practice for another real application. The chosen project was a single-family house renovation. As such, it provided the opportunity to deal with a more complex project phasing arrangement in the BIM model, handling with objects that need restoration or that will be reused in the design. Besides, the project stage was more advanced and developed in comparison with Lagoa House, with all architectural construction documentation almost finished. The modelling issues were expected to be more preponderant in this case, once the BIM model was not driven initially to be the source for a digital solution for coordinated specification, quantity take-off and preliminary cost estimation.

The testing started by running the module 1 of TIE. The checking and validation procedures identified the modelling issues and the lack of correspondence of some elements in the database. Based on the established framework, MC team addressed the modelling issues, assigning missing classification codes for some objects, and created the custom attributes in the project file (Table 4), filling them with their required values when necessary. They also added in the DB the records of elements still not stored in there and adjusted the ones with a missing price and with the wrong attribute assigned to be read by TIE once dealing with the BIM model.

After addressing the modelling issues pointed by module 1, TIE module 2 was executed. From the generated coordinated report, it was possible to identify some missing activities/elements. These items were the ones related to the needed interventions without graphical expression assigned for particular objects, considering the project phase the objects were created, and the phase the intervention would be performed, once the user has the option to filter the objects by project phase. The problems in the script code at dealing with these objects were identified and corrected step by step issuing new versions of the report, to confirm the problem-solving. In the end, the script generated the coordinated specification, quantity take-off and architectural cost estimation report successfully, matching all the expectations, and in compliance with the proposed framework. The produced outcome was delivered to the clients, as part of the architectural project documentation for the detailed design stage, alongside all construction drawings. The produced MTQ by TIE was used for the first time to support the tendering of real construction.

As a renovation, most os the objects that composes the body of the house were kept in the proposed design. Therefore, they were not included in the MTQ (except the ones that suffered any intervention). Due to the filters set by the user, and the values assigned to the custom attribute for interventions, only the new constructed elements or the existing ones that will have some intervention will be listed in the coordinated report. Calvelhe renovation project demanded from TIE the processing of 2633 objects instances, representing 262 object types, from 15 native authoring tool categories. In the end, The coordinated report presented 111 items, identified by their unique classification code, taking around 2 minutes to run the script and release the report. The following images illustrate the BIM model visualization before (Figure 37) and after (Figure 38) running de add-in.

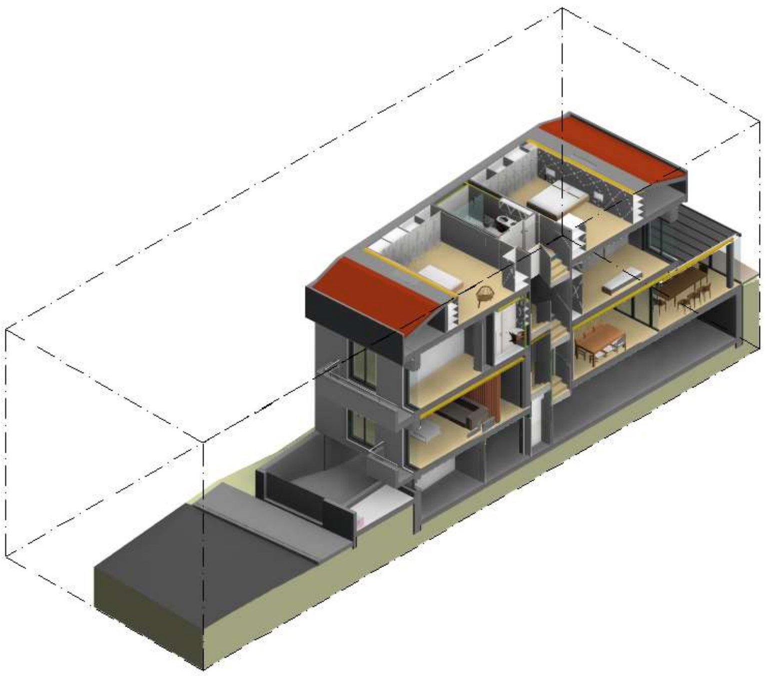


Figure 37 – BIM model visualisation before TIE module 2 execution

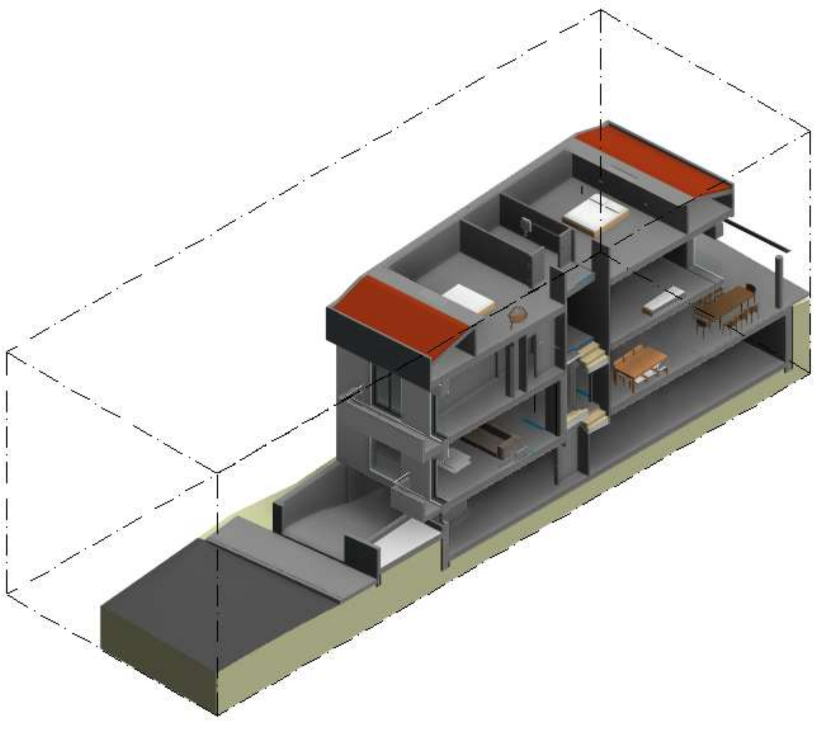


Figure 38 – BIM model visualization after TIE module 2 execution

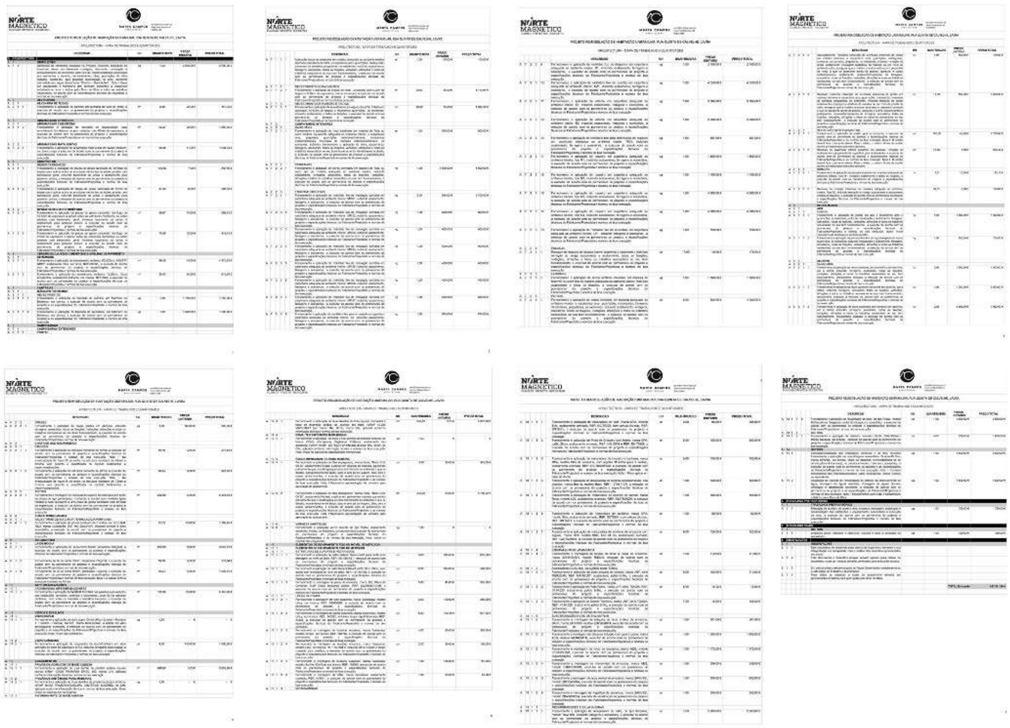


Figure 39 – Overview of the coordinated specification, quantity take-off and preliminary cost estimation for the Calvelhe project (the final version of the report)

5.4. Framework and digital solution achievements

The efficiency of the proposed framework/digital solution, embedded in the TO-BE process, was assessed and compared with the AS-IS process, and traditional methods for producing the coordinated report for specification and quantity take-off (MTQ). The comparison was made by interviewing the head of MC, based on the analysis of historical project management data of the architectural office.

Considering projects with the same scale and complexity as Calvelhe (2 real case scenario), Marta Campos, head of MC, reported that before using BIM-based methods the whole process, including quantities extraction, coordinating it with the specification data and structuring the report, would take two/three weeks when performed by one person. After implementing the BIM-based specification and quantity take-off (AS-IS), the same process for similar conditions took the average of one week to be performed. By using TIE, starting from the same stage of the model completeness, and considering the same conditions, the process took one day, for running the checking and validation module, making the necessary corrections and adjustments in the BIM model and DB records, and lastly, generating the coordinated report. This comparison stands positively for the proposed framework and resulting digital tool, highlighting their potential for increasing the level of digitalization inside the company. The add-in, based on the proposed framework, represents a powerful tool that enabled a value addition to the MC business model.

Due to the earlier project stage, the BIM model for the Lagoa house was developed in parallel to the framework and digital solution. For this reason, the information modelling activities did not demand any extra effort once they meet the framework requirements regarding the custom attributes and the use of simplified geometries to represent elements/activities not graphically expressed, and database management, in real-time. As the project progressed, the modeller/designer ran the checking and validation to guide necessary adjustments. Therefore, the report generation could be performed instantaneously, taking only the time for the add-in the execute the script (around 1 minute).

In the case of Calvelhe, the project stage was already advanced, and the construction drawings were about to be extracted from the BIM model. Hence, the framework/digital solution (embedded in the TO-BE process) demanded a little bit more time and resources to drive the information modelling for the intended BIM uses (specification and quantity take-off) in comparison to the AS-IS, once it requires to assign values for each one of the proposed objects custom attributes. It also requests the inclusion of the simplified host-based objects (the Magic Cubes) as a representation for activities without graphical expressions, such as cleaning or repairing. However, the one day demanded to drive the building information modelling to produce the coordinated report for specification and quantity take-off is worth of spending once it still represents 1/5 of the time in the process AS-IS and at least 1/10 the time of traditional methods.

6. CONCLUSION

6.1. General conclusions

The present dissertation focused on the following question: How to re-engineer BIM-based specification and quantity take-off processes in order to make them more automatized, accurate, integrated, faster and cheaper? The proposed framework addressed the problem, leading to the development of the TIE add-in. The developed tool is a BIM-based digital solution which automatically generates a databased coordinated report for specification and quantity take-off, setting up also a preliminary cost estimation. The work development relied on the collaboration with the architectural firm Marta Campos Atelier de Arquitectura as an object of study.

Through the conducted research, the dissertation exposed the importance of the digitalization as a mean for adding value to business models, enabling more efficient re-engineered processes. It also has demonstrated that BIM has a crucial role in transforming the AEC industry towards digitalization. However, BIM-based specification and quantity take-off still lack a complete and integrated digital approach requiring manual glue processes (Turk, 2006) to be performed, which implies excellent opportunities to make them reach higher levels of digitalization.

The dissertation has also evidenced the importance of standards and pre-establish routines as enablers of digitalization. The information must be produced, exchanged and consumed in compliance with some pré-set rules, which will allow digital platforms to read and interpret it, mitigating human interventions in the processes and providing the expected outcome.

As a result, this dissertation has proposed a framework structured in three major topics based on the referred object of study. Firstly, it was made a diagnosis of the current workflow for producing coordinated specification and quantity take-off at MC, mapping the whole process AS-IS. Secondly, the previously mapped process was assessed identifying its pros and cons, regarding procedures, standards, information modelling and database management. Lastly, it proposed a new framework that attempted to address all found issues, providing guidance and the bases for the development of TIE. The proposal represents a re-engineered version of the process AS-IS, the called process TO-BE.

Even though the MC office already used Uniclass 2015 as a consistent system for indexing elements, the new framework and the resulting digital solution demanded a complete redesign of the DB structure, followed by the decision of adopting an adequate RDMS. New tables, fields and queries were created, driving the database to match the framework standards and the digital solution requirements, assuring the usability of its data as inputs for the TO-BE process. A UI was developed in the DB environment to allow the users to manage all the elements/activities information more practically and safely.

The whole process to generate the coordinated report was performed in one day, against one week spent in the process AS-IS and two/three week for traditional methods considering similar conditions. The extra effort demanded to drive the information modelling to the framework/digital solution requirements pays-off. Furthermore, as another crucial advantage, all required specifications data or their path are stored in the BIM model. In contrast, in the AS-IS process, sometimes this information was scattered in different sources and only gathered "by hand" in the final coordinated report.

It is essential to highlight that the proposed framework does not require significant changes in the modelling activities, as long as they follow established recommendations and standards. As mentioned already, the high level of maturity for modelling at MC has been leading them to produce BIM models, containing standardized objects, which are indexed based on the Uniclass 2015 classification system. Also, the use of custom attributes and phasing were performed consistently in the office. Nevertheless, during the dissertation development, (as shown in the framework proposal chapter 3, section 3.3), some incongruities were identified in the objects coding that demanded its restructuring.

The dissertation work has achieved the goal of providing a framework for BIM-based specification and quantity take-off through digital modelling. It successfully embodied the developed framework into a digital tool (an add-in) able to generate as an outcome a coordinated databased specification and quantity take-off, also setting up a preliminary architectural cost estimation. The achievements faced the challenge of setting methods and standards and restructuring a DB. TIE enabled extraction from the BIM model, matching this information with correspondent data in the DB, granting the expected outcome demanding considerably fewer resources and less time than those processes used to consume.

6.2. Future developments

Even though the dissertation, comprising its conceptual (framework) and practical (add-in) work accomplished their goals, some issues are still not contemplated due to the time limitation and some improvements that would enhance the work were identified.

As a further development, TIE could be tested in other real cases scenarios, covering more projects with different scales, types, complexities, and also in distinct stages. Besides, it could also be used in the context of structural and MEP disciplines. The tests using real projects served this work as a significant mean to identify information modelling issues, not initially comprised by the proposed framework, which were addressed later. Testing on a broader sample of real case scenarios would allow the proposed framework to incorporate unpredicted demands, providing the guidelines to enable the scripts to process them, enriching the add-in performance.

Additionally, the modelling issues could be assessed and addressed in more detail, guiding design firms which do not have the same level of maturity for information modelling as MC. This work considered the current stage of MC to base the proposed solutions once it was necessary to frame the problem to the time available. For this reason, straightforward modelling issues, such as overlapping objects, that were already overcome by the AS-IS BIM-based process for specification and quantity take-off, were put aside, to focus on re-engineering those that would represent an obstacle on the development of the TO-BE process, enabling a higher level of digitalization for the MC business model.

Also, The resulting digital solution for coordinated specification, quantity take-off, and preliminary cost estimation is by the moment restricted to a specific authoring tool environment. It was tested to execute the script importing an Industry Foundation Classes (IFC) model into the authoring tool without successful results. Some adjustments in the script are necessary in order to enable it to process IFC object classes. Dealing with models in .ifc format, which enables interoperability among different BIM platforms would be a significant further development that will enrich the proposed framework, expanding its approach.

Finally, the framework and the developed digital tool have great potential for integrating with other external databases, allowing the communication enabled by the TIE between the BIM model and the framework DB to perform richer outcomes. For instance, the elements table in the DB which stores the unitary price for each element could be linked to an external price list, assuring the preliminary cost estimation provided by TIE will be based on up to date prices. The Uniclass 2015 classification system data are already partially integrated to the DB, once they can be downloaded from NBS website and imported into the DB. However, the importing process could be automatized. The connection with external databases would empower the proposed framework to deal with other BIM uses.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEC	Architectural, Engineering and Construction
API	Application Programming Interface
BIM	Building Information Modelling
DB	Database
GUI	Graphical User Interface
IFC	Industry Foundation Classes
MC	Marta Campos Atelier de Arquitectura
NBS	National Building Specification
RDMS	Relational Database Management System
TIE	Technical Information Exchange
UI	User Interface
XAML	Extensible Application Markup Language
WPF	Windows Presentation Foudations