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Quantity take-off and cost estimating with OpenBIM models: process automation for buildings

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

RESUMO

A quantificação e a estimativa de custos é uma etapa importante no ciclo de vida de um edifício, uma vez que estabelece um orçamento através da medição, quantificação e estimativa dos elementos necessários para um projeto de construção. Tradicionalmente, este processo era baseado na interpretação de desenhos 2D por técnicos especializados, o que muitas vezes conduzia a desafios devido à falta de informação. No entanto, este processo melhorou com a introdução da Modelação da Informação da Construção (BIM), melhorando a precisão e a colaboração entre as diferentes partes interessadas. Uma estimativa de quantidades baseado em BIM automatiza o processo de medição, extraindo a informação geométrica e alfanumérica de todos os elementos do modelo 3D.

Mesmo através de uma estimativa de quantidades baseado em BIM, ainda persistem alguns desafios, principalmente devido à inconsistência no processo de modelação e aos silos de dados entre as partes interessadas. O estudo que se segue tem como objetivo resolver estes problemas através do estabelecimento de um procedimento preciso e eficiente de estimativa de quantidades e estimativa de custos em três etapas principais: primeiro, a criação de regras de modelação e o estabelecimento do nível de informação necessária; segundo, a criação de um processo simplificado e normalizado através de uma estrutura WBS (fornecida pela CYPE, a empresa envolvida neste estudo); e terceiro, o seguimento de uma abordagem baseada no OpenBIM que assenta no esquema IFC. O objetivo é promover a interoperabilidade e assegurar um processo QTO mais normalizado, eficiente e acessível.

O principal objetivo deste trabalho consiste na proposta de um novo fluxo de trabalho definido por um processo de modelação padronizado, uma verificação da informação geométrica e alfanumérica e uma estimativa de custos de todos os elementos necessários para um projeto. Este processo deve ser aplicado a várias instâncias arquitectónicas para determinar um processo de modelação adequado a cada uma delas, seguido do estabelecimento do nível de informação necessário para obter as informações solicitadas para gerar um orçamento final do projeto.

Este fluxo de trabalho será gerado através da definição de uma revisão da literatura sobre o processo de levantamento de quantidades e estimativa de custos no momento e ensaios de modelação de cada instância de arquitetura estudada. Através deles, o processo foi estabelecido para os elementos de arquitetura mencionados, testando a sua exportação através de um ficheiro IFC e atribuindo o seu custo numa plataforma de base aberta que permite a integração de um projeto utilizando um serviço de nuvem, permitindo que todos os intervenientes carreguem e tenham conhecimento do trabalho dos outros.

Palavras chave: Estimativa de custos, estrutura de repartição do trabalho, IFC, estimativa de quantidades, nível de necessidade de informação, OpenBIM.

ABSTRACT

Quantity take-off and cost estimation is an important step in the lifecycle of a building since it establish a budget by measuring, quantifying, and estimating the elements needed for a construction project. Traditionally, this process was generated through the interpretation of 2D drawings by quantity surveyors, which often lead to challenges due to missing information. However, this process improved by the introduction of Building Information Modelling (BIM) by improving accuracy and collaboration between the different stakeholders. A BIM-based quantity take-off automates the measuring process by extracting the geometrical and alphanumerical information from all the elements of the 3D model.

Even through a BIM-based quantity take-off process some challenges still persist mainly because of inconsistency in the modelling process and data silos between the stakeholders. The following study aims to solve these issues by establishing an accurate and efficient quantity take-off and cost estimation procedure through three main steps: first, the generation of modelling rules and establishment of level of information need; second, generate a simplified and standardized process through a WBS structure (provided by CYPE, the company involved in this study); and third, following an OpenBIM-based approach which relies on the IFC schema. This aims to promote interoperability and assuring a more standardized, efficient, and accessible quantity take-off process.

The main goal this work consists of the proposal of a new workflow defined by a standardized modelling process, a verification of the geometrical and alphanumerical information and a cost estimate of all the elements required for a project. This process should be applied to several architectural instances to determine a proper modelling process for each of them, followed by the establishment of the level of information need to get the information requested to generate a final project budget.

This workflow shall be generated through the definition of a literature review of the quantity take-off and cost estimation process at the time and modelling trials of each studied architecture instance. Through them, the process was established for the mentioned architecture elements by testing its export through an IFC file and by assigning their cost in an open-based platform that allows the integration of a project by using a cloud service, letting all stakeholders to upload and be aware of others work.

Keywords: Cost Estimation, IFC, Level of Information Need, OpenBIM, Quantity Take-off, Work Breakdown Structure.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

One of the most important phases in the lifecycle of a building is the creation of a cost estimation through a quantity take-off procedure. This process generates the budget by measuring, estimating, and quantifying the materials and jobs required for the completion of a construction project. It also provides stakeholders with accurate information regarding the project costs and provides the customers with options that are valued-assisted and aids in cost-cutting. (Olsen & Taylor, 2017)

Conventionally, quantity take-off consisted on a manual process based on 2D drawings and quantity surveyors interpreting them and measuring each building element, which, due to the lack of information on the drawings sometimes required an inferring process for this missing information, (Khosakitchalert et al., 2019). This changes by introducing a BIM-based approach to the traditional QTO method, since it becomes a more accurate, efficient, and collaborative approach. According to Olsen & Taylor (2017), a BIM-based quantity take-off process consists on measuring automatically BIM models by extracting geometrical and alphanumerical properties of each of the building's elements.

By working in a BIM-based quantity take-off approach the process will need fewer manual steps between the different involved actors, which facilitates sharing information and conflict resolution. Unfortunately, this process could be affected by several issues, such as: a non-well modelled 3D project, inconsistencies between the model, limited access to the model for stakeholders, software incompatibility, incomplete or inaccurate and even sometimes excess of information in the model.

Opting for an open approach would help minimize the before mentioned problems that the user may find when using a BIM-based process for QTO. BuildingSMART developed a collaborative process called OpenBIM, which allows a collaborative seamless information exchange by improving accessibility, usability, and management of digital data in a project. This can be accomplished by using one of the most important standards of buildingSMART, IFC, which consists on a neutral-vendor format that allows information exchange in a more standardized way, avoiding confusion and data silos in the process. (buildingSMART, 2022c)

Integrating OpenBIM to the quantity take-off process will allow a multi-disciplinary collaboration, enabling access to quantity surveyors to real-time data from all the involved stakeholders. This process leads to better cost project management, a more efficient communication and a better collaborative process which minimizes the project risks and improves the outcomes without depending on a specific software by relying in well-defined structure, accessible to all the parties involved, the IFC schema.

Through bibliographic and online research and considering experience from the involved company, Top Informatica, it was established that not using OpenBIM for quantity take-off and cost estimation process may lead to some challenges and limitations to the users. First, without a collaborative and open approach, achieving interoperability for the exchange of information will become difficult due to the different authoring tools available in the market. Second, a process without any standardized data format (ex: IFC), may require a manual data entry, which may lead to a time-consuming process and the increase of a human error during the estimation process, reducing efficiency and accuracy in the quantity take-off and cost estimation process. Third, it is important to mention that most of the research papers published on this topic are based on outdated IFC versions (mostly IFC 2x3).

The purpose of this work is to generate a proper quantity take off and estimation process that will be consisting on accomplishing the following objectives: creating general modelling rules to create an accurate 3D model (assure the same criteria for 3D objects in the model), generate a simpler and a standardized process (following a WBS structure provided by a database from CYPE) and most importantly, make all the information in the model accessible to all actors involved by using an Open BIM file type, IFC.

To fulfil the before mentioned objectives, it is necessary to propose a new workflow and modelling rules for several architectural elements until the quantities, related works and information are exported and extracted properly from the IFC. The final test will consist of generating a quantity take-off and cost estimation through a case study provided by the company. As a result, it is expected that this work will lead to a reduction in the whole process time, creation of modelling rules for quantity take-off and an increase in quality and quantity of information, all this using Open BIM process and software.

The following work is mainly divided into three parts: a literature review, definition of a quantity take-off and cost estimation methodology and case study.

The first chapter in the work defines the research, main concepts and examples of the entire workflow and each element needed for a quantity take-off and cost estimation process. The chapter is mainly divided in three parts: first, through it a description of OpenBIM approach, the standards involved and the relationship between IFC and the quantity take-off is included. Second, it explains what a work breakdown structure is, its relevance for the studied process and examples on how to use them and how are they defined. Third, quantity take-off is defined with their attributes and gaps involved through different examples of workflows to get a cost estimation.

The second chapter describes the proposed workflow and each stage of the work with their respective outcome. This chapter is divided into the main steps of the workflow. First, it establishes modelling rules and guidelines to the most used architectural instances, with an explanation discussing how an IFC file should be exported. Second, a model verification that checks the alphanumerical and geometrical information of the project. Third, how to generate a cost estimate through a coding system, extracted from a deliverable-based work breakdown structure and its respective report.

The third chapter shows a case study which was done by testing the proposed quantity take-off workflow in a real-life project. It describes how the model was done in order to be well-structured to have a much better understanding on how to manage the project. It also includes some lessons learned that help to generate a consistent model and as a result, a well-done cost estimate report.

2. LITERATURE REVIEW

Building Information Modelling (BIM) consists of facilitating collaboration and coordination among the stakeholders using digital models to support virtual design and construction of a project. It refers to the process from developing the digital model as well as the process of keeping and exchanging it over the project life cycle (Borrmann et al., 2018).

Lately, the construction industry has long relied on accurate quantity take-off and cost estimation processes to ensure successful project planning and execution by introducing BIM into their projects. Through this process, the concept of OpenBIM has been introduced and revolutionized these practices by providing a collaborative and interoperable platform for sharing project data across various stakeholders. OpenBIM enables seamless integration and exchange of information between different software applications, facilitating a more efficient and accurate quantity take-off and cost estimation process. This technology has significantly enhanced the ability of construction professionals to extract quantities from digital models and generate reliable cost estimates.

The following literature review discusses several aspects of the building process for quantity take-off and cost estimation through OpenBIM, highlighting its potential to have a more accurate QTO through modelling rules, a proper level of information and a well-defined Work Breakdown Structure (WBS).

2.1. OpenBIM

OpenBIM increase the benefits of using BIM by improving the usability, accessibility and management of all digital data included in the project. It is defined by BuildingSmart (2022c) as a collaborative process defined by using neutral software providers, so that all the information can be sharable and accessible for all the stakeholders throughout all the stages of the lifecycle of the building, just as shown in the Figure 1.

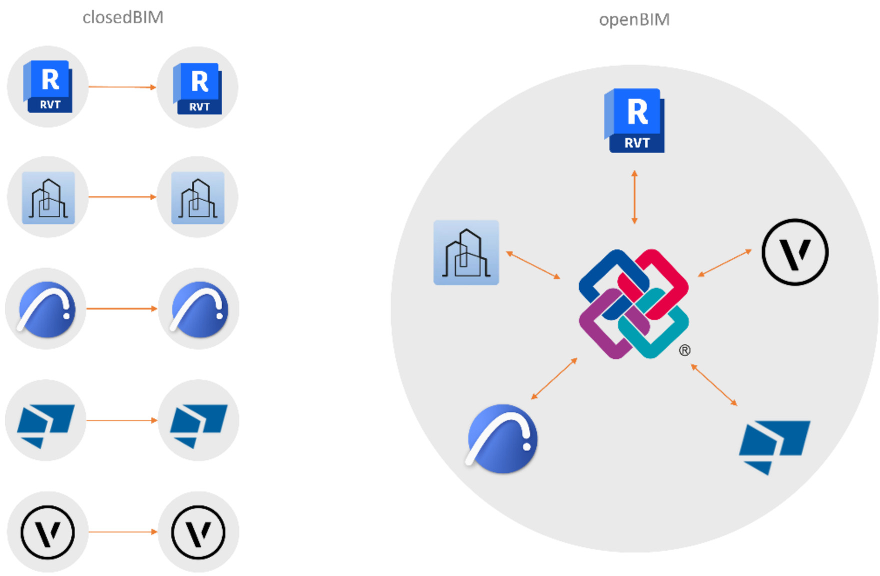


Figure 1 – OpenBIM versus closedBIM
Adapted from: (Acca Software, 2021)

According to BuildingSmart (2022c), the project delivery and asset performance can be greatly improved by breaking down data silos, which can be accomplished by developing a cross-party collaboration, enhanced communication, and industry standard exchange methodologies. This delivers better project outcomes, greater predictability, improved performance and increased safety with reduced risk.

According of the description provided by BuildingSmart (2022c), OpenBIM is composed by six principles: Interoperability, open and neutral, reliable data, collaboration, flexibility and sustainability; properly explained by the Figure 2 .

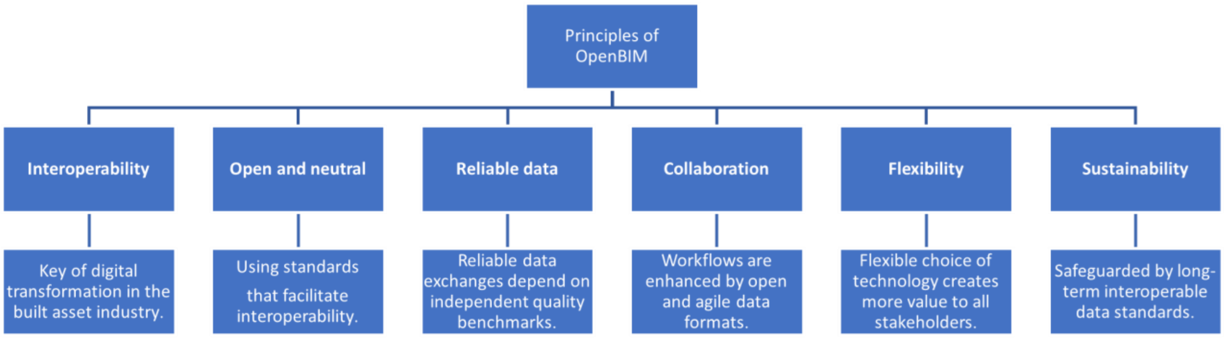


Figure 2 – Principles of OpenBIM. Adapted from: (buildingSMART, 2022c)

As described by Gerbino et al. (2021), OpenBIM is a path to define interoperability. It enables a full cooperation between the stakeholders by connecting the work of different actors and facilitating exchange of information through all the lifecycle of a building. Its most relevant advantages is the ability of: combining the geometric and alphanumerical information of different software applications, compare results between different analysis runs and sharing updated information across different actors and phases of the project.

OpenBIM facilitates the connection and communication between the stakeholders, processes and data by creating a common alignment and language between the different elements used in the projects. Through this, the management of data and disconnected workflows improves and allows a more reliable open data exchange by using vendor-neutral formats such as: IFC, BCF, COBie, etc. (buildingSMART, 2022c)

It's most common used standard is the Industry Foundation Clasess, IFC, also developed by buildingSMART. As defined by Gerbino et al. (2021), IFC can be labelled as the core of a collaborative-lifecycle BIM and aims interoperability of BIM softwares. The IFC file format (".ifc"), allows the exchange of geometrical data (properties of the components such as floors, walls, windows) and heterogenous attribures (such as mechanical properties, costs, construction work time).

2.1.1. Benefits and Challenges

Using OpenBIM offers several benefits for the construction industry, which had helped to improve the collaboration and efficiency between the stakeholders, but it also generated some challenges for the users. According to BuildingSmart (2022) and Gerbino et al. (2021) there are several benefits of an OpenBIM approach and the most relevant for the purpose of this work are the following:

- Collaboration of a project delivery. OpenBIM promotes interoperability by using open standards and file formats. It allows applications to exchange data seamlessly, enabling coordination and collaboration among the stakeholders.

- Creation of a common alignment and language: this is accomplished by adhering to international standards and commonly defined work processes.

- Improved accuracy: OpenBIM enables the integration of detailed information within the BIM model (product data, material specifications, quantitative information, etc).

- Enables better asset management: it allows integration of diverse data sources and formats, including geometric and non-geometric information.

- Streamlined workflows: It enables real-time collaboration and coordination among the stakeholders. By using open standards, different disciplines can work together seamlessly, reducing delays and improving the efficiency of the quantity take-off.

On the other hand, Migilinskas et al. (2013) explains the challenges that implies to work with BIM and OpenBIM.

- Data consistency. Achieving data consistency across different software and disciplines may be difficult. Ensuring that information is accurately represented, consistent and complete throughout the project lifecycle requires careful attention to data management and coordination.

- Standardization and its adaptation. OpenBIM relies on the implementation and adherence to open standards; encouraging industry-wide acceptance and consistency can be a challenge, particularly in highly fragmented environments.

- Interoperability. Despite its significant contribution to BIM, some software still doesn't support open standards and it may require additional efforts to ensure correct data exchange.

- Overall acceptance. The barriers include fears of too low success low or big failure, a high initial investment of training and capacitation of the team, lack of support from the company or even the cost-benefit of an already bought license collection (especially for small companies).

Even though there are still some challenges for the implementation of OpenBIM, its benefits are greater and help improve collaboration, and efficiency for a better project outcome. They may be addressed by proper planning, cooperation, and training.

2.1.2. BuildingSMART standards

BuildingSMART is an international organization that develops different types of open standards and workflows to promote interoperability and facilitate the exchange of information between different software applications and disciplines involved in the construction industry. Jiang et al. (2019), describes that OpenBIM standards are divided into three main categories: buildingSMART international standards, candidate standards and other related standards.

2.1.2.1. BuildingSMART international standards

As explained by BuildingSmart (2022), the buildingSMART standards is one of their most important developments. They include all the final standards that have been voted by the Standards Committee as being final standards. A brief explanation of them is exposed in Table 1.

Table 1 – Brief summary of BuildingSMART standards. Adapted from: (Jiang et al., 2019)

Name	What it Does
IFC Industry Foundation Classes	Transports information or data
IDM Information Delivery Manual	Describes processes
MVD Model view definitions	Translates processes into technical requirements
BCF BIM Collaboration Format	Change coordination
BsDD BuildingSMART Data Dictionary	Defines BIM objects and their attributes
IDS Information Delivery Specification	A computer interpretable document that defines the information that should be delivered and exchanged.

All of them aim to achieve international consensus among the stakeholders for a more well-organized process. Each of them covers different process and information capabilities according to a specific purpose related to the construction industry.

Information Delivery Manual. This standard was created by buildingSMART to define a methodology to set and explain the different processes and information flow during the lifecycle of a building. It can be applied to documentation of an existing or new process and describe the associated information that must be exchanged among the involved parties. (buildingSMART, 2022b)

Remarked by buildingSMART (2022b), for this standard to be effective when applying to any process the Information Delivery Manual, IDM, must be supported by a software. The main purpose of the IDM is making sure that the most important data is communicated in a way that it can be interpreted by the software of the receiving party.

Model View Definition. The model view definition, MVD, defines a specific implementation level of IFC to describe a specific use or workflow. For a long time, everyone could create and define their own MVD and approach software vendors to implement it. This led to a situation when MVDs became not interoperable with each other. (buildingSMART, 2022b)

There are three base MVDs which are the levels of implementation of IFC: Coordination view (IFC 2x3 & Reverence view IFC4), Alignment based Reference View (IFC4.3) and Design transfer View (IFC 2x3, IFC4). (buildingSMART, 2022b)

BIM Collaboration Format. This standard is a simplified and open standard that uses an XML format to encode information that allows to communicate model-based issues with each of the involved parties by using IFC models that have been previously shared. (buildingSMART, 2022a)

According to BuildingSMART (2022a), the BIM collaboration format, BCF, works by transferring XML formatted data that contains information about an issue directly referencing a view, captured by PNG or IFC coordinates, and BIM elements by using their IFC GUIDs, from one application to another.

BuildingSMART Data Dictionary. The buildingSMART Data Dictionary (bsDD) is an online service that defines classifications and their properties, values, units, and translations, some of them shown in the Figure 3. (Jiang et al., 2019)

The bsDD has many applications and it provides flexibility according to the user's needs. BIM modelers use it to have easy and efficient access to all kinds of standards to complement their model. On the other hand, BIM managers use it to check BIM data validation. (Jiang et al., 2019)

It provides a shared system for identification and validation of the names of objects and their respective attributes used in the projects. This helps to have a better understanding of the general concepts of each object, thereby improving the information interoperability during the different stages of the project.

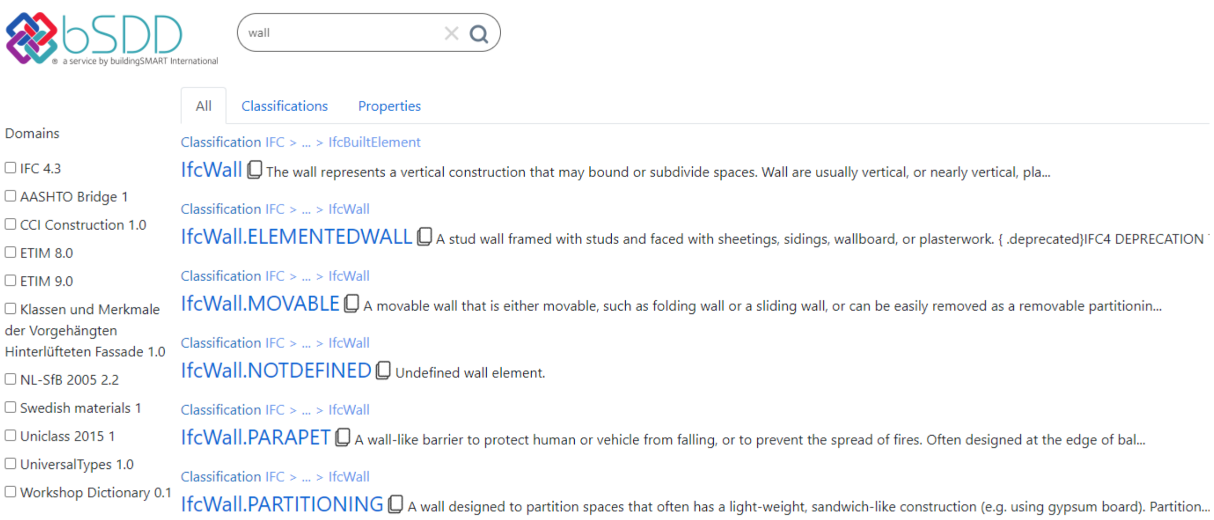


Figure 3 – bsDD online service. Source: (buildingSMART, 2022c)

Information Delivery Specification. According to buildingSMART (2023),the Information Delivery Specification, IDS, is composed by specifications designed to be easy for humans to understand and also, it is well-structure for a computer software to automatically check the included information. It is divided into three main parts:

- Description: a description of why the Specification is important to the project and instructions of how to achieve it. This part is designed for humans to read and understand why information is being requested.

- Applicability: which type of objects the Specification applies to. There are different types of objects in IFC models, such as walls, doors, and windows, but each Specification will only apply to certain objects.

- Requirements: what information is required for the specified objects. Ex: properties or classifications.

Applicability and requirements are defined by using Facets. A facet is the description of the information that a single entity (ex: wall, floor, door, etc.) may have in the model. Following buildingSMART (2023), there are six different facets of information, which are defined on the Table 2.

Table 2 – Information facets, IDS. Adapted from: (buildingSMART, 2023)

Facet Type	Facet Parameters	Example applicability	Example requirement
Entity	IFC Class and Predefined Type	Applies to "IfcWall" with predefined type of "SHEAR"	Must be an "IfcWall" with a predefined type of "SHEAR"
Attribute	Name and Value	Applies to elements with the attribute "Name" having the value "W01"	Must have the attribute "Name" with the value "W01"
Classification	System and Value	Applies to elements classified under "Uniclass 2015" as "EF_25_10_25"	Must have a "Uniclass 2015" classification reference of "EF_25_10_25"
Property	Property Set, Name, and Value	Applies to elements with a property set of "Pset_WallCommon" with a "LoadBearing" property set to "TRUE"	Must have a "Pset_WallCommon" property set with a "LoadBearing" property set to "TRUE"
Material	Value	Applies to "concrete" elements	Must have a "concrete" material
Parts	Entity and Relationship	Applies to elements that are "contained in" an "IfcSpace"	Must be "contained in" an "IfcSpace"

This standard will be applied to the proposed QTO workflow explained in the chapter 3 of this document.

2.1.2.2. BuildingSMART candidate standards

The BuildingSMART Candidate Standards are processes that are not yet recognized as international standards but are under a procedure of getting an international consensus so they can then be submitted to the Standards Committee for a final vote to become official standards.(buildingSMART International Limited, 2022). A few of them as an example are the following:

- Quantity Take-Off Information Delivery Manual
- Quantity Take-Off MVD
- IFC Rail Project - Conceptual Model Report
- UML Model Report – Part 1: Introduction to the IFC Harmonized Schema Extensions.

2.1.2.3. BuildingSMART related other standards

According to buildingSMART International Limited (2022), these ones are formed to supplement the OpenBIM standards. An example could be of this could be COBie and LandXML.

LandXML

This standard was launched in 2000 to tackle some problems of job sites at the time. There were no standards for files that machines could understand in order to perform the tasks needed, and often they would need to convert the different CAD software files into different types that the construction machines could understand and would take a lot of time and was not efficient at all. This is where LandXML comes into play, it provides a standard that can use XML files in order to store data like points, parcel measurements, surfaces and cross-sections and makes all the parties involved capable of reading and working with these files, eliminating the need of converting files.

Construction operations building information exchange (COBie)

In short, COBie can be defined as a set of spreadsheets that contains information of buildings on a project, as complete and useful as possible. It is defined as .CVS files or .XLS files. It was developed by different US agencies to improve how building information could be handed over to building-owner operators.

2.1.3. Industry Foundation Classes (IFC) and Building Information Modelling (BIM)

The demand for interoperability between different software packages has experienced increased growth in the AEC market, especially in Europe, where regulatory bodies have issued new rules for the digitalization of the construction sector. (Liao & Teo, 2017)

The mandatory use of the BIM format on a large scale has expanded the need for easy and reliable information exchange processes that are able to preserve data and their quality. The best neutral and open format used in BIM is the IFC, which can be labelled as the core of a collaborative-lifecycle BIM since it aims to ensure the interoperability between stakeholders. (Gerbino et al., 2021)

Industry Foundation Classes or IFC, is a standardized, digital description of a built environment, including buildings and civil infrastructure. It is an open, international standard (ISO 16739-1:2018), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases. (buildingSMART International, 2022)

IFC standards can be used to unify the format of information generated by different types of software so as to realize the free conversion of building information (Jiang et al., 2019). This can be achieved though the IFC schema specification which is the primary technical deliverable of buildingSMART International to fulfill its goal to promote openBIM (buildingSMART International, 2022).

It is important to highlight that IFC is constantly evolving and has been continuously developed by buildingSMART since its first data model standard release in 1996, IFC 1.0 (Gerbino et al., 2021). The latest version is the IFC4 ADD2 TC1, which was published in October 2017.

As shown in the Figure 4, IFC file enables the exchange of data not only associated with geometrical properties of the components, such as walls, columns, and slabs, but also heterogeneous attributes of the project like cost, construction work time and more. This format enables an object-oriented data model truly interoperable between different software packages.

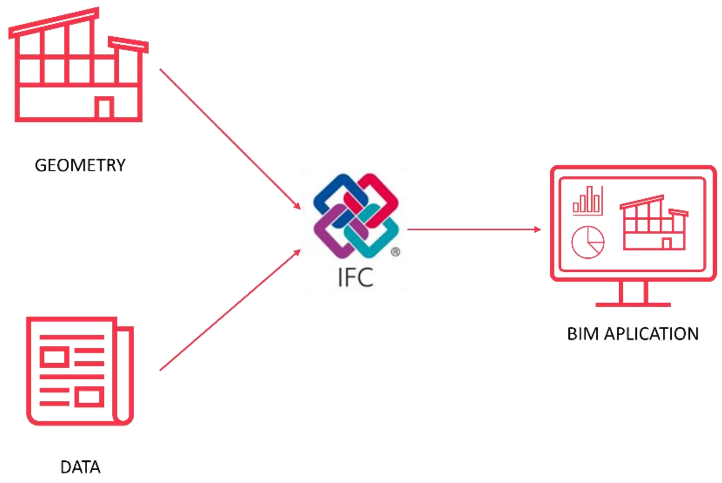


Figure 4 – Industry Foundation Classes Use in BIM. Adapted from: (BIM Corner, 2018)

Since the following work is focused on quantity take-off and cost estimation based on an IFC estimation, it is required to have a BIM model and a database for unit cost information. According to Choi et al. (2015), an accurate QTO is the result of a high-quality BIM model with physical and properties quality.

As defined in the Figure 5Figure 5, an OpenBIM based quantity take-off is generated through an IFC file that needs to have a physical and property quality that enables to have a more accurate and appropriate quantity take-off. To ensure the quality of the elements, it is necessary to make the model suitable for its project phases by defining a suitable level of detail or level of information needed to avoid missing or giving more information than needed.

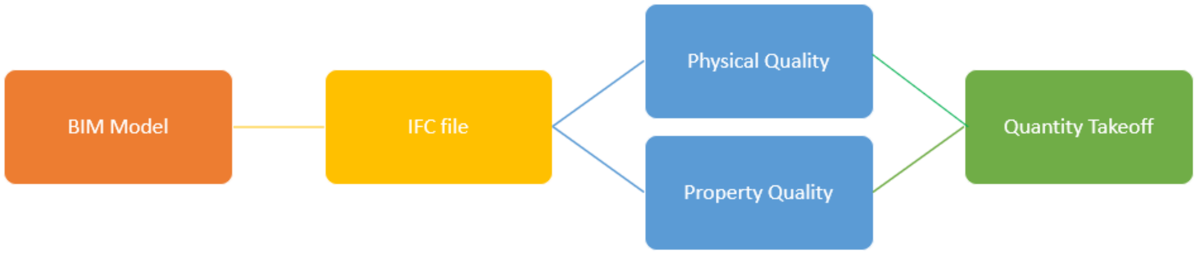


Figure 5 - General steps for a IFC format quantity take-off. Adapted from: (Choi et al., 2015)

The process of quantity extraction is defined by the Figure 6, in which shows the attribute inheritance of the object according to the IFC schema, in this case, of a wall. A quantity take-off process that is done throught IFC is usally generated by mapping the properties of the Quantity Set and the Material Layer Set of each element. It is also shown that through the properties several quantities can be extracted and if needed it allows to create formulas in the quantity software to generate more data.

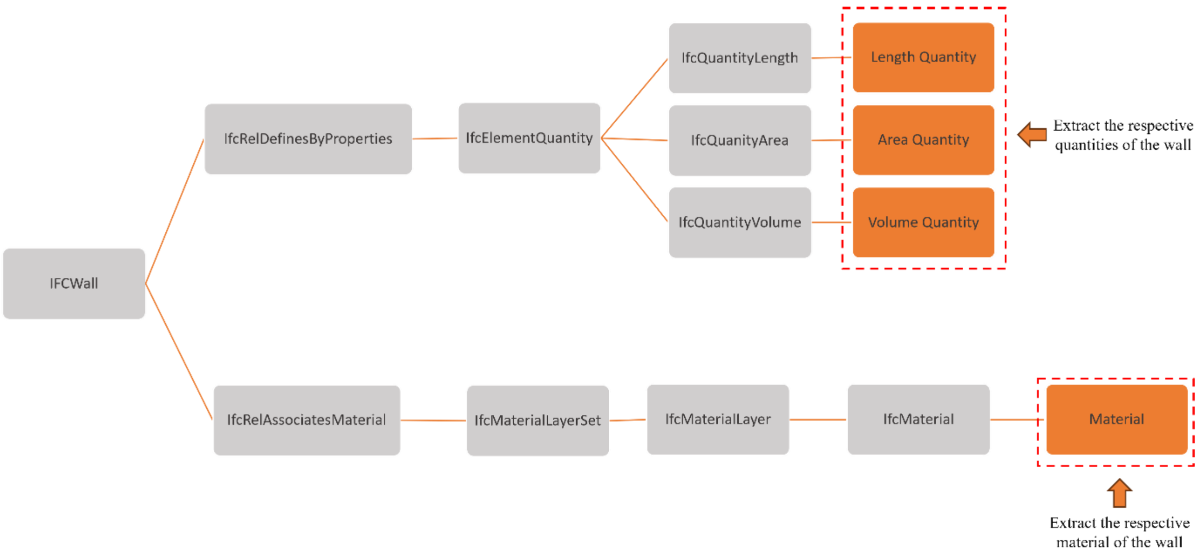


Figure 6 – Quanities into the IFC schema. Source: Self-generated.

The most relevant property sets for this work is the Quantities Property Sets and the Material Property Set. According to what is defined in the IFC4 ADD2 TC1 documentation, the quantity property set is the one that defines the values of each element used in the project which its mainly composed by length, area, volume, weight, time, or a combination of quantities. Each of these is defined by its name and value. These values set the base for each of the elements included in the cost estimation process.

Meanwhile, the material property set is the one that defines the material applied to a specific construction element. The materials can be arranged by layers and applied to compound (layered) elements, usually walls and slabs; and also, can be applied to elements that use profiles such as beams, columns, or members.

Even though using IFC helps improving the process of quantifying and making a cost estimation of a project, there are still some limitations that may affect the efficiency of the process. As presented in the work of Jiang et al. (2019) and Gerbino et al. (2021) the implementation of IFC still presents some limitations that are necessary to know for a better implementation of the standard in any process:

- Missing information. In many cases, when a model is exported to an IFC format, it does not keep all the initially inherited data. It is stated that some software tools have this issue more often than others and that usually takes an easy procedure to fix.

- Limited Level of detail. Defining a level of detail through IFC may end up in a loss of information or oversimplification of the objects during the data exchange.

- Material layer limitations. In most cases the material's name is the only property included in the export. A customized property defined in the authoring software won't be exported using IFC (except ArchiCAD and AllPlan) even if the properties are related to the PsetMaterial properties.

- File size. When approaching a large or complex project we can expect a significant file size and may affect the performance during data exchange and collaboration. This can be addressed by establishing a fragmentation of the project into sections, construction phases, or types of elements involved in the project.

- Limitation against Advanced Features: Some advanced features that are supported by authoring software may not be well-address or even included when exporting to IFC. Sometimes it can end in elements not being well-represented or missing data.

All the above-mentioned limitations are situations that can be managed and addressed, in most cases, easily. It is important to know the purpose of the IFC to minimize the number of possible errors in the file. It is also important to expose that many times, as the researchers pointed out, these types of limitations or issues may come from lack of practical knowledge of IFC or deficiency on the management procedure. Even with all the limitations, IFC proves to be an important approach to any type of process involved in the construction industry, that creates many opportunities and benefits than constraints in the process.

2.2. Work breakdown structure (WBS)

2.2.1. Definition of WBS

A WBS is a deliverable-oriented hierarchical decomposition of the work to be executed by the project team that establishes a common understanding of the project scope. It is a hierarchical description of the work that must be done to complete the deliverables of a project. (Alutbi, 2020)

Just as shown in Figure 7, a WBS is composed by a hierarchical composition because it uses a level-based structure in which the top level or node, represents the 100% of the project itself and when going down the levels, we decompose it in smaller parts that each of those would also represent the 100% of the parent node, or the level above. (Duke, 2023)

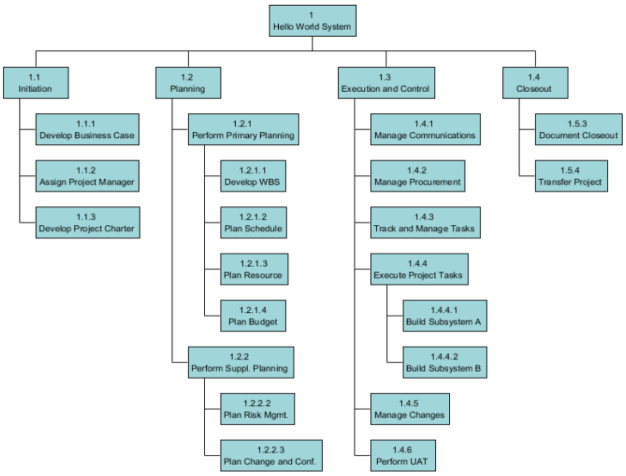


Figure 7 – Example of the hierarchy of a WBS. Source: (Alutbi, 2020)

According to Alutbi (2020), a well-designed WBS makes it easy to assign elements of the WBS to any project activity. To guarantee a well-structured project by using a WBS, there are some important characteristics to take into account:

- Definable: it is easy to understand by the other team members
- Manageable: a specific amount of work can be assigned to a person.
- Estimable: the time required and costs (resources) of its completion can be estimated.
- Independent: should not interfere with other elements
- Unifiable: other elements of the project can be easily unified, with the respective cost estimates and schedules.
- Measurable: should have deadlines and in-between goals so it can be used to measure progress
- Adaptable: any changes on the project work should not critically affect the WBS framework

2.2.2. Types of WBS

Following the article created by (Duke, 2023), it is necessary to define the two most used types when integrating a WBS into a project.

- Deliverable-Based WBS: Breaks down the project into elements that are usually the end results, things that should be produced or obtained with project tasks, just as shown in the Figure 8.
- Phased-Based WBS: The project is divided into 5 main categories (or phases) which are initiation, planning, execution, control and close. Below that level, there are levels that are formed with deliverables for each stage. This WBS is common for general contractors.

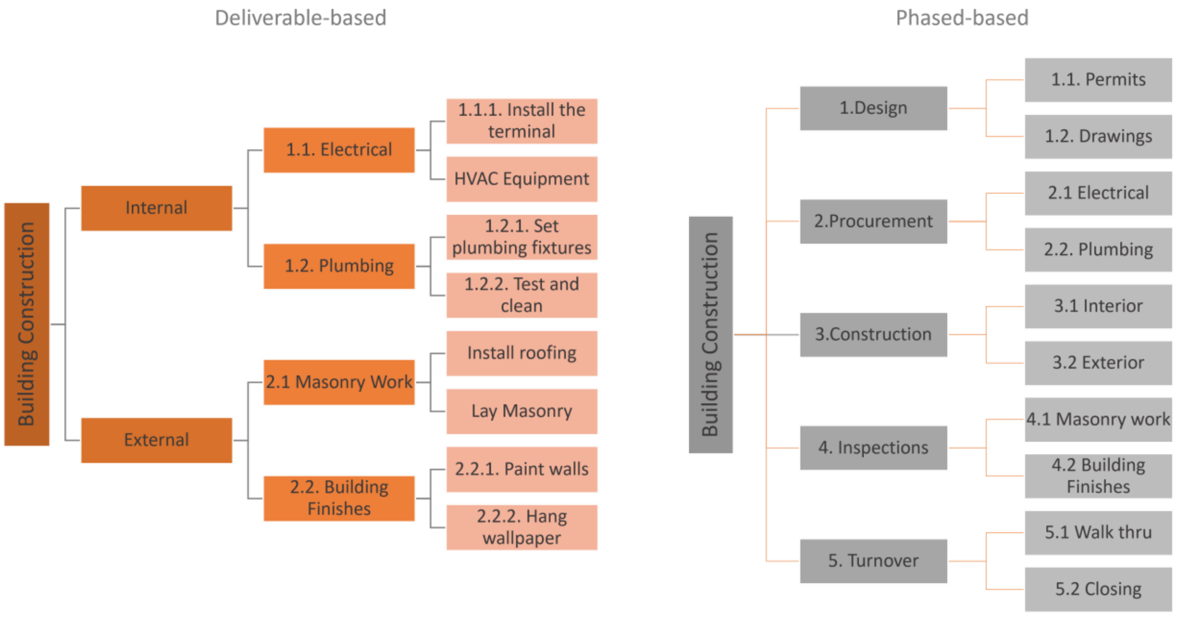


Figure 8 – Types of WBS. Adapted from: (Abrevaya, 2021)

When applying a WBS to a quantity take-off and cost estimation process the most common approach is to use a deliverable-based work breakdown structure. According to Abrevaya (2021), there are several reasons why a deliverable-based WBS is a more preferred option among the actors. First, when dealing with a QTO, elements are counted as one entity; giving as a result all the countdown of the elements involved in the project with their respective properties. Second, it gives subcontractors a more reliable definition and scope of work because it is focused on the project deliverables, ensuring that all the components required to produce final outputs are being counted. Third, it integrates with project management methodologies that prioritize deliverables and project-oriented outcomes. Even though the deliverable-based WBS is the most common approach, its necessary to consider that each project is different, and the approach taken by the companies may have a different scope, so its recommendable to define the purpose of the WBS and then choose the best option for the project.

2.2.3. WBS and QTO

Integrating a Work Breakdown Structure (WBS) in quantity take-off (QTO) and cost estimation process is essential because it provides a structured framework for organizing project elements, breaking them down into smaller, manageable components.

A WBS can be integrated into a QTO process by creating an organization, that provides a structured and systematic breakdown of the project focus into smaller, manageable components, (Duke, 2023) .These components may be represented as the materials and works needed in order to construct one element in the project, just as shown in the Figure 9, which thanks to its structure allow each of these elements to be individually assessed, measured, and quantified reducing the risk of overlooking or double-counting elements during the estimation process. (Alutbi, 2020)

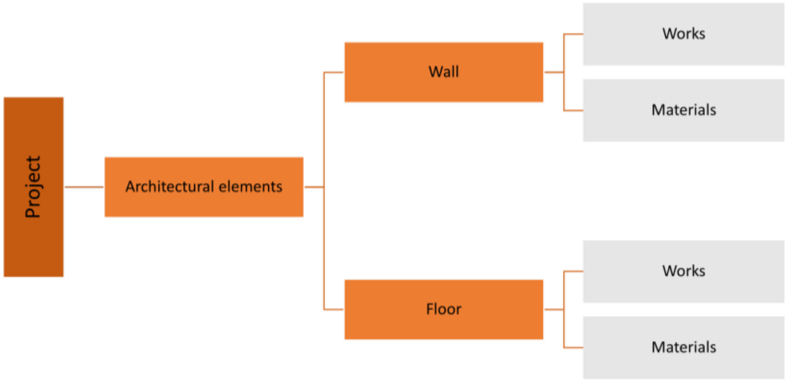


Figure 9 – Schematic WBS for Quantity Take-off. Source: self-generated.

Since it is a hierarchical system, it gives the project a sense of clarity and consistency. This is achieved by identifying the components or elements to be measured and quantified, which in many cases are mapped by a coding system related to a standardize organization or classification system. (Abrevaya, 2021)

Lastly, a WBS helps streamline the quantity take-off process. It provides a clear structure of all the items required for a project, including the tasks, materials, unit of measurement and cost, that allows quantity surveyors and estimators to focus on specific work packages or components, improving efficiency and reducing the likelihood of errors or omissions. (Abrevaya, 2021)

2.2.4. Existing work breakdown structures

The following sub-chapter provides an analysis and evaluation of the current work breakdown structure that may be used in a construction project. According to what is mentioned before, for the scope of this work a WBS will set a base for the quantity take off and cost estimation process in the proposed methodology on chapter 3.

There are several existing work breakdown structures in the industry, most of them are developed by public authorities of the country. They usually define each element used in the project, its units of measurement, works involved and equipment. They may be complemented by other country regulations.

2.2.4.1. Generador de Precios

The Generador de Precios (GP), in English Price Generator, in Portuguese Gerador de preços, is a complete computer tool that allows to obtain prices for construction projects developed by CYPE Ingenieros, Spain. It facilitates the preparation of quality project documentation for the different phases of the building's lifecycle: preliminary studies, preliminary draft, basic and execution project, management, execution of construction, use and maintenance, demolition, and recycling (CYPE, 2019). All of the categories are subdivided according to the element or material requested by the user, as shown in the blue rectangle of the Figure 10, and it includes a general code according to the element selected with its corresponding units of measurement (upper left side of red rectangle in Figure 10).

It is also important to mention that this database is generated by using national materials, works and equipment costs. At the moment, there are twenty—seven countries with a price list on the Generador de Precios webpage. The countries included in the Generador de Precios are mostly located in Europe, America, and Africa. It provides free access and setup by logging in to its website: http://www.generadordeprecios.info/ .

The Generador de Precios was designed to organize the process of generating a detailed construction cost estimate by providing a very complete database of construction materials, equipment, and labor costs. Users can modify some of the attributes of each element in order to get a more accurate quantity estimate of materials and a more well-defined cost estimate, as shown in the yellow rectangle in the Figure 10. Also, according to the setup of all attributes, the tool generates a description of the selected item with the properties defined by the user that should be included in the cost estimate report (red rectangle in Figure 10). This can be exported to other CYPE programs, Presto, FIEBDC-3 and Excel (orange rectangle in Figure 10).

Another aspect of the Generador de Precios is that according to the setup defined by the user it will generate a cost estimate that includes all the materials, equipment, and labor costs necessary to build the selected element (green rectangle in Figure 10).

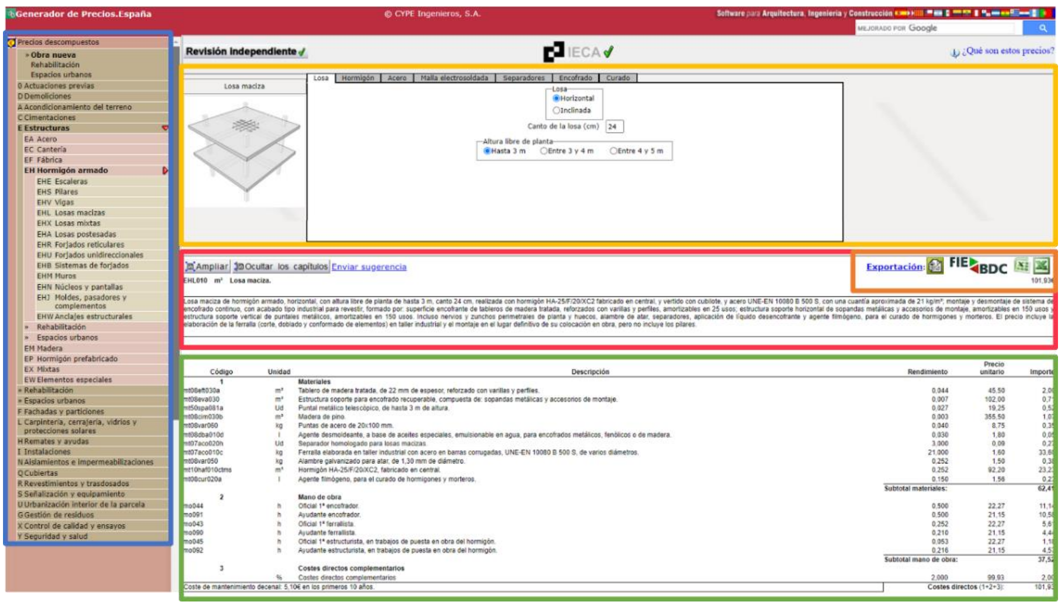


Figure 10 – CYPE Generador de Precios. Source: (CYPE, 2019)

2.2.4.2. Italy's Regional price list

Italy's Regional price list refers to a standardized cost and price for construction materials, works, equipment rental and services used for public projects. It follows a decentralized approach and gives a price list according to each region of the country, considering regional variations in costs, market conditions and regulations. The Regional price list studied for the purpose of this work will be Lombardy regional price list.

According to the Consiglio Regionale della Lombardia (2023), the regional price list was created with a collaboration between the Municipality of Milan and the Interregional Superintendency for public works of Lombardy and Emilia-Romagna, with a signed agreement with Politecnico di Milano.

The document provides the cost of the product, equipment, and process to a definitive quantification of spending limit to execute public works, which is determined by a an annually updated regional price list. This list is composed by:

- Execution times of the works. This are deduced from information in official publications and information of expert technicians or companies.

- Labor cost. These are extracted from official tables of the Ministry of Labor and Social Policies of Italy.

- Cost of materials. This list is deduced by producers' price list, considering the opinion of the MIT (Italian Ministry of Infrastructures and Transport).

- Freight costs. This one is taken from the marked and from the cost of diesel recorded at the Milan Chamber of Commerce.

As shown in the Figure 11, the Italian Regional price list is a clear example of a WBS. This coding resides to the different categories of works and elements integrated in the standard, generating a hierarchy between the elements, and facilitating its understanding to the users. Each element code is defined by a specific item, and it starts subdividing according to the chosen variation of the element, giving a description of it and its respective unit of measurement.

LIST

1C.06 - WALLS - TABLES - ANCHORS

CODE	DESCRIPTION	UM	PROCESSING	% Inc. MO	% Inc. MAT	% Inc. ATTENTION
1C.06.250	WALLS IN EXPANDED CLAY BLOCKS	m²	71.93	30.70%	44.46%	
1C.06.250.0050	Masonry in hollow blocks in cement and clay conglomerate foam, for plastering, nominal dimensions 40 x 20 or 50 x 20 cm. Including: the special pieces for shoulders, vaults, fixings, suitable clamps for anchoring the walls to the load-bearing structure, the mortar of adequate class, the internal worktops, excluding stiffeners from count separately if necessary:					
1C.06.250.0050.a	- thickness 8 cm - REI 120	m²	29.55	47.72%	24.50%	
1C.06.250.0050.b	- thickness cm 12 - REI 120	m²	31.72	44.45%	30.01%	
1C.06.250.0050.c	- th. cm 15 - REI 120	m²	35.43	39.80%	33.90%	
1C.06.250.0050.d	- thickness cm 20 - REI 180	m²	39.35	37.99%	34.79%	

Figure 11 – Fragment of Italy's WBS. Source: (Consiglio Regionale della Lombardia, 2023)

Most importantly, it integrates the estimated cost of an element according to its unit of measurement. The fourth column represents the total cost of the item in which, according to the standard, the cost of the works involved (% Inc. MO, fifth column of the figure), the cost of the materials (% Inc. MA, sixth column of the figure), and the freight cost (% Inc. Freight, seventh column of the figure) are already included and shown with their respective percentages over the final cost.

This is a good example of a well-integrated WBS since it allows different types of elements and combinations between them. It also provides a standardized coding system for each item that can be applied in any project, not only public ones, and gives a clear understanding of which elements are included in them with their respective unit of measurement. The only "downside" of this standard is that in some elements the description of them does not include the list of works required to complete the job, which in some cases may be necessary for the cost estimation of the project.

2.2.4.3. New Rules of Measurement - RICS

The New Rules of Measurement or NRM is a standard of measurement rules for construction projects created by the Royal Institution of Chartered Surveyors (RICS). They comprise rules for the measurement of the construction, repair, renewal, maintenance and demolition of built assets. (RICS, 2021). It is divided into three volumes:

- NRM 1: Order of cost estimating and cost planning for capital building works.
- NRM 2: Detailed measurement for building works.
- NRM 3: Order of cost estimating and cost planning for building maintenance works.

As shown in the Figure 12 the NRM defines an element and its types according to a structured system that contains the measurement unit and the rules of how to measure the object. It also divides the element according to the job and gives specification following the stage of construction in which the element is going to be quoted.

Item or work to be measured	Unit	Level one	Level two	Level three	Notes
Plain in-situ concrete					
Reinforced in-situ concrete					
Fibre reinforced in-situ concrete					
Sprayed in-situ concrete					
1 Mass concrete.	m^3	**1** Any thickness.	**1** In filling voids. **2** In trench filling. **3** In any other situation, details stated.	**1** Poured on or against earth or unblinded hardcore.	**1** Mass concrete is any unreinforced bulk concrete not measured elsewhere. **2** The volumes of each type of mass concrete work may be aggregated or given separately.
2 Horizontal work.	m^3	**1** ≤ 300mm thick. **2** > 300mm thick.	**1** In blinding. **2** In structures.	**1** Poured on or against earth or unblinded hardcore. **2** Reinforced > 5%.	**1** Horizontal work includes blinding, beds, foundations, pile caps, column bases, ground beams, slabs, coffered and troughed slabs, landings, beams, attached beams, beam casings, shear heads, upstands whose height is less than or equal to three times their width, kerbs and copings. **2** The volumes of each type of horizontal work may be aggregated or given separately. **3** Work laid in bays should be so described giving average area of bays.

Figure 12 – NRM structre example. Source: (RICS, 2021)

As shown in the Figure 77, in the appendix section, the level of description and works involved is structured according to the RIBA stages and generates a direct connexion and follow up with another standard applicable in the UK. This helps the user to identify how detailed the cost estimation should be, and which elements should be added into the process.

The NRM may be considered as a WBS structure since it gives hierarchy to the project according to the stage of the life cycle of the project. It explains what elements are going to be described in each chapter and the characteristics involved. To be a better WBS for cost estimation, it should define a better coding system, add a suggested cost according to the UK market and give more information about the jobs and materials without relying on other chapters.

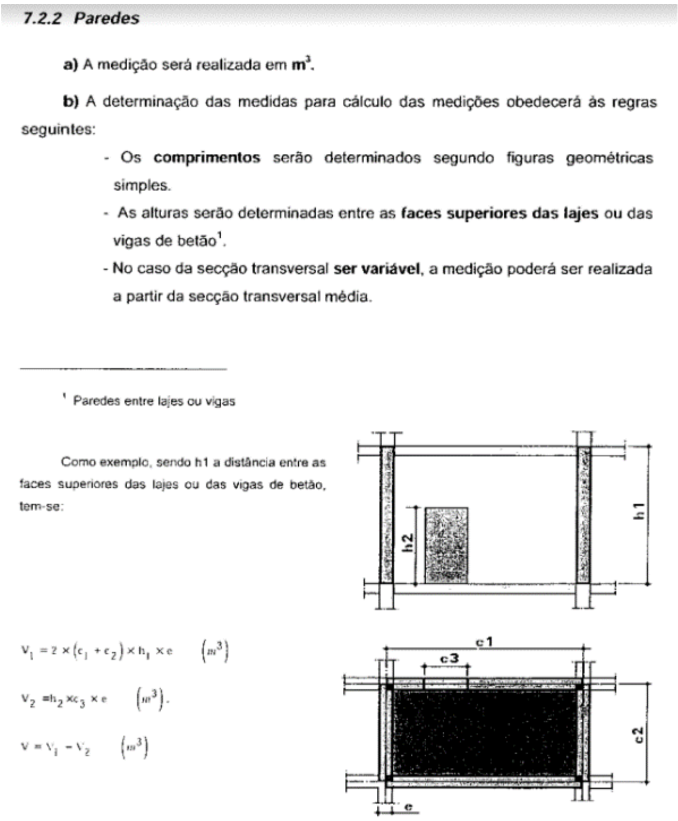
2.2.4.4. Rules of measurement for construction, Portugal

According to Fonseca (2003), the rules of measurement for construction in Portugal intend to quantify the different types of construction works already established by representatives of different public and private entities related to construction back in the 70's. This document defines more accurate measurement rules based on that criteria without making radical changes that will affect having an accurate result.

It establishes the importance of the measurement procedure in the project and its rules since they are associated to objectively define and quantify the work involved in the project. Due to this thought, they define the objectives of the work, which are summarized in:

- Measurement Units: They define the standardized units of measurement to be used for various construction elements.
- Measurement Methods: It stablish methods and procedures for measuring different construction elements.
- Systematic Classification: The rules include a classification system for grouping construction elements into specific categories or "elements."
- Documentation: They provide guidance on documenting the measurement process, including the format and necessary supporting documentation. This ensures consistency in reporting and facilitates communication between stakeholders.
- Estimation of Quantities: It provides guidelines for estimating quantities based on the measured dimensions. They even note formulas or calculation methods.

As shown in the Figure 13, the rules provide first, the unit of measurement of each element. It also includes a set of measuring rules and considerations to consider when quantifying the quantitative properties of each element. Another characteristic of it is that sometimes it includes graphs to help understand the object and its measurements, and some formulas to establish a calculation method every time is needed.



7.2.2 Paredes

a) A medição será realizada em **m³**.

b) A determinação das medidas para cálculo das medições obedecerá às regras seguintes:

- Os **comprimentos** serão determinados segundo figuras geométricas simples.
- As alturas serão determinadas entre as **faces superiores das lajes** ou das vigas de betão[1].
- No caso da secção transversal **ser variável**, a medição poderá ser realizada a partir da secção transversal média.

[1] Paredes entre lajes ou vigas

Como exemplo, sendo h1 a distância entre as faces superiores das lajes ou das vigas de betão, tem-se:

$V_1 = 2 \times (c_1 + c_2) \times h_1 \times e \quad (m^3)$

$V_2 = h_2 \times c_3 \times e \quad (m^3)$.

$V = V_1 - V_2 \quad (m^3)$

Figure 13 – Preview of the rules of measurement for construction. Source: (Fonseca, 2003)

This standard helps to create a Work breakdown managed by generating a hierarchy between the elements and including a coding system that even if it is not that detailed, it helps to understand the structure of each element and how they should be manage in the project.

The last time it was modified was back in 2003, when BIM wasn’t at the level of impact that it has now, this opens the door to elements that might not align with the 3D representation of building elements in authoring software. As mentioned, several times during meetings with the company involved in this work, there are some attempts to generate a new edition of these rules with a focus on a relationship between these elements and a BIM methodology. But, up until now, these rules remain as a reference document for Portuguese construction companies.

2.2.4.5. ProNIC, Portugal

ProNIC or Protocol for the Standardization of Technical Information in Construction is a research project whose objective is to create a set of technical content supported by modern IT tools to standardize technical information for the construction industry. (Inesc Tec, 2008)

The project was approved in 2005 and it has been managed by the IHRU (Institute for Housing and Urban Rehabilitation). It was created through a consortium formed by the Institute of Construction, National Laboratory of Civil Engineering, and the Institute of Computer Engineering of Porto, which aimed to establish guidelines and standards for the exchange and sharing of technical information related to construction projects in Portugal.

According to Inesc Tec (2008), the scope of the project resided in two major areas: Buildings in General and Road Infrastructure. The specification of these two areas is detailed in their database which includes technical information about:

- Detailed and exhaustive articulations for mapping of jobs and quantities.
- Work execution sheets.
- Material sheets.

ProNIC is a reference of a WBS since it gives detailed information on jobs and their respective materials and activities. As mentioned before, in the chapter 2.2.4.4, the Rules of Measurement in Portugal does not apply for the use of BIM, but ProNIC does. It gives a standardized and more present approach to the quantification and cost estimation of a project. The issue with this standard is that is extremely closed to the public, not all people have access to it, which is the opposite of their main objective.

2.2.4.6. WBS analysis

As mentioned before each of the WBS examples has its advantages and disadvantages, and some of them may be more fitted for the scope of quantity take-off. In terms of time, the rules of measurement in Portugal should be updated for them to be applicable to a BIM-based project. The NRM is a good approach for a consistent workflow since it follows the same logic of RIBA, but it lacks a well-defined coding system and a reference cost of each element. Lastly, the ProNIC of Portugal seems like a better approach for a WBS for quantity take-off but since it is not a fully open standard, its application to most projects in Portugal seems far away from possible now.

One of the best WBS studied for this work is the Italian Regional price list. It is constantly updating their information, the prices are per region, so it is a more realistic cost per element, it has a coding system that helps to keep everything in order and gives the user a more detailed and realistic approach to each element of the project. The only downside is that the whole standard is Italian regional approach and when applying to other country, it may not give correct approach for local quantity take-off.

For the scope of this work the WBS will be defined by the Generador de Precios, developed by CYPE. Generador de Precios is a WBS that has a database per country, giving the possibility of integrating it to projects from all over the world. It gives the user a more friendly experience by creating a database that includes all the materials, works and tools needed for the construction of a project and it enables to create a more accurate and detailed cost estimate by modifying each element according to the user's needs, saving significant time compared to manual calculations. Also, it is important to mention that it is regularly updated giving more accurate prices compared to other WBS. Lastly, it is an OpenBIM-based tool since it allows collaboration between different types of software, and it is a free open source for everyone to include it in their project.

2.3. Quantity Take-off and Cost Estimation

Quantity take-off and cost estimation are important parts of the lifecycle of a project. QTO involves measuring and quantifying the materials, components, and resources needed for a project, while cost estimation predicts and determines the approximate expenses associated with that project. Together, these processes enable accurate budgeting, resource allocation, and financial planning.

By assessing quantities and assigning costs to each element, quantity take-off forms the foundation for cost estimation, ensuring that projects are adequately funded and managed within budget constraints. Effective quantity take-off and cost estimation are essential for successful project execution and financial control.

2.3.1. Definition of quantity take-off and cost estimation

Quantity take-off is a process that involves measuring, estimating, and quantifying the materials and jobs required for a construction project. Its purpose resides on including cost estimation, cost management, procurement and if possible, construction schedule planning. (Olsen & Taylor, 2017)

Traditionally, it consisted of a manual process based on 2D drawings and human interpretation. The process consisted on quantity surveyors interpreting a set of drawings provided by the design team and measuring each building element. This process depended mainly on the phase of design, knowledge, and experience of the surveyor, specifically when there isn't too much information on the drawings and the surveyor had to infer the missing information. (Khosakitchalert et al., 2019)

BIM has revolutionized traditional QTO process by introducing a more accurate, efficient, and collaborative approach. Quantities can be measured automatically from BIM models by extracting geometrical and semantic properties of each building element by using a BIM-based quantity take-off. In terms of time, the amount of reduction in time spent on can be as much as 80% while providing quantity take-offs and estimates that are accurate to within 3%.(Olsen & Taylor, 2017)

According to Khosakitchalert et al. (2019), BIM-based quantity take-off is both more time saving and reliable than the traditional method. However, if the BIM model is not comprehensive or accurate, the extracted quantities may be insufficient or inaccurate. To ensure precise quantities, it is essential to develop a BIM model that closely represents the actual construction.

Cost estimation, CE, is the process of determining the approximate expenses associated with the quantities provided by the QTO. Estimators may use tools such as cost databases, cost models, or software applications to assist in the estimation process. (Zaman & Nast, 2022)

2.3.2. BIM-based QTO and its limiting factors

Creating a quantity take-off and a cost estimation through a BIM-based process has revolutionized the traditional workflow, by improving its accuracy, efficiency, and consistency through the process. However, even with all the progress made in recent years, BIM-based quantity take-off and cost estimation still face some limiting factors that may affect the process and accuracy of the final quotation.

BIM-based process efficiency and accuracy for QTO rely on driving the information modelling activities to ensure a complete, granular, and adequate model for the intended purpose. However, conventional models often fall short of meeting these necessary requirements in practical scenarios. Therefore, this process still relies on manual or semi-automatic efforts to refine the extracted quantities and carry out downstream analysis and procedures. (Vieira et al., 2022)

One of the main issues for BIM-based QTO is the modelling quality and consistency, this is because of the lack of modelling guidelines that obstructs the quantity take-off process. The model should be created in a way for the quantity surveyor to easily understand the project (Khosakitchalert et al., 2019).

Meanwhile, Smith (2016), describes that part of the limitations that a BIM-based QTO and CE confront is the incomplete/inaccurate data. He states that the main reason evolves around whether the design fees include allowance for the input of fully comprehensive data and whether the BIM team have the expertise/knowledge/information to input the necessary information into the model. Many clients do not see the value in paying the necessary fees for comprehensive models or may not have sufficient knowledge/advice to know whether this has been achieved.

Also, Olsen & Taylor (2017), study assures that one of the main limitations is the size of the BIM models. BIM models can become increasingly complex, and they can lead to having extremely big files to manage and extract the quantities of the project can be time consuming and may require specialized expertise to understand and interpret the data effectively. It is mentioned that for a more manageable model is necessary to divide the model according to its purpose, and just integrate the necessary information into the 3D model.

Another aspect mentioned by Olsen & Taylor (2017), is the level of information in a 3D model, both geometric and alphanumerical, not corresponding to the phase of the building lifecycle. Sometimes, the model may not include all necessary information at the desired level of granularity, leading to limitations in accurately quantifying specific elements or attributes. A clear example of this may be that the 3D model shouldn’t be the same for a QTO for a schematic design phase and a construction phase.

For some projects, the problem resides in the manual interventions to create a QTO and cost estimation process. These manual interventions involve data exchange and addressing elements and activities that were not initially modeled but are necessary to be included in the project's supplementary documentation, which covers quantities and specifications. Having a highly detailed model would solve these challenges. However, creating such a model for designers may require resources that are potentially unjustifiable, representing an obstacle for efficient and accurate quantity take-off (Vieira et l., 2022).

Lastly, Choi et al. (2015), mentions that one of the issues that a quantity take-off process may suffer is the lack of interoperability between the involved parties. Quantity take-off relies on BIM software tools, and limitations in software compatibility with other tools can affect the efficiency and accuracy of the process. Incompatibility between different software applications or versions may hinder data exchange and integration.

Even though there are several limitations to a quantity take-off and cost estimation process, the benefit of using a BIM-based process is more favourable than the traditional QTO. According to the research made for this work, one of the main issues, which are not mentioned by most of the researchers previously cited, is the lack of international standards for creating a model for accurate quantity take-off process, international units for the involved measurement and rules to measure the elements.

It is necessary to be aware of these limitations and to learn how new studies are making their way to make this process more accurate and accessible. Each of these limitations may be solved through a well-organized workflow, a set of rules between the involved parties, constant supervision and working in an open-base format. Most of the researchers previously mentioned, created a solution and suggestions for many of these limitations and how to handle them, which will be described in the chapter 2.3.5.

2.3.3. Quantity Take-off through construction phases

According to Zaman & Nast (2022), the quantity take-off and cost estimation process should be done according to the stage of the lifecycle of the project. Depending on the purpose of the QTO, less or more information should be added to the model. In this study, each phase is studied according to a respective level of detail.

- <u>Schematic Design:</u> Through this phase an initial concept estimate is effective and a fast route towards the calculation of the cost of a project and enables decisions to be made rapidly and with certainty. During the phase of concept design is mainly used to examine and determine which design option is viable.

  This is carried out by using an elemental format and explains each elemental unit rate and quantity by dealing and working with the overall massing model in any authoring tool. Not everything should be modelled and 2D on-screen measurement should be implemented when necessary.

- <u>Developed Design:</u> This presents an elemental format for detailing the generic building materials, finishes, and services standards. In this case, the model is mapped, and a general pricing code is added to the model information. This is needed to generate a more well-organized structure for the QTO. Also, elements should be represented as a whole and not divided into all the materials or works involved.

- <u>Construction Design</u>: Through this stage the cost plan should show a hierarchy of the elements involved in the project, with specific construction materials, finishes, and works involved in each task.

  At this stage of development, more costing detail is added to the model information. Each element should be defined by a hierarchical coding system which enables us to integrate the labor and materials involved in each element and its corresponding cost (unit and total).

Table 3 – Cost estimation through project phases. Adapted from: (Zaman & Nast, 2022)

	Schematic Design	Developed Design	Construction Design
3D modelling	Data which is non-geometric or line work, volume, or areas.	Showing purpose and maximum size of 3D generic elements.	The information of geometry of particular elements of the 3D object with dimensions, space relationships and capacities.
Cost estimation	Conceptual such as cost per square foot or cubic foot.	Mainly consists of measurement of general elements.	Mainly consists of measurement of specific assemblies.

Generating a quantity take-off and cost estimation process by defining the phase of the lifecycle of the building is a reasonable approach that generates some sort of rules for a better management and quality of the Bim model. As stated by many of the studies cited in this work, one of the most important aspects of any process relying on a BIM methodology is defining a purpose and generating a 3D model according to its functionality.

By dividing the project into distinct phases, quantity take-off can be performed more efficiently and accurately since each phase has unique requirements and information. It gives a glimpse of how the result may be and it can be complemented by Level of information need to generate a clearer idea of how to manage both the project and each of its elements.

2.3.4. Level of Information Need

The level of information need is a framework that defines the quantity, quality, and granularity of information requirements. Defined and studied by British Standard in their BS EN 17412-1:2020 standard, it is used to communicate a clear degree of information according to its purpose.(Bolpangi et al., 2021)

The level of information need framework helps in determining the essential information requirements for each specific purpose. Any extra information beyond these requirements is considered unnecessary and should not be specified. The “over definition” or “under definition” of the information requirements are considered risky since they don’t support efficiency for the use of information. These are aimed for all the actors involved in the asset lifecycle (owner, asset manager, design team, technical specialists, etc.). (The British Standard Institution, 2020)

The document specifies the characteristics of different level used for defining the detail and extent of information required to be exchanged and delivered throughout the lifecycle of the project and it gives guidelines for principles required to specify information need, just as shown in the Figure 14.

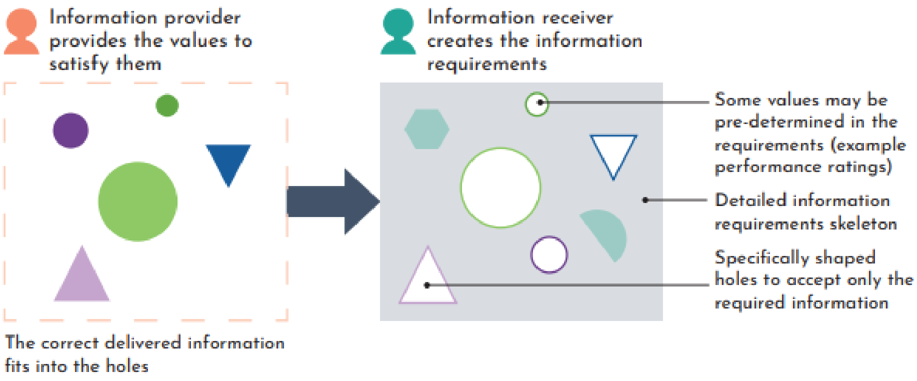


Figure 14 – Level of information Need. Source: (Bolpangi et al., 2021)

The level of information need is usually defined by the client according to the purpose of the project. This may differ according to the stage of the lifecycle, which may require more or less information according to the requirements of the client. For example, during the design and construction process is possible that more information will be required by the client. (Bolpangi et al., 2021)

According to (The British Standard Institution, 2020), there are some prerequisites to be considered to specify the level of information need and how it should be delivered:

- Define a purpose for the use of the information to be delivered.
- Information delivery milestones for the delivery of the information.
- Actors who are going to request and actors who are going to deliver the information.
- Objects are organized in one or more breakdown structures.

Following this, the level of information need should be described by different concepts:

- **Geometrical information**: refers to data related to the shape, size, position, and orientation of objects in a three-dimensional space. This shall be defined by detail, dimensionality, location, appearance, and parametric behavior.
- **Alphanumerical information:** consists of data represented using alphanumeric characters, such as letters, numbers, and symbols. It is defined by the standard by identification and information content.
- **Documentation.** It refers to the documents for an object or set of objects that are required to support processes, decisions, and verification of information deliverables. Usually, it is composed by technical requirements, documents for approvals, manuals, photographs, sketches, signed documents, etc.

  Documentation can integrate one or more construction elements, spaces, construction entities, etc. It can be related to other information containers by linking, attaching, or referencing to the information model by using classification and identification methods by using breakdown structures. Also, it can be interoperable and machine interpretable.

Since the study is main focused on the process of Quantity Take-off and cost estimation, the level of information need will be defined by geometrical information and alphanumerical information, documentation is not required, this is because this type of information is more related to installation manuals or technical documentation, which is not an output of this process.

2.3.4.1. Geometrical Information

According to The British Standard Institution (2020), the geometrical information mainly refers to the geometric characteristics and properties of construction objects and elements. As mentioned before, the geometrical information is divided by:

- **Detail**. The aspect of geometrical information that describes the complexity of the object geometry compared to the real-world object. It can be classified as simplified or detailed. This depends on the phase of the project since it can contain more features or be more decomposed to become a better approximation of the shape of a real-world object, just as shown in the Figure 15.

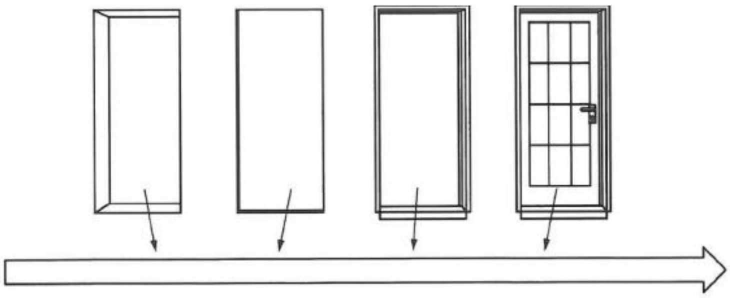
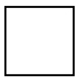
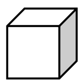


Figure 15 – Detail by BS EN 17412-1:2020. Source: (The British Standard Institution, 2020)

- **Dimensionality**: dimensionality is the number of spatial dimensions that characterize an object. It can be divided as shown in Table 4.

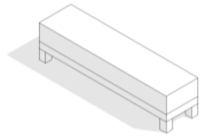
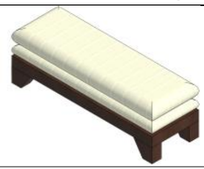
Table 4 – Dimensionality by BS EN 17412-1:2020. Adapted from: (The British Standard Institution, 2020)

DIMENSIONALITY		
Dimension	**Description**	**Example**
0D	Location point of the object.	●
1D	Line, curves, or paths.	———
2D	Surface or face of the object.	
3D	Body or volume of the object.	

- **Location**: refers to the placement and orientation of an object. It can be absolute, against a reference point, or relative, against another object.

- **Appearance**: The appearance describes visual representation of an object. According to the standard this may be classified from symbolic to realistic compared to the real world, just as shown in the Table 5.

Table 5 – Appearance by BS EN 17412-1:2020. Source: self-generated.

Appearance Scale		
SYMBOLIC	It refers to a simplified or abstract representation of an object.	
REALISTIC	It aims to fully represent an object's physical attributes such as textures, colors, or other visual details.	

- **Parametric Behavior:** It describes whether the shape, position and orientation are dependent on other information associated to the object, into which the object is placed, allowing full or partial reconfiguration.
  This behavior can be transferred as part of the information delivery or not. For information exchange the parametric behavior can be fully, partial, or not requested. I can also be divided according to its degree of parametrization:

  - Explicit geometry: It defines the shape as a boundary representation (vertices, edges, and faces) that doesn't allow shape modification by any other parameters.

  - Constructive geometry: It defines the shape of the object as a constructive solid geometry based on primitives and swept solids that allows modification of it through shape parameters.

  - Parametric geometry: Defines a singular shape or group of shapes by equations that provides values for the shape parameters allowing their modification based on object or context characteristics.

2.3.4.2. Alphanumerical Information

Alphanumerical information refers to data that contains both alphabetic characters and numeric characters in a mixed format. This type of information often includes text-based descriptions, codes, identifiers, labels, or any other data that combines letters and numbers to represent specific items, elements, or attributes. According to the The British Standard Institution (2020), it can be divided into two main elements:

- **Identification**. Its purpose resides in providing a breakdown structure identification to an object. This can consist mainly on assigning a name, standardized coding system or an international identification format to the object. A clear example of it could be: Uniclass classification system.

- **Information content:** The information content refers to a list of properties or attributes that are required to fulfill the purpose of the project, as shown in the Figure 16.

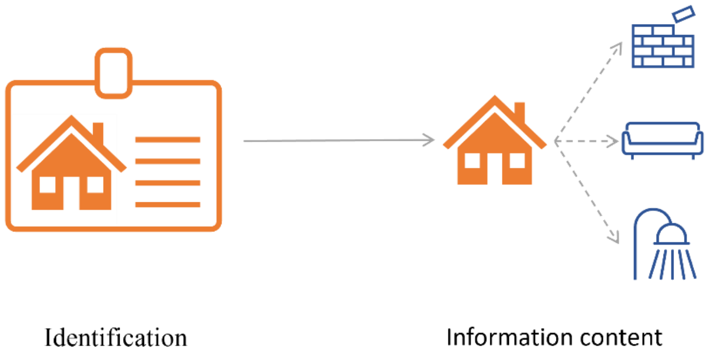


Figure 16 – Alphanumerical information by BS EN 17412-1:2020. Source: self-generated.

Based on the previously mentioned concepts, this methodology offers significant advantages to all stakeholders involved in different lifecycle phases of built assets. It shares an understanding of the appropriate level of information required to avoid unnecessary information overload. Defining the level of information need aims to prevent the delivery of excessive information. Effective information exchange ensures that the right information is delivered for the agreed-upon purpose, facilitating verification and validation processes.

In the scope of Quantity Take-off, both geometrical information and alphanumerical information shape and define the process and its content due to their complementary roles in representing and organizing data. The geometry of the project's model is the one that generates the data for the quantity taken off per element, which can be mapped and measured by the alphanumerical data that represents it. In this process both types of information are dependent on each other and settles the base content for the cost estimation.

Following what is mentioned before, it is important to establish a level of information need defined by both types of data mainly focused on the project purpose. More information of the level of information need related to quantity take-off and cost estimation and how they were defined for the purpose of this work is described in the chapter 3.3.3.

2.3.5. Process for quantity take-off and cost estimation through BIM

Quantity take-off and cost estimation is a process that requires different factors to generate an accurate and precise quotation. At the moment, there is no standard that determines the more fitted workflow or rules to manage a 3D model to generate a project's quotation.

As mentioned before, a BIM-based quantity take-off has revolutionized this process by turning it into a more well organized, accurate and time-saving process. Through several approaches, nowadays, estimators and quantity surveyors utilize intelligent 3D BIM models to extract accurate quantities of materials, components, and jobs for construction projects.

It is important to understand and get to know different workflows on how a QTO is created and managed. These processes may depend on the intention, techniques, and the tools that the researcher is using in order to accomplish the purpose.

2.3.5.1. Visual programming quantity take-off framework

Zaman & Nast (2022), developed two separated workflows to approach quantity take-off and cost estimation through different tools. For both procedures they used Revit 2021 as the authoring tool stating that the main purpose of this decision resides in Revit being considered one of the most used software's in the AEC industry.

Through the study they explain step by step the whole process to generate a QTO and CE for a building. It is stated that their workflow is defined by the 3D modelling of the project in Revit, then they generated some nodes to extract the desired information of the model and finally exported in excel as a final document for quotation, just as shown in Figure 17.

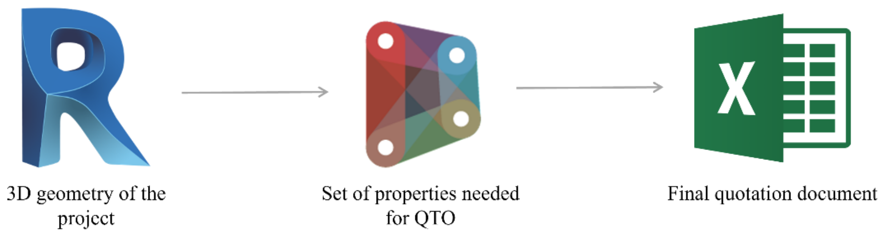


Figure 17 – Revit, Dynamo and Excel workflow. Adapted from: (Zaman & Nast, 2022)

As defined by Zaman & Nast (2022), this process consists of three steps: modelling, setting properties and the final quotation. Each of them is dependent on each other and assures updated information by using a visual programming platform like Dynamo.

Before starting to model the project, they generate some properties to add the information in the objects, they decided generate project parameters. These parameters are unique to every individual project, this means they are applied just to the project where they are created and cannot be shared to other projects. The type of parameters settle in this step includes mainly general cost of item, cost per material, dimensions of implemented materials, volume of an object, etc.

After creating the necessary parameters per element, the 3D geometry of the project should be generated. The main purpose of this step is to arrange and create a dataset on which further actions could be performed. This allows data and information to be loaded, edited, or delated at any instance of the project. Also, they mentioned that for this process is necessary to use correct object for them to be mapped properly, this means that, if a wall is generated it should be by using the tool “wall” on the modelling tools, not by creating a generic model or similar.

The next step for this workflow is to create a script by using a visual programming tool, which in this case the selected platform was Dynamo. Dynamo is a plug-in that in this case is used to take out all the required information of the elements that are involved in the project. How it works is defined by using general nodes of dynamo to generate a list to export to excel. Also, by using this platform they mentioned they ensure constantly updated information if any changes are made in the program by running the script at any change made in the project.

As shown in the Figure 18, the scripting process is done per categories since there are different types of “families” in their project. As they extract the selected properties per element, they generate a list by using the node “List.Create”, which combines all the data into a single list and then transposed to settle the number of rows and columns of the table. Lastly, they define a parameter of the name of the categories to generate the table for Excel to recognize the parameters’ data when exported.

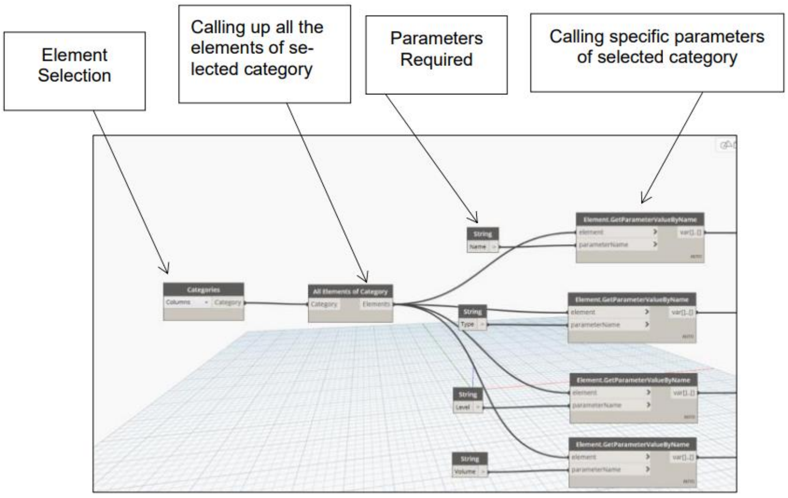


Figure 18 – Script to extract properties. Source: (Zaman & Nast, 2022).

To extract the quantities, the script can extract certain quantities defined by the parameters set in the first step of the process. When an extraction requires calculation or another operation, it must be done through the script and not in the excel file. An example of this can be the computation of the height of a column or the calculation of the bars needed for that column, just as shown in the Figure 19.

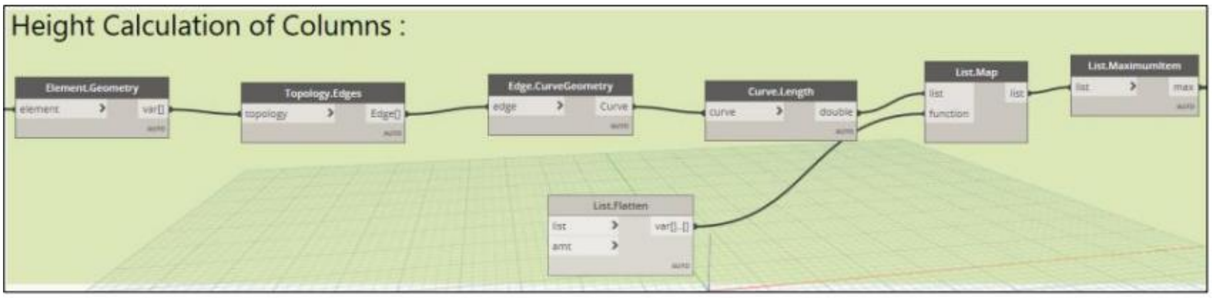


Figure 19 – Example of a script for calculation of objects. Source: (Zaman & Nast, 2022).

The last step for this workflow is to integrate one node for exporting all the lists into a table in Excel. This table contains the overall general and specific information of the quantities and costs involved for the elements that composed the project. When exported some style configurations shall be made to present a quotation.

Overall, this process is well structured, easy to understand and to apply and the final quotation is automatically generated by the software and in an open format file. But, compared to the other workflows bellow mentioned, lacks several steps to generate an accurate and proper quantity take-off.

One of the main issues of this workflow is the management of the resources. First, it happens when generating too many properties per element in the authoring software, an example of this is the category “cost” created as a new parameter. In Revit each family allows to enter a base cost of the element in their properties. By generating more attributes in the authoring tool, the size of the file gets bigger, and it may cause troubles when the size of the project is big.

Another issue of the management of the process is mainly in Dynamo. At the end of the paper, a screenshot of the entire script is added, and it looks like an overload of nodes, that may not be the best solution especially if the file is going to be opened by another user. It can cause confusion and it’s hard to keep track of the parameters and calculations per object. One of the most used ways to manage this is to generate these calculations directly in Excel or in software to generate quotations. The model is easier and smaller to manage and is easier and better structured for understanding.

2.3.5.2. CPI-based quantity take-off (RIBITWO 5D)

The following workflow also defined by Zaman & Nast (2022), is generated through iTWO, which is a cloud base-platform for management and construction for buildings. To generate the final quotation the process consists of three steps between the tools, just as shown in the Figure 20. The first one consists on defining and generating a 3D model in Revit which will be exported as CPI file to translate the geometry and alphanumeric information into an iTWO readable file. The las step consists in adding work and cost to each element and generating a final quotation of the project.

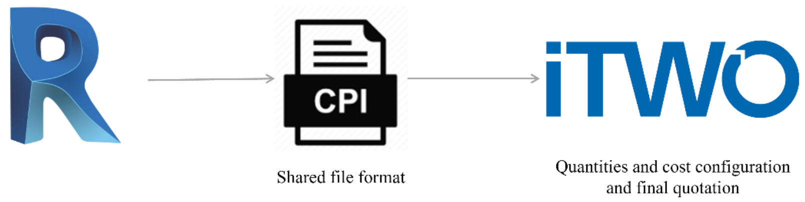


Figure 20 – Revit, CPI and iTWO workflow. Adapted from: (Zaman & Nast, 2022)

For the whole process to work, it is necessary to install the RIB iTWO plug-in for the authoring tool, in this case, Revit. By using this plug-in, the option of CPI export is selected to generate a file that will be recognized by iTWO. The CPI stands for Central Project Information, which serves as the central repository that hosts all project information, including the building model, views, sheets, annotations, and other project-related data.

When exported into an CPI file, the software asks for a quality check up so iTWO would recognize all the elements in the project. The process consist in the examination and improvement of the 3D building model and helps the transfer of data into the iTWO 2021 database. It comprises several other functions which include room correction, intersection check, etc. to evaluate the quality of the imported data. (Zaman & Nast, 2022)

As a result of the last step an analysis is run for the 3D model and the results of it marks many erros that the user has to solve in order for the export to be finnished. Fortunatelly, the software generates a list of the issues in the model and gives a sample of the quality of the project, just as shown in the

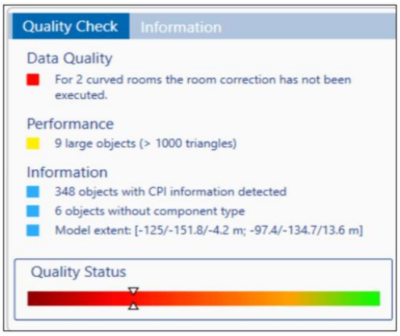


Figure 21 – Quality check for CPI. Source: (Zaman & Nast, 2022)

The authors disccuse that the inaccuracy of the model showned by the platform which resides on mainly the geometry of the model, incorectly assigned component types, or the intersection of componenets. For the export to work properly is suggested to adress as many issues as possible. This step helps the model to be more accurate and supervised compared to the first workflow shown in the chapter 2.3.5.1.

As a next step after the model checking process, the export has to be done in CPI throught the plugin on the authoring tool. Then, a list of all the works, items and materials involved in each activity should be generated by mapping properties of each element, which if they are made correctly, when another CPI file is exported and integrated into the iTWO file, all the properties should be recognized automatically and won't be necessary anymore. Also, during this process all the rules of measurement and formulas shall be created in the iTWO software for them to work properly.

Something that is important to state is that in order to generate a succsesfull quantity take-off, each element shall be calculated individually so the software will generate an automatic fuction to calculate the total of the elements.

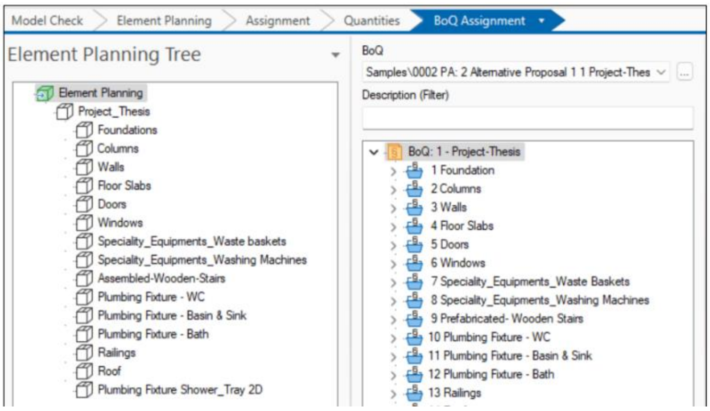


Figure 22 – Assignment window per element. Source: (Zaman & Nast, 2022)

After generating this measuring rules, shown on the Figure 22, each element is divided by categories and planning works. The relationship of each element must be done by the user. Finally, a quotation is generated by the software which can be used by many users thanks to the cloud-based software.

This workflow is a more realistic and reliable way to generate a quantity take-off and cost estimation process. It is important to highlight that includes a quality check step and if the model is not well prepared it is not possible to generate a quotation. This is important since it assures that the data is going to be accurate, since each element was analyzed through a modelling criterion which purpose is to have a better-quality 3D model for the quantity extraction process.

As a downside, the two processes generated by Zaman & Nast (2022) lack of explanation of modelling criteria and a missing classification system. This may affect the accuracy of the elements as well and by using cloud-based software, a classification system is needed to clarify to other stakeholders the nature of each element in the project. Also choosing the CPI format instead of the IFC format might not be the best choice. Let’s remember that iTWO is a cloud-based software that allows other stakeholders to take part in the project, and IFC is a format that involves collaboration with external teams using different BIM tools and prioritize open standards for data exchange.

2.3.5.3. Semi automatized quantity take-off framework

The next workflow was created by Vieira et al. (2022) and it proposes a BIM-based framework for automatized coordinated construction specification and quantity take-off. It involves definition of modelling requirements, creation of a construction specification database and an add-in for the authoring tool that generates construction specifications and quantity take-off automatically. Its purpose is to generate a workflow that mitigates the number of non-automatized intermediary steps by mainly using the authoring tool.

As described by Vieira et al. (2022), the framework consists mainly on three cross-referenced dimensions: an approach of definition of Level of Information Need, development of a structured database for external specification and creation of a Revit add-in to integrate the BIM model to the proposed DB, just as shown in the Figure 23.

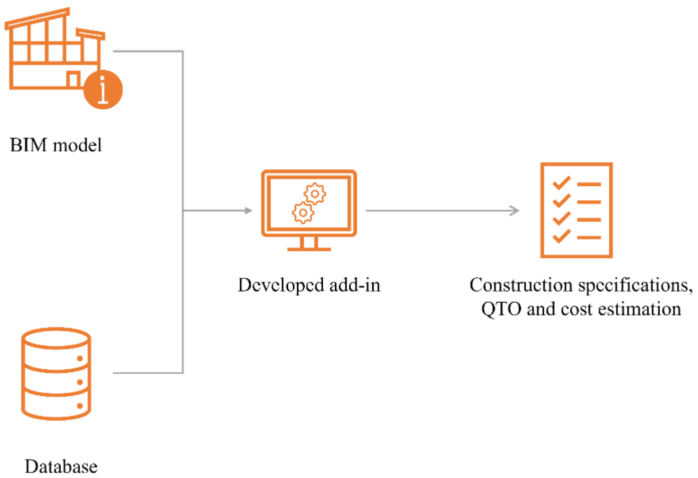


Figure 23 – Semi automatized QTO workflow. Adapted from: (Vieira et al., 2022)

The proposed system maps 116 categories of construction elements. It also includes modelling requirements for elements and activities with a physical quantity and proposes solutions for elements that are small or don't need a representation on the 3D model. (Vieira et al., 2022)

All of above-mentioned systems are worked under the use of a classification system (Uniclass 2015). It is characterized as the core of the workflow since the code defines the construction elements and activities since it sets the link between the BIM model and the external DT, allowing the coordination of information stored in both. Also, is important to mention that besides the classification system coding it was necessary to add a higher level of information specification by adding a suffix to the code.

Another important aspect of this work is the generation of modelling specifications for quantity take-off. They were divided into two main groups: objects graphically expressed in the model and objects, activities and interventions not graphically represented in the BIM model. The first one defines objects considering the most suitable category to ensure access to the correct property set and level of information need for QTO. The second one refers to all objects that do not possess any graphical representation in the BIM model. The reason why resides in modelling simplification or intangible characteristics.

Also, some other considerations for modelling were integrated. It is stated in the work that instead of using compound elements (layered elements), each layer will be modelled as an independent element according to their real dimensions, as shown in Figure 24 .Even if there are tools to work as a compound element it was preferred to continue this way to avoid limitations in the management and use of attributes necessary for the study.

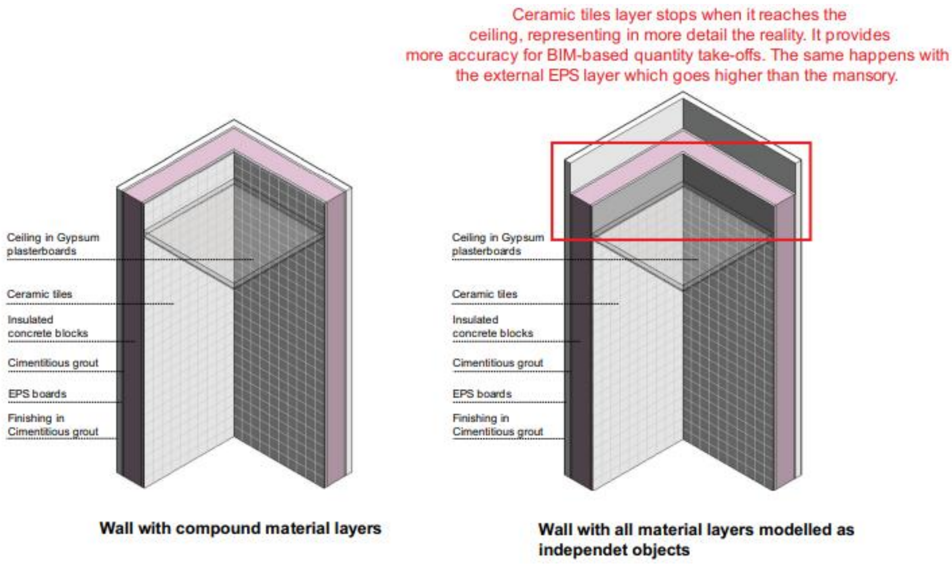


Figure 24 – Compound vs independent layers. Source:(Vieira et al., 2022)

The second step consists on generate a database structured according to the classification system. Its importance resides in its function since it is necessary to centralize specification information at the organizational level, connecting it with instances of the BIM model by matching their classification codes with the elements and activities. The database is created by linking the different elements inside of it, this means that if one item is changed, all the other items related to it will change.

Also, a graphical user interface, Figure 25, based on VBA programming language, was developed for managing the database, allowing users to check, query, add, edit, and delete instances. (Vieira et al., 2022)

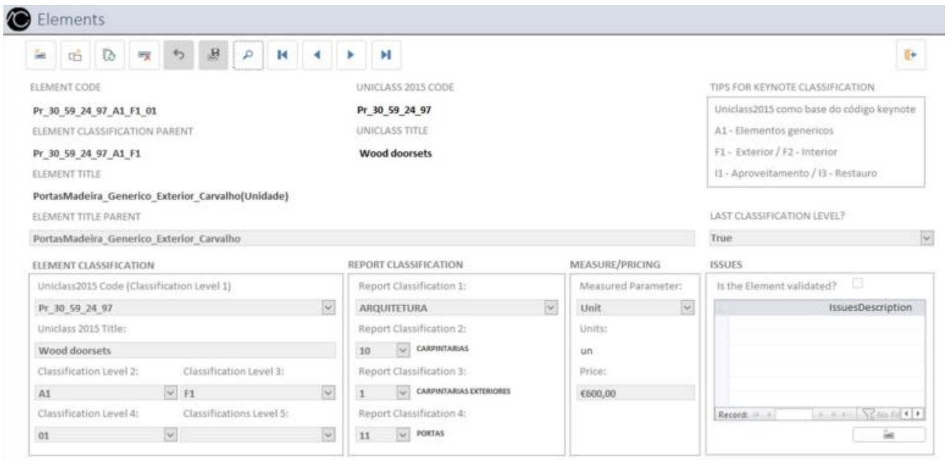


Figure 25 – Graphical user interface for database. Source:(Vieira et al., 2022)

The third step of the workflow is the generation of the add-in for Revit 2020, named TIE (Technical Information Exchange). It retrieves data from the BIM model and correlates it with the specifications stored in the database to generate specifications and quantity take-off documentation. This process identifies digitally represented objects and activities in the BIM model using their classification codes and matches them with their corresponding instances in the database.

Lastly, the quantity take-off and cost estimation report can be made. To do so, a model checking, and validation is integrated to the workflow and after it, the script generates a coordinated specification, QTO and cost estimation report in Excel spreadsheets, when minor adjustments can be made. It also highlights the errors that might occur and informs the user how to fix them. After addressing the errors, the user can generate a new report without issues.

This study is a clear example of how to manage a quantity take-off, cost estimation and specification process. It involves several key elements to ensure accuracy and efficiency, and most of all a well-constructed structure. Also, is important to mention that this workflow was done for small and medium companies, that’s the main reason why the study is mainly focused on using just one or two main tools to generate the QTO report. It opens the possibility of precise and accurate information to this type of actors without generating a big expense regarding software licenses.

As mentioned before, this workflow was aimed to generate a QTO and CE process through a semi automatized workflow by using a well-structured database. It would have been interesting to integrate an OpenBIM approach. Right now, the whole workflow is only thought for one authoring software, relying only in a closed BIM base for architecture. By adding an OpenBIM approach, it could have made an interesting way to integrate interoperability since OpenBIM grants an open and collaborative approach by allowing seamless information exchange between different software tools, ensuring full interoperability, and avoiding data silos between stakeholders.

2.3.5.4. OpenBIM workflow (IFC2X3)

The last workflow presented on this work presents an OpenBIM approach for quantity take-off created by Choi et al. (2015). The main goal of the study is to generate a quantity take-off and cost estimation process by using IFC for the schematic design phase. As stated by the authors the main core resides in the BIM model and a database for unit cost information.

As shown in the Figure 26, the workflow is composed by four main steps: the generation of a BIM model, verification of the physical quality of the model, each elements’ properties verification and finally the quantity take-off. All the exchanges done between each step is by using an IFC 2x3 format.

For the first step of the workflow the author refers to the AIA, the American Institute of Architects, to set a LOD, level of detail, according to the purpose and the scope of all the objects that are going to be used in the project. Since the study is mainly focused on a schematic design, the level of detail suggested by domestic and international guides is the LOD 2 which refers only to the physical representation of the object, with requires them to be generic elements with maximum size, approximate shape, location, quantity, and orientation.

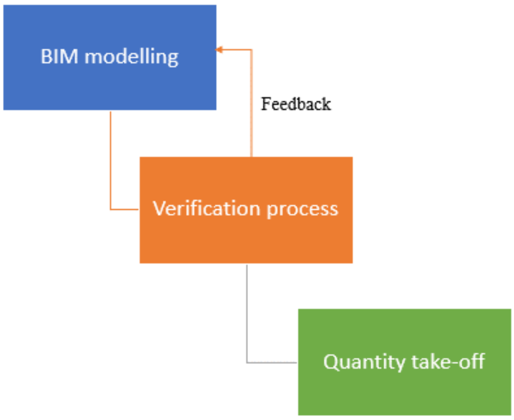


Figure 26 – Openbim workflow. Adapted from: (Choi et al., 2015)

Choi et al. (2015) explains that for this phase of construction (schematic design) is possible to calculate the quantity of basic building elements by sorting them according to their IFC structural property. By following the IFC schema the authors decide to focus mainly of 5 elements that take part of the architectural systems defined by IFC 2x3. These elements are beams, columns, slabs, stairs, and walls.

When the model is complete a project parameter is added to all the categories in the authoring software to add a classification system defined by the authorities of South Korea named ""Construction Code Operating System – Construction Classification". This coding system defines the element according to South Korea's regulations and gives a unit of measurement per element.

The next step of the workflow is the verification process which is mainly divided into two parts: physical and properties verification. The physical quality of the project is checked by settling minimum requirements for the shape representation and intersections among the elements. This process is done through Solibri Model Checker for a more accurate quantity take-off. The properties verification is done through InSightBIM pre check and it creates errors if any object doesn't possess a correct code.

The last step of the workflow is the quantity take-off which in this case is divided into two main parts: one that includes all the reinforced concrete elements and the other that includes all the steel building frame. The reinforced concrete elements can be extracted through the IFC schema, which only needs to map every object and relate it with their corresponding code. For the steel frame the quantities are mainly extracted by using the length of each object. Additional elements that take part of the QTO are calculated by using formulas based on the exported objects.

This process evaluates new possibilities for a quantity take-off and cost estimation process by generating the whole process using mainly IFC files for information exchange, generating a more efficient option for communication and collaboration between stakeholders. Since the work is mainly focused on a schematic phase of design there is not too much detail included when generating the elements or a pure definition of accuracy between the different parts of a single element (ex: walls). Following this logic, as the construction of the model is done, it isn't mentioned any type of modelling guidance to facilitate the modelling process or to set a base of rules for other stakeholders use the same logic as they did. Lastly, since the study was created using the IFC 2x3, the study is outdated and may vary if another actor wants to put it into practice.

3. QUANTITY TAKE-OFF AND COST ESTIMATION METHODOLOGY

3.1. Establishment of quantity take-off and cost estimation methodology

Quantity take-off is a key process for the development of a project since it establishes its budget, allowing the client to evaluate the feasibility of a project and it may lead to adjustments in the design and management of the project. This is why generating an accurate, consistent, and reliable QTO and CE is an important process in the lifecycle of a building.

This following work presents a different workflow in order to generate a quantity take-off through an OpenBIM approach with a seamless integration of BIM data by generating consistency in the modelling practice through the establishment of modelling rules. The purpose of this workflow is to break down building projects into a simpler deliverable-based work breakdown structure, to have a more organized and accurate cost estimation of the components of the project and their involved costs.

According to the research paper done by Martins (2018), a conventional workflow for a BIM-based QTO and CE process is represented by five main steps, as shown in the Figure 27. The initial step involves the generation of a BIM model per discipline within the authoring tool. The next step the workflow determines the systematic extraction of project quantities, often generated by the authoring tool by using automated QTO. The subsequent step consists of the integration of the works and materials for each element of the project to export the data to a spreadsheet. The next step is to map the elements and assign a correct price according to supplier specifications to generate a cost estimate.

The main issue with this approach resides in its lack of consistency. If the model doesn't fit the suppliers' specifications it could require a reconfiguration of both construction materials and works, or even a modification on the 3D model making the user repeat the entire cycle again. This cycle repetition can, consequently, result in a waste of time and resources. Also, this process lacks a verification step to determine if the model is well-modelled or if any information required to the construction of the project wasn't included in the report.

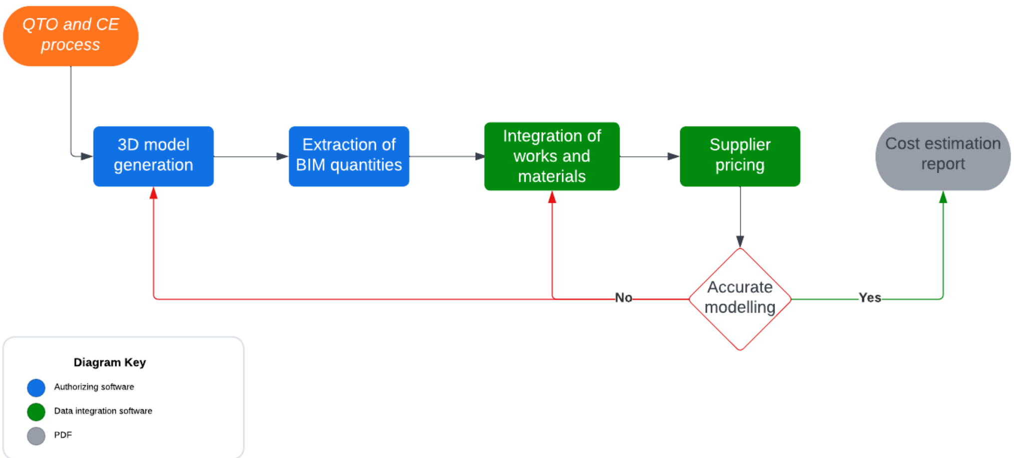


Figure 27 – Traditional BIM based QTO and CE workflow. Adapted from: (Martins, 2018)

The presented workflow addresses the challenges that a traditional BIM based QTO and CE faces. As shown in the Figure 28, the workflow is composed by five main steps: Definition of a WBS, 3D model generation, verification, cost assign process and cost estimation report. The entire workflow looks for data consistency, accuracy of quantities extraction, and the definition of a proper level of information need for each architecture element studied in this work. All of this managed through an OpenBIM format, IFC.

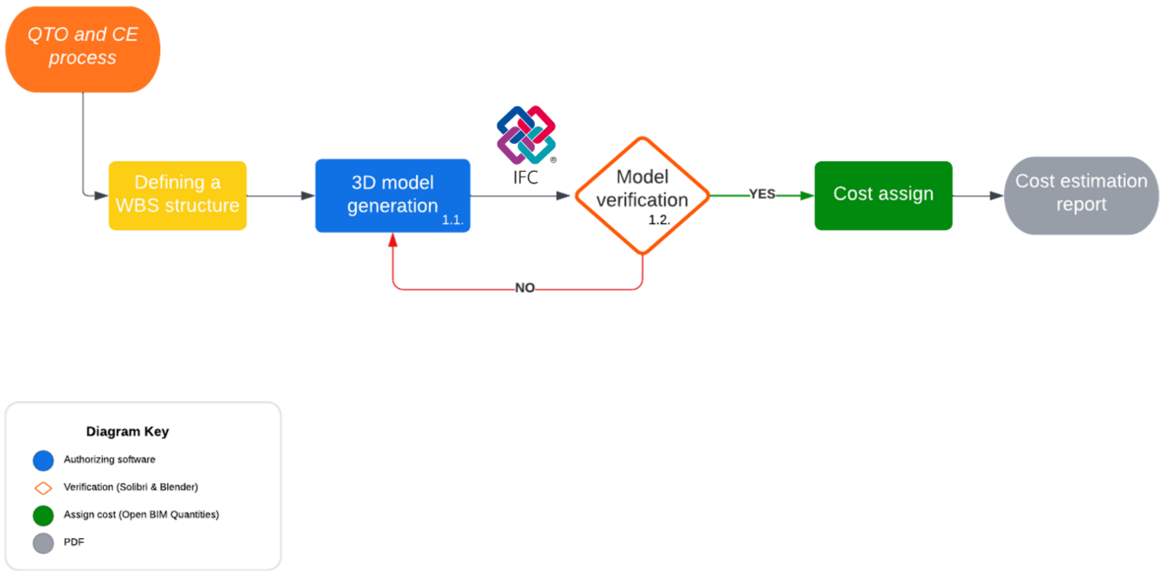


Figure 28 – QTO and CE workflow.

3.2. Work breakdown structure definition

Consistency in data is one of the main problems presented by Khosakitchalert et al., (2019). Inaccuracies or discrepancies in data may lead to mistaken estimations and subsequent a non-well generated cost estimate of the project. Consistency in data guarantees that the estimators are working with reliable information and one same "language" between the stakeholders. This facilitates effective communication between all the involved parties as everyone is on the same page regarding specifications and requirements.

The proposed methodology starts by introducing a work breakdown structure to the project as a strategic approach to ensure accuracy and reliability for the process. First, defining a WBS for the project is needed to stablish the elements that will compose the project and their respective components (unit of measurement, materials and works needed, and if possible, their cost). Second, through the WBS structure a hierarchical nature is established in the project, this allows a systematic breakdown of the before mentioned components and their respective tasks for a better understanding and management of each of them. Third, according to the coding system that a the chosen WBS should have, it provides a foundation for traceability. The coding schema allows seamless interconnection of individual instances across the different QTO stages proposed in the methodology. When revisions or updates are done, the coding system allows automatic synchronization between the modified model and the rest of the process.

For the scope of this study, the selected work breakdown structure is defined by the Generador de Precios by CYPE. This WBS provides all the necessary elements to generate a proper quantity take-off: a hierarchical structured database that allows modifications according to the user's need, coding system, unit of measurement, a list of materials and its necessary works to generate a cost estimate report.

The first step to establish the WBS of the project is to select the materials that are going to be used in each element that composes the project. As shown in the Figure 29, the Generador de Precios has three main elements used for this step. The blue square is all the elements that compose the selected element, in this case, the materials that compose a concrete slab, each of this can be modified when selecting the specific material and setting the properties shown in the orange rectangle.

Figure 29 – Parts of Generador de Precios.

The code of the selected material and its unit of measurement is shown in the red rectangle of the Figure 29. It is important to mention that this code is defined by a general code system that the database provides according to the selected material, it doesn't change when the properties are modified. This may be a small issue when you have the same category for one object, but its properties are different. For example, the cost, materials needed, and the description of a 25 centimetres slab is not going to be the same as a 30 centimetres slab, but the code in the WBS will remain the same for both.

To address this issue, an effective strategy is to integrate an additional identifier (suffix) to the coding system. As illustrated in the Figure 30, the code structure is composed by three distinct components: firstly, the WBS code; secondly, a designated number for the proposed material; and thirdly, a numerical indicator denoting the variations withing the WBS. The variation number is defined by instances characterized by identical identification, yet differentiated by the properties settled by the user, just as explained in the example of the previous paragraph. The parts of the code should be separated by an underscore. A precise establishment of the coding system holds a significant importance, as it is the core of the linking between the model and its corresponding materials and works.

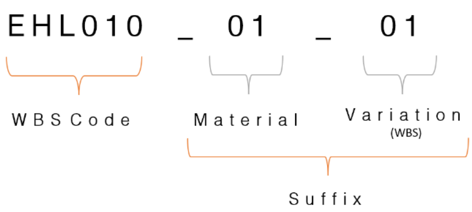


Figure 30 - Coding system.

As a suggestion, to have a better control and management of all the selected materials per instance it is better to generate a table similar to Table 6. The table is categorized based on floor levels, subsequently segmented by architectural instances, each of them with their respective coding system. It is important to add the name for a better understanding of how the instances are being composed. Furthermore, the addition of their respective description and code suffix to distinguish instances with identical materials, but with differences that resides on their respective properties.

Table 6 – Example of WBS table.

Code	Suffix	Item	Layer	Description	Unit
First floor					
Slab					
EHL010	_01_01	Losa maciza	Main Structure	Losa maciza de hormigón armado, horizontal, con altura libre de planta de entre 3 y 4 m, canto 25 cm, realizada con hormigón HA-25/F/20/XC2 fabricado en central	m2
RSG120	_01_01	Pavimento interior de piezas de gres porcelánico esmaltado.	Finish	Pavimento interior de piezas de gres porcelánico esmaltado, de 200x200x10 mm, gama alta, capacidad de absorción de agua E<0,5%	m2
RSM050	_01_01	Rodapié de madera	Map element	Rodapié de madera maciza de pino, de 60x10 mm, acabado barnizado en taller, fijado al paramento mediante adhesivo.	m
Wall					
FSM010	_01_01	Sistema ETICS de aislamiento térmico por el exterior de fachadas	Exterior layer	Aislamiento térmico por el exterior de fachadas, con sistema ETICS, compuesto por: panel rígido de poliestireno expandido, según UNE-EN 13163, de superficie lisa y mecanizado lateral recto, de color blanco, de 60 mm de espesor, fijado al soporte con mortero	m2
EHM010	_01_01	Muro de hormigón	Core layer	Muro de hormigón armado 2C, de hasta 3 m de altura, espesor 30 cm, superficie plana, realizado con hormigón HA-25/F/20/XC2 fabricado en central, y vertido con cubilote	m3
RGS010	_01_01	Revestimiento con mortero acrílico	Interior layer	Revestimiento decorativo en fachadas, con mortero de naturaleza sintético mineral, de 2 a 3 mm de espesor, color Blanco, acabado fratasado.	m2
Door					
LPM010	_01_01	Puerta interior abatible, de madera.	none	Puerta interior abatible, ciega, de una hoja de 210x82,5x4 cm, de tablero aglomerado, chapado con pino país, barnizada en taller, con moldura de forma recta	Ud
Second floor					
Roof					
EHL010	_01_02	Losa maciza	Main Structure	Losa maciza de hormigón armado, horizontal, con altura libre de planta de hasta 3 m, canto 25 cm, realizada con hormigón HA-25/F/20/XC2 fabricado en central,	m2
QDB010	_01_01	Cubierta plana no transitable, no ventilada, con grava, tipo convencional.	Finish	Cubierta plana no transitable, no ventilada, con grava, tipo convencional, pendiente del 1% al 5%. FORMACIÓN DE PENDIENTES: mediante encintado de limatesas, limahoyas y juntas con maestras de ladrillo cerámico hueco doble y capa de arcilla expandida, vertida en seco y consolidada en su superficie de cemento	m2

3.3. 3D model generation

For the scope of this project, it was established that the main focus was the definition of modelling rules for an architecture construction phase. To have a better understanding on how to generate an accurate and reliable quantity take-off and cost estimation, the scope was defined by generating trials and establishing guidelines for the modelling process of the most used architectural elements described in the sub-chapter 3.3.4.

The expected outcome of this segment is to establish modelling guidelines for the mentioned elements and to define a correct export to IFC for the next steps involved in the workflow. As shown in the Figure 31, in pursuit of reaching the objective of this phase, the process of generating this 3D model is partitioned into four main stages.

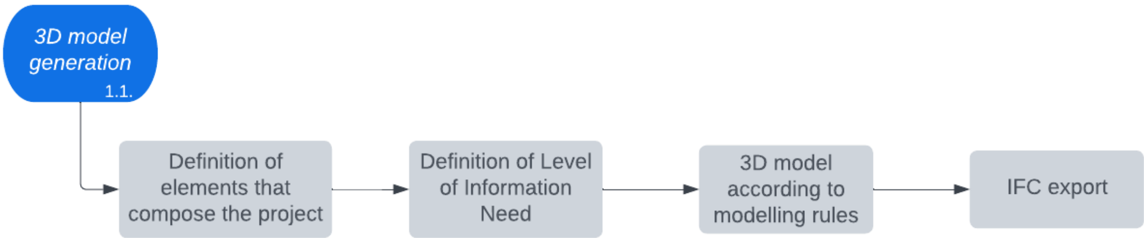


Figure 31 – Process to generate the 3D model.

The first step of the process is mainly based on the definition of the WBS and the architectural design of the building, it includes and indicates what type of instances are the ones selected for the project. The next steps are defined in the following chapters.

3.3.1. Modelling trials

In order to define all the steps that compose the 3D model generation phase, a sequence of trials was made, primarily focused on establishing accuracy in the modelling process, especially on the compound elements, always considering what the WBS needed to assign the cost to each element. In this process it was defined that for this study all the layer elements shall be treated as compound elements and not as separate instances. This means that when an element is composed by two or more layers, the object should be treated as just one system.

Also, these trials were done in different authoring tools but with a special focus on Autodesk Revit. The main reason resides on its direct connection to the CYPE tools and its level of relevance in the AEC industry by being one of the most used authoring tools.

In the next sub-chapters, even though the study required several tests, a definition of the two most important trials shall be presented and briefly explained.

3.3.1.1. Quantity take-off test # 1

The following test presents two main elements: one wall and one floor. Through the definition of hierarchy on the Revit properties, the elements that are composed of concrete were marked as priority against the other layer, which were marked as finish layers (giving a higher hierarchy to the finish of the slab than the wall, so when they unite the union will be represented the same as reality).

As shown in the Figure 32, both components, the floor and wall, were submitted for a quantity take-off procedure conducted by the authoring software. It is important to note that, although categorized under a unified element, each of the layers are supposed to have a different area mirroring their real-world construction. The dimension of each of these layers were modified by using the join tool of Revit. Visually, each layer has different dimensions, meaning that its area and volume will differ even if we are talking about the same family. For instance, consider the case of a composite wall of two layers: a concrete core and a surface finish layer. According to its properties, the concrete layer had an area of 18 m^2. If the join tool really changes the geometry of the object by following the specified hierarchy of the properties, the finish layer should have a smaller area than the core layer (< 18 m^2), which in this case, didn't happened.

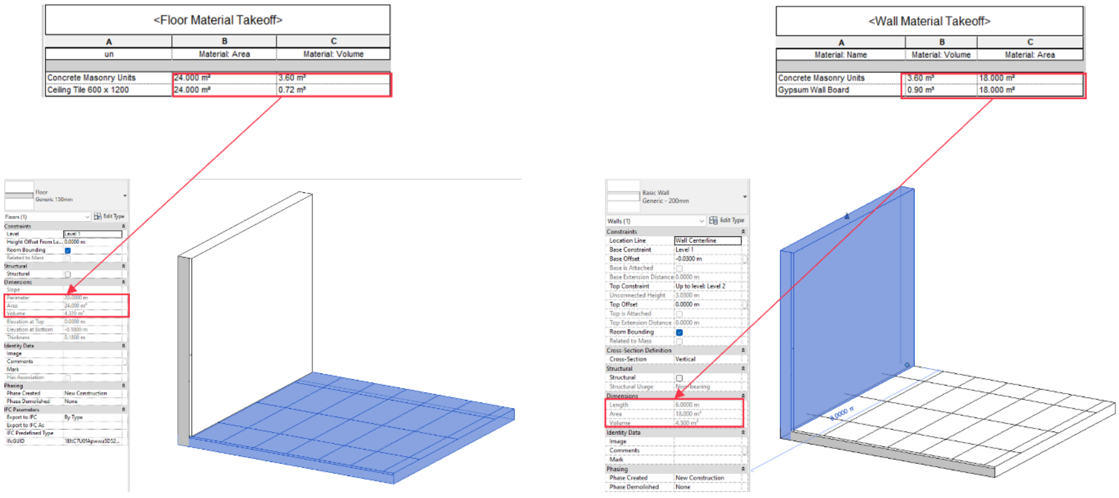


Figure 32 – Modelling trial #1.

The same issue happened to the slab and its two layers. The reason why this happens is that even by using the join layer, the change only applies to the visual geometry of the object while its dimensions are constrained by the general geometry of the object. This means that even if the height of the wall are shown different, the program will recognize only the general quantities of the wall. This problem was shown when trying to extract the quantities of the families and even on a material take-off schedule. There are two possibles solutions for this issue: first, divide each instance in layers, this may help to achieve accuracy but dividing each layer may lead to a more complex project in terms of file size, difficulty when a change in the model is needed, or even error when adding an object based family (windows, doors, etc.). The second option is to work with parts, which will be explained in the next trial.

3.3.1.2. Quantity take-off test # 2

The second quantity take-off addresses the issue generated by the lack of accuracy of using the join geometry tool of the authoring software. At that moment of the study, it was necessary to find out a way of using compound elements' layers as individual objects with their own geometry and properties. To solve this, it was decided to use the Parts tool.

The parts element is a tool that lets the user divide elements with layers or subcomponents to individual parts which will be created from those elements. They are automatically updated and regenerated when the original element from which they are derived is modified. By using them, the project parameters and shared parameters are propagated to the parts.

Through many trials it was established that in order for them to work properly each of the layered elements in the project should be divided into parts. The option of "show shape handles" should be activated on the properties tab so Revit will let adjust the dimensions of each layer to be as realistic as possible. This tool is shown in the identity data section of one of the examples shown in the Figure 33.

As represented in the Figure 33, the wall, which is divided into two parts: the concrete core layer and the surface finish layer shows different dimensions between them on the area and volume properties tab and the material take-off schedule. Contrary to the first trial in which both layers of the wall were defined by an overall area of 18 m^2, each of the materials show their real material take-off, which in this case is 18.18 m^2 for the concrete layer and 18 m2 for the finish of the wall.

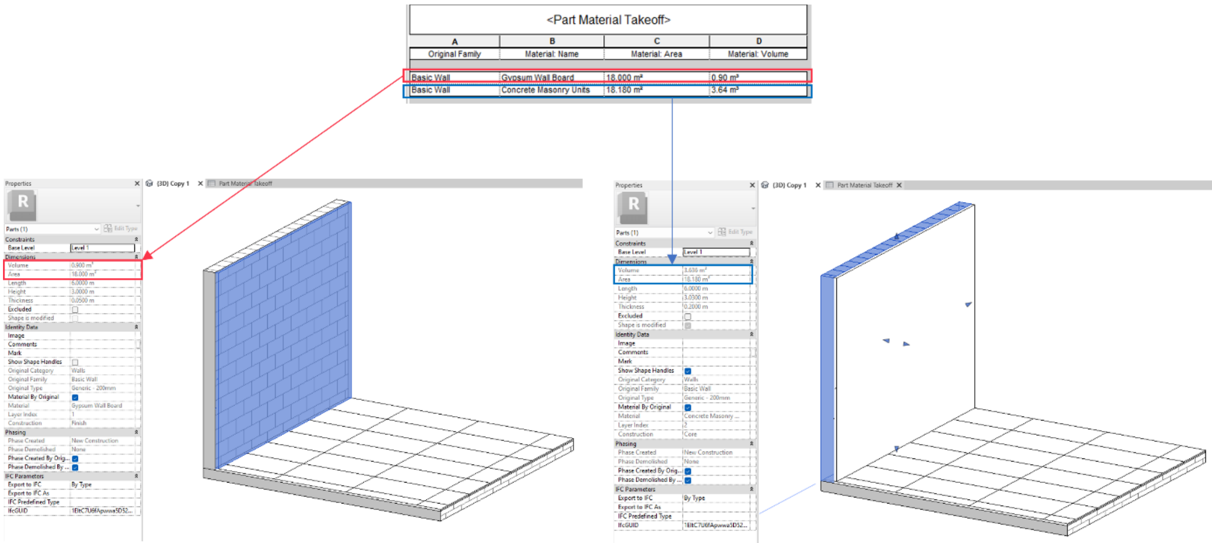


Figure 33 - Modelling trial #2.

It is important to acknowledge that by working with parts a more precise quantity take-off may be achieved. Even if in an individual situation the difference between their elements is not a significant amount of material, when generating all of these geometries in each element, the quantities will affect the cost estimation report in a positive way. Also, when working with parts, each element is represented as a single element not as a compounded element, this allows the user to indicate specific properties needed for the quantity take-off process such as WBS code, individual quantities, and even materials set up.

3.3.2. Modelling rules

The establishment of modelling rules is one of the most important steps in the workflow since they are one of the main tools to generate consistency for the model generation. They were systematically generated through several modelling trials, previously presented, aimed to simplify the modelling process, while upholding the requirements to work according to the WBS the project.

Setting modelling rules for a quantity take-off model is an important step for the process. They work as a structured framework that establishes how the elements and components in the project should be represented. There are many key advantages by establishing these rules:

- Accuracy and consistency. Through the modelling rules all the elements are modelled and generated uniformly and accurately. This consistency eliminates discrepancies between different modelling practices, leading to more reliable quantity calculations.

- Efficiency. The modelling rules streamline the modelling process by providing initial guidelines, which lead to reduction of time regarding the creation and modification of the elements of the project, enhancing overall the project efficiency.

- Easy approach. Since the modelling rules adheres standardized approach of modelling, the projects are more likely to be understandable with other coworkers when needed.

- Integration with the WBS. The modelling rules have to be aligned to the project's WBS to ensure an easy and efficient breakdown for the quantity take-off process since it enables a straightforward cost distribution and tracking.

The modelling rules that were established for the scope of this work are the following:

- Follow a WBS: Choose a Work Breakdown Structure to use in the project. This will be the main breakdown structure for the division of the parts of the architectural elements. It should always be followed. The information given by the model should correspond to the needs of the WBS, especially for the units of measurement of each instance in the project.

- Define a proper level of information need: The level of information need is established on section 3.3.3 of this document. The non-graphical information is mostly defined by the IFC quantity takeoff property sets to identify the data needed for the cost estimation. If one element is missing, especially the properties defined by the level of information need, map it by using a self-made property set.

- Minimize geometrical information: Compound elements should have the minimum number of layers possible to avoid excess data in the model. The number of layers should be defined according to its main purpose, the guidelines for this section can be founded in chapter 3.3.4.

- Follow real-world precision: Verify that the geometry of objects in the model precisely reflects the real-world physical dimensions of the building components. Avoid excessive overlaps, gaps, or missing elements, as they can introduce inaccuracies when performing quantity calculations.

- Avoid excessive modelling components in the project: To reduce the amount of information in the model, some objects may rely on other elements dimensions for its quantity takeoff and don't have to be created in the 3D model. Some examples: skirting, flashing, wall top/middle beam, etc.

- Use the proper IFC schema: Properly classify and assign appropriate object types to the elements in the BIM model This includes distinguishing between walls, floors, roofs, doors, windows, etc. Consistent and accurate object classification is crucial for quantity take-off, especially when software automatically assigns an IFC type according to the type of family (ex: CYPE Architecture).

3.3.3. Definition of Level of Information Need

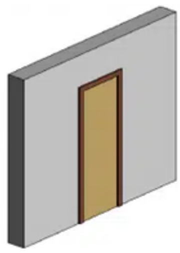
As defined in the chapter 2.3.4, the level of information need for this work will be mainly focused on the geometrical information and alphanumerical information focused on the quantity take-off process. To do this, each of these categories were studied and defined according to its purpose to generate a definition of level of information need for each architectural element studied in this work.

3.3.3.1. Geometrical Information

The geometrical information according to the BS EN 17412-1:2020, shall be divided into the following categories:

- **Detail.** The detail scale is described as simplified or detailed. The detail for the scope of this work is establish on the Table 7.

Table 7 – Detail scale for quantity take-off.

Detail Scale		
Scale	**Description**	**Example**
SIMPLIFIED	The object is graphically represented within the model as an object entity with real size, shape, and location. It should be a single element with no layers included. Design may not be the same as the finish product. Material is specified on the description on the WBS, not necessary in the object.	
DETAILED	The object is graphically represented within the model as a object entity with real dimensions, shape, thickness, volume and location. It should be a single element with all its layers and components with the real size and attributions. Material should be included in the model and exported into the IFC file.	

- **Dimensionality**. For the purpose of this study, even though some elements only require a 1D or 2D dimensions, for requirements directly connected to the quantity take-off process, most of the objects are required to be presented in three-dimension (3D).

  The exception to this rule resides in items that represent a specific activity, and it is measured as a whole, in this case, elements may be represented as a 0D element, a point, just to integrate this activity to the final cost estimation.

- **Location**. The location information is not a definitive factor for the process of quantity takeoff and cost estimation, this is because the position in the authoring tool doesn't affect the value of the quantities. For this reason, most of the elements can be categorized as "Not applicable". Other elements should be represented as "Relative location" as a requirement of the WBS chosen in this work. This is because for some elements like roof and ceilings, during the process of choosing the attributes of the element in the WBS their height must be considered and it changes the price of the element according to it.

- **Appearance**. The visual representation of an element can be described as symbolic or realistic according to the standard. For the scope of this work, it was needed to add one more classification to the scale, which is defined as "Consistent colors". As shown in the Table 8, it applies to all elements composed by layers to help surveyors to have a better visual understanding of the project when validating or checking.

Table 8- Appearance scele for quantity take-off.

Appearance Scale	
SYMBOLIC	Objects shall be displayed with a gray or white color, for a better understanding of its dimensionality.
CONSISTENT COLORS	Objects must display all the layers and surfaces according to the RGB color like its material. Textures shouldn't be included.
REALISTIC	Objects shall be displayed with real life textures and colors.

- **Parametric Behaviour.** Since the work is focused on using an IFC file as the exchange format, this aspect classifies as "Not Applicable". This is because the purpose of this project is an accurate quantity take-off from the project, modifications or configuration shouldn't be allowed since it can lead to inaccuracies between the 3D model in the authoring tool and the IFC file.

3.3.3.2. Alphanumerical Information

Following the BS EN 17412-1:2020 standard, the Alphanumerical information should be divided into: Identification and Information content.

- **Identification**. The identification will be defined by the Generador de precios coding system. All of the applicable categories described in the WBS are shown in Table 9, for layered objects and Table 10, for single objects.

Table 9 – WBS Coding categories for layered elements.

WBS Coding Categories for layered elements										
Object	**Walls**			**Floor**		**Roof**		**Ceiling**	
Layer	Exterior	Core	Interior	Slab	Finish	Slab	Finish/ Insulation	Structure	Finish*
WBS Category Code	FA	EC	RA	EA	RS	EA	QA	RT	RI
	FS	EH	RD	EH		EH	QM		
	FV	EM	RI	EM		EM	QB		
	FF	EP	RP	EP		EP	QD		
	FE	FB	RG				QS		
	FB	FT	RK				QE		
	FN	FU	RR				QV		
	FK	FI							
	FL	FO							
	FJ								

*** IMPORTANT NOTE:** The presented codes are just the applicable categories to each element. It does not represent the entire WBS code. The entire code can be found on the Generador de Precios webpage: http://www.generadordeprecios.info/

Table 10 – WBS Coding categories for single elements.

WBS Coding Categories for single elements							
Object	**Window**		**Door**	**Stairs**	**Railing**		**Curtain Wall**
Layer	Frame	Glass	Whole	Structure	Finish	Whole	Whole
WBS Category Code	LC	LV	LC	EA	RE	FD	FM
	LS		LE	EH	EAE		
			LP	EP			
			LT				
			LB				
			LR				
			LF				
			LN				
			LU				
			LG				

*** IMPORTANT NOTE:** The presented codes are just the applicable categories to each element. It does not represent the entire WBS code. The entire code can be found on the Generador de Precios webpage: http://www.generadordeprecios.info/

- **Information Content.** For this work all categories belong to the Quantity set extracted from the IFC schema of each object. All the properties needed per each element can be found in the next section or a table with all the elements shown in Appendix 2.

3.3.4. Selected architecture instances

This study is mainly focus on a quantity take-off for an architectural discipline in a construction phase of the project. To generate a more accurate approach to it, it was established to work on the most important and used instances of an architecture construction phase: walls, floors, roofs, ceilings, doors, windows, curtain walls, stairs, and railings. They are going to be explained in two main approaches: modelling the object and defining its level of information need.

The modelling part will be divided on three main steps: first, some modelling guidelines according to the type of element; second, the properties needed for the quantity take-off according to the WBS per element (a table with all the elements is shown on Appendix 3); and third, a graphical representation of the division of the parts and relevant information for their quantity take-off.

Meanwhile, the Level of information need will be defined per element according to what was establish on the 3.3.3 chapter. This will be divided into two main parts: definition of geometrical information and the definition of alphanumerical information.

3.3.4.1. Walls

Through several tests some modelling guidelines were established: First, the wall should be treated as a compound element composed by three main layers according to their purpose: an exterior finish, core, and interior finish layer. This was mainly decided because the WBS of the GP divides each element according to its function, also the layers could be grouped following the proposed structure since whatever the material is, its dimensions are usually the same (example: one category in the WBS is a gypsum wall, another, is the finish painting of that wall; even though they are listed with different codes, its dimensions are going to be the same). Second, the wall has to be divided into parts and each of it should represent its real height and width for a more accurate quantity take off; and third, the WBS code should be integrated to each of the layer's properties. It shouldn't be mixed to avoid mistakes.

As shown in the Table 11, each of the layers correspond to a different type of WBS category decided by the purpose of the material. Also, it shows the unit of measurement that the WBS establish and what IFC property is the most appropiated one for its quanity take-off.

Table 11 – Wall WBS attributes.

WBS properties - Wall						
Name		Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Insulation and Finish**	Exterior layer	m²	IfcWall	NetSideArea	F - Fachadas
2.	**Main structure**	Core layer	m²			E - Estructuras
3.	**Interior finish**	Interior layer	m²			R - Revestimientos

A geometrical representation on how the layers should be settle and a brief of the most important properties needed for the quantity take-off are shown in the Figure 34.

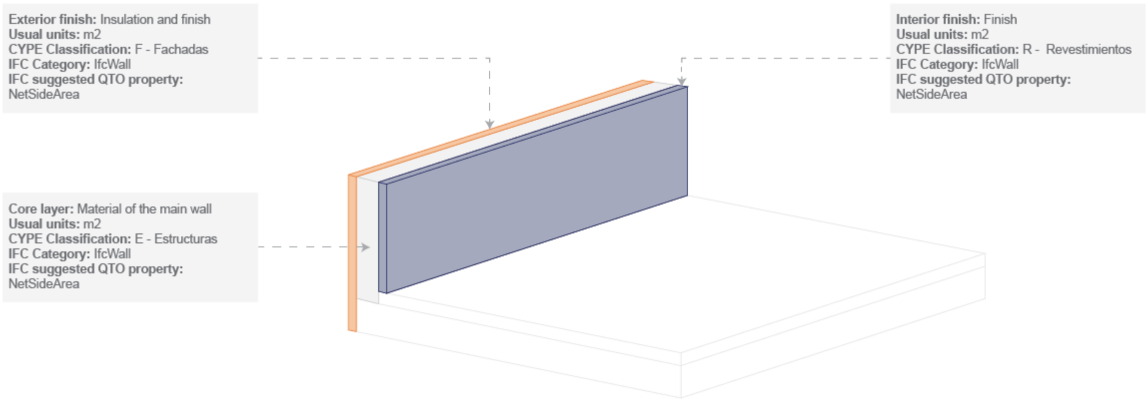


Figure 34 – Wall layer configuration.

Definition of level of information need.

The level of information need for the wall is defined by the content in Table 12. The information content for the wall can be found on Table 13.

Table 12 – Wall level of information need.

Object	**Wall**
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Detailed
Dimensionality	3D
Location	Not applicable
Appearance	Consistent colors
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 13

Table 13 – Information content for walls.

Information content - Wall						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_WallBaseQuantities	Wall	All included	IfcWall	Defined by user	NetSideArea	m²

3.3.4.2. Floors

The guidelines for modelling a floor are the following: first, it should be divided into two layers: the core and the finish. Following the same logic of the parts division of the wall, the core layer should be defined as the slab and the finish may represent mainly the insulation and all the elements involved to install the floor. Second, each layer should be modelled according to its real length and width for a more precise material take-off. Third, if a cut is needed in just one layer, use the exclude parts tool and then divide parts and create a sketch of the wished cutted area, don't use model in place voids. Fourth, the WBS code should be applied to each part, not to the general object.

The WBS category that defines each part of the floor system is shown in the Table 14, alongside with the required unit of measurement and the NetArea as the suggested IFC property for quantity take-off.

Table 14 – Floor WBS attributes.

WBS properties - Floor						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Finish**	Finish layer	m²	IfcSlab	NetArea	RS - Pavimentos
2.	**Main Structure**	Core layer	m²			E - Estructuras

The graphical representation on how the parts should be modelled according to its real-world practice is shown in the Figure 35. Also, a description of the WBS category and IFC schema definition is shown per element.

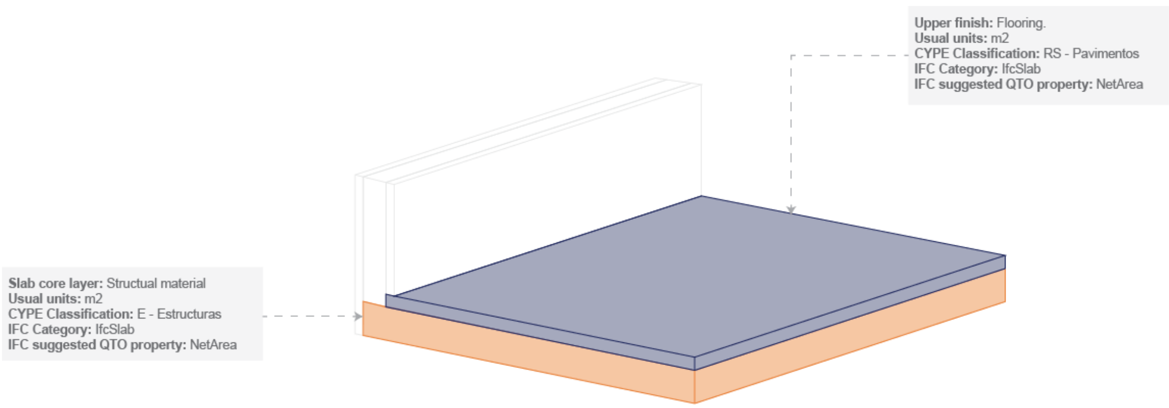


Figure 35 – Floor layer configuration.

Definition of level of information need.

Similar to the level of information need presented in the wall section, the floor's attributes are defined by the Table 15. Complementing the information required for the QTO process of the floor the Table 16 defines its information content.

Table 15 – Floor level of information need.

Object	**Floor**
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Detailed
Dimensionality	3D
Location	Relative location
Appearance	Consistent colors
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 16

Table 16 – Information content for floors.

Information content - Floors							
Property Set		**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_SlabBaseQuantities	1	Floor finish	Finish layer	IfcSlab	Floor	NetArea	m²
	2	Slab	Core layer		Baseslab		

3.3.4.3. Roofs

The guidelines for this instance are the following: the initial step should be defining the roof as a two layered element (core layer for the slab and upper layer for insulation and finish) and then split into parts. This was settled following the same division logic as the wall. Next guideline, if applicable, the boundary of the roof should exclude the exterior finish of the wall and parapet. Finally, the WBS code should be assign to each part of the element, not to the general element.

According to the Table 17, the roof is divided into the two parts. Even though there is one category in the WBS specifically for roofs, the slab is categorized into the E – Estructuras (structures) set and the finish, which mainly consist on the insulation system or exterior finish is defined by the Q – Cubiertas (Roof) category.

Table 17 – Roof WBS attributes.

WBS properties - Roof						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Insulation and Finish**	Exterior layer	m²	IfcRoof	NetArea	Q - Cubiertas
2.	**Main structure**	Core layer	m²			E - Estructuras

The geometrical set up of the roof's layers is shown in Figure 36 with the WBS specifications needed for each element.

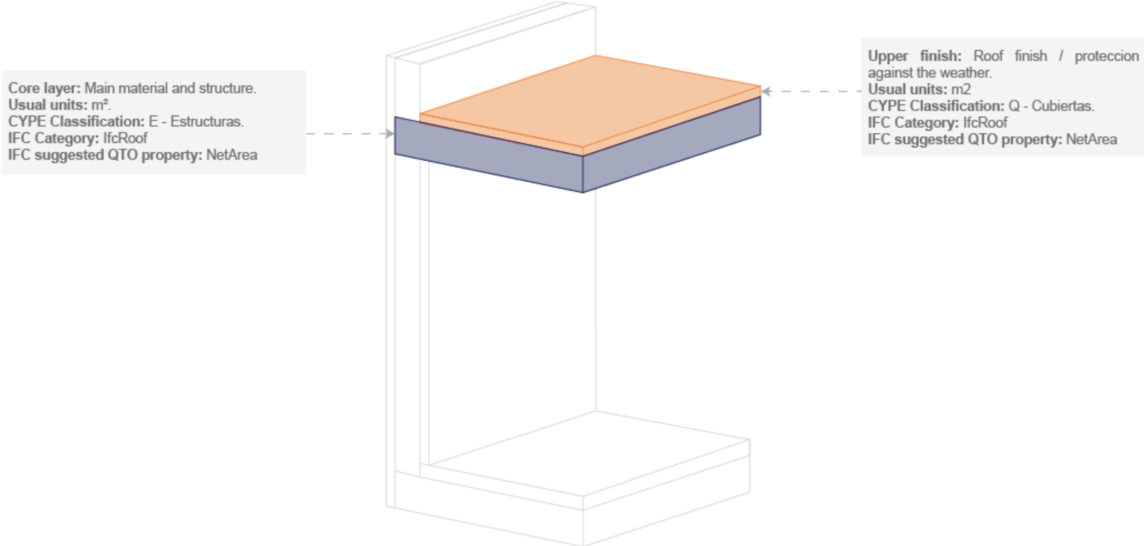


Figure 36 – Roof layer configuration.

Definition of level of information need.

The roof level of information need is defined in the Table 18 with a complementary information content shown in Table 19.

Table 18 – Roof level of information need.

Object	**Roof**
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Detailed
Dimensionality	3D
Location	Relative location
Appearance	Consistent colors
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 19

Table 19 – Information content for roofs.

Information content - Roof						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_RoofBaseQuantities	Roof	All included	IfcRoof	Defined by user	NetArea	m²

3.3.4.4. Ceiling

The modelling guidelines for the ceilings are the following: use only one instance divided on two parts. The structure of the ceiling shouldn't be modelled since it's measured through an approximate calculation on the WBS specifications. Next, according to the Generador de precios, pipe holes shouldn't be considered for the QTO. Lastly, if finish is not included on the description of the celling in the Generador de precios, another layer should be added to the model with its respective WBS code.

As shown in the Table 20, the two possible layers are described under the category R – Revestimientos y acabados (finishes) but with a different subdivision. Most of the ceilings in the WBS have the finish already estimated in the cost, but if they aren't specified the user should add a new category to quantify the finish (ex: paint).

Table 20 - Ceiling WBS attributes.

WBS properties - Ceiling						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Main structure**	Core layer	m²	IfcCovering.Ceiling	NetArea	RT - Revestimientos
2.	**Interior finish** (if not included in the WBS)	Interior layer	m²	IfcCovering.Ceiling	NetArea	RI - Revestimientos

The graphical representation on how the ceiling has to be modelled according to its real-world system is shown in the Figure 37. Depending on the design, the finish of the wall may not end below the ceiling.

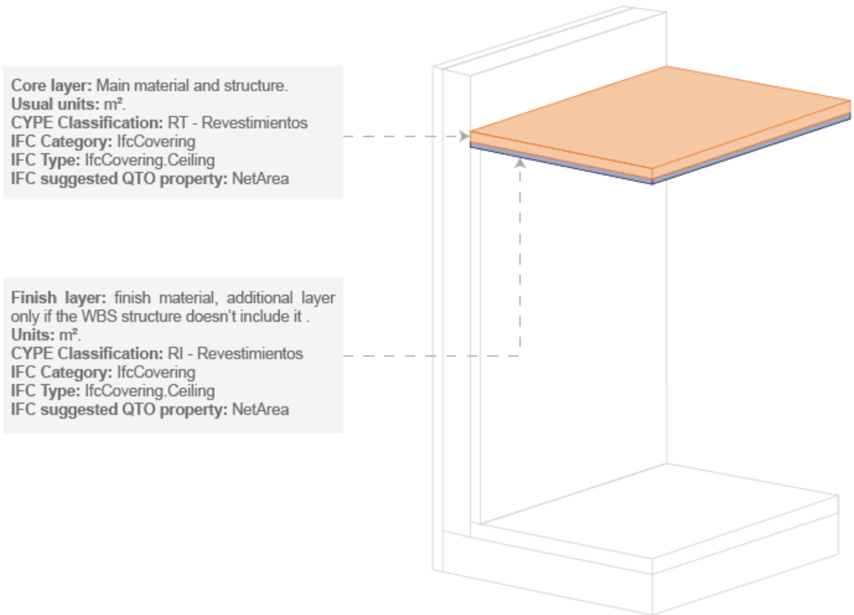


Figure 37 – Ceiling layer configuration.

Definition of level of information need.

The definition of the level of information need for the ceiling is shown in the Table 21, the main difference from other layered elements, excluding the roof, is that the location is needed for its QTO.

Table 21 - Ceiling level of information need.

Object	Ceiling
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Detailed
Dimensionality	3D
Location	Relative location
Appearance	Consistent colors
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 22

One important aspect of the ceiling is that does not possess a specific IFC category. As shown in Table 22, the ceiling is an IFC type that belongs to the Covering category.

Table 22 – Information content for ceilings.

Information content - Ceiling						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_CoveringBaseQuantities	Ceiling	Core layer	IfcCovering	Ceiling	NetArea	m²

3.3.4.5. Curtain Wall

According to the modelling tests some guidelines were determined to model a curtain wall. First, as an element measured by square meters, the width and height should be as precise as possible. Second, the WBS code should be added to the properties of the Curtain Wall, it shouldn't be added in any of the curtain wall elements (mullions or panels). Third, the 3D model of the curtain wall will only be relevant if the user needs to count the elements of the curtain system, otherwise, the QTO following the WBS is done by area and all its elements are quantified by the specifications applied on the WBS. Fourth, as shown in the Table 23, the curtain wall is composed by only one instance, it shouldn't be divided into it's components (structure and glass).

Table 23 – Curtain Walls WBS attributes.

WBS properties – Curtain Wall						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Curtain Wall**	Structure and panels	m²	IfcCurtainWall	NetArea	FM - Muros cortina

The graphical representation shown in Figure 38 is an example on how the curtain wall may be represented. As mentioned before the design of the curtain wall doesn't matter in this case since the WBS allows the personalization of the object and according to these settings, the cost estimation is done.

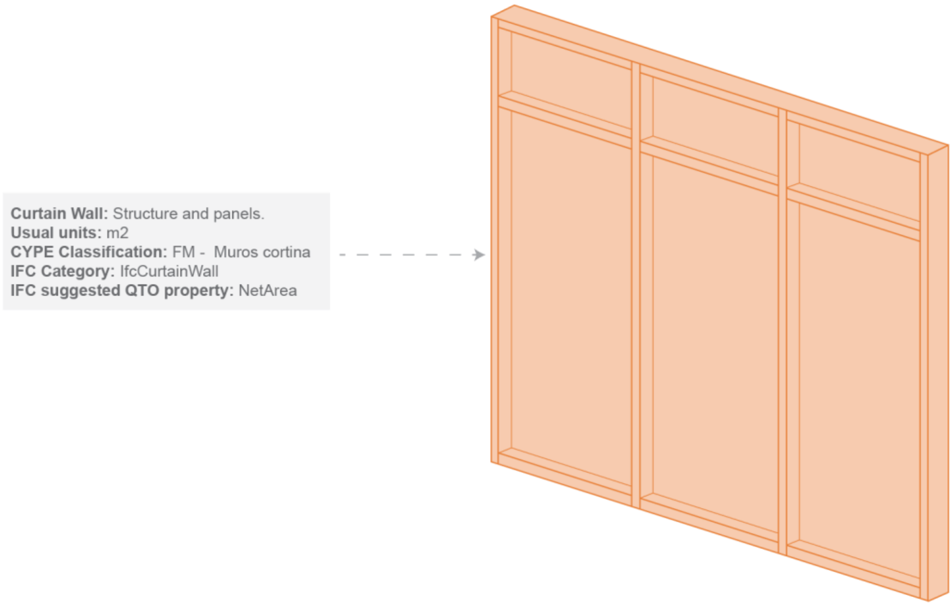


Figure 38 – Curtain wall geometrical representation.

Definition of level of information need.

The level of information need for the curtain wall is shown on the Table 24 and according to the modelling guidelines of the element, it’s detail scale is defined as a simplified.

Table 24 – Curtain Wall level of information need.

Object	**Curtain Wall**
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Simplified
Dimensionality	3D
Location	Not applicable
Appearance	Consistent colors
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 25

One important aspect of the information content for the curtain walls is that, in contrast of the others elements studied in this work, its IFC type is defined as Userdefined and does not posses any types according to its IFC schema, just as shown in the Table 25.

Table 25 – Information content for Curtain Walls.

Information content – Curtain Walls						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_CurtainWallQuantities	Curtain Wall	Structure and panels	IfcCurtainWall	Userdefined	NetArea	m²

3.3.4.6. Door

According to the requirements established by the WBS the door should be modeled as just one element, even if it's composed by more than one sheet or frame. Also, for an accurate QTO, the model of the door should generate the exact cut through the wall. If the characteristics of two or more doors are the same but their dimensions changes, a new WBS code should be added, just as explained in the chapter 3.2.

As shown in the Table 26, the door is composed by only one element and does not need a property of the IFC schema for its take-off since it is counted as a single element.

Table 26 – Door WBS attributes.

WBS properties – Door						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Door**	One element or family.	Ud.	IfcDoor	None. Counted as single element.	L - Carpinteria y Vidrios

The Figure 39 shows an example of the geometrical representation of the door, the geometry of it does not affect its quantity take-off since the cost is already estimated according to the specifications stated in the WBS.

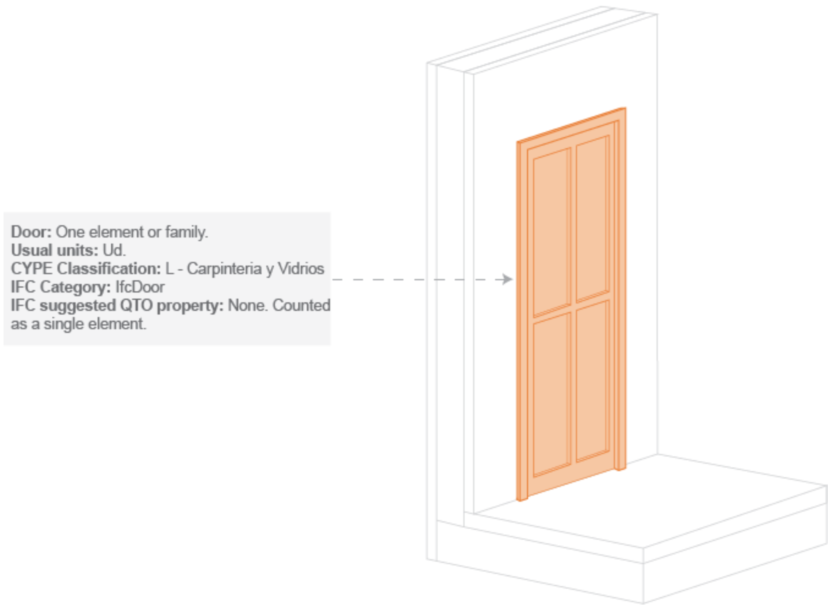


Figure 39 - Door geometrical representation.

Definition of level of information need.

The level of information need of the door is defined by the description of each category showed on Table 27. Following this table, the definition of the information content is shown on the Table 28.

Table 27 – Door level of information need.

Object	Door
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Simplified
Dimensionality	3D
Location	Not applicable
Appearance	Symbolic
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 28

Table 28 – Information content for Doors.

Information content - Door						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_DoorBaseQuantities	Door	One element or family.	IfcDoor	Door	None. Counted as single element.	Ud.

3.3.4.7. Window

The window modelling guidelines are divided in two different criteria because according to the chosen WBS to have a complete quantity take-off, two codes should be added to the object, one for the frame and the other for the glass. The reason why this works this way resides on the customization of the glass, and it depends on the user which one they should choose.

The first one follows the WBS criteria for the quantity take-off of the window. The WBS asks for the total of m^2 of the window for the quantity take-off of the frame and the same quantity for the glass, this approach gives a general material take-off of the glass, and it does not look for accuracy for that specific element, as shown in the Figure 40.

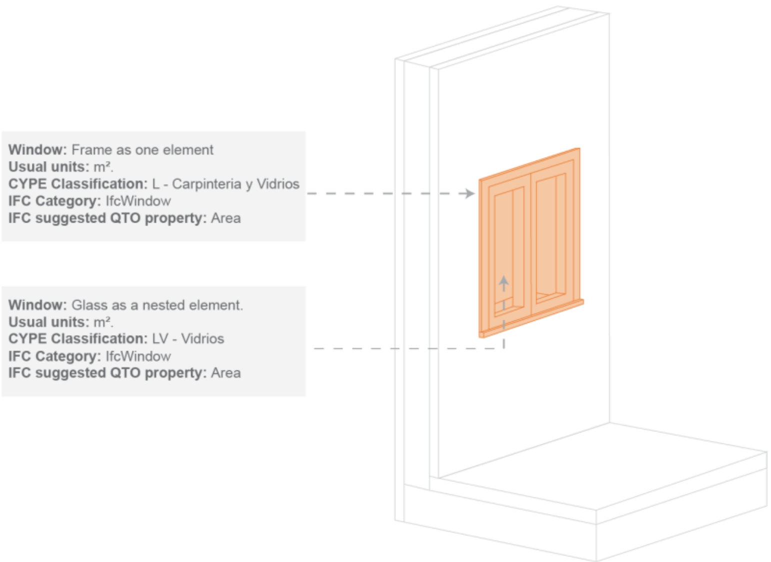


Figure 40 – Window WBS-based approach of quantity take-off.

The second approach is focused on accuracy but still considering the WBS. This one proposes to extract and map the quantities of the windows by using shared parameters. For this to work, on Revit, the glass of the window has to be a nested family with the "shared" option selected. This will transfer the data of the exact area that the glass has. The frame has to be quantified as the total window area. Its division is shown on the Figure 41.

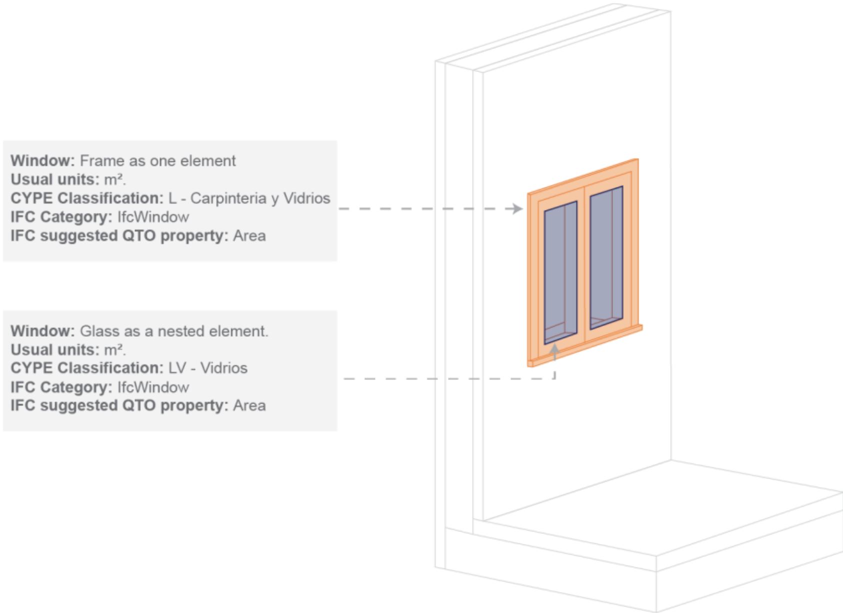


Figure 41 – Window accuracy-based approach of quantity take-off.

In either of the two approaches, the properties needed for the quantity take-off according to the WBS and its category are shown on the Table 29.

Table 29 – Door WBS attributes.

WBS properties – Window						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Window frame**	One element or family.	m^2	IfcWindow	Area	L - Carpinteria y Vidrios
2.	**Glass**	Nested element.	m^2			LE – Vidrios

Definition of level of information need.

As shown in the Table 30, regardless of its modelling approach, the level of information need for the window is defined as a simplified object with a symbolic appearance. The information content for this instance is defined on Table 31.

Table 30 – Window level of information need.

Object	Window
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Simplified
Dimensionality	3D
Location	Not applicable
Appearance	Symbolic
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 31

Table 31 – Information content for Windows.

Information content - Window						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Window						
Qto_WindowBaseQuantities	Window	One element	IfcWindow	Window	Area	m²

3.3.4.8. Stairs

The stairs modelling guides are divided into four main considerations: first, they should be modelled as one element in which each of the IFC stairs decomposed element (refer to Figure 42) should be recognizable when exported to IFC. Second, according to the WBS provided by Generador de precios, the finish, railing and structure will have different type of measurement and to achieve this a specific QTO procedure has to be done, as shown in Figure 43. Third, the stairs measurement is different compared to the other elements presented on this work, in order to obtain the QTO according to the WBS, mainly for the stairs structure, you should follow the instructions on the Figure 43. Fourth, for coding, one stair should have two coding categories: one for the structure and another for the finish. The railing should have its own code on its properties.

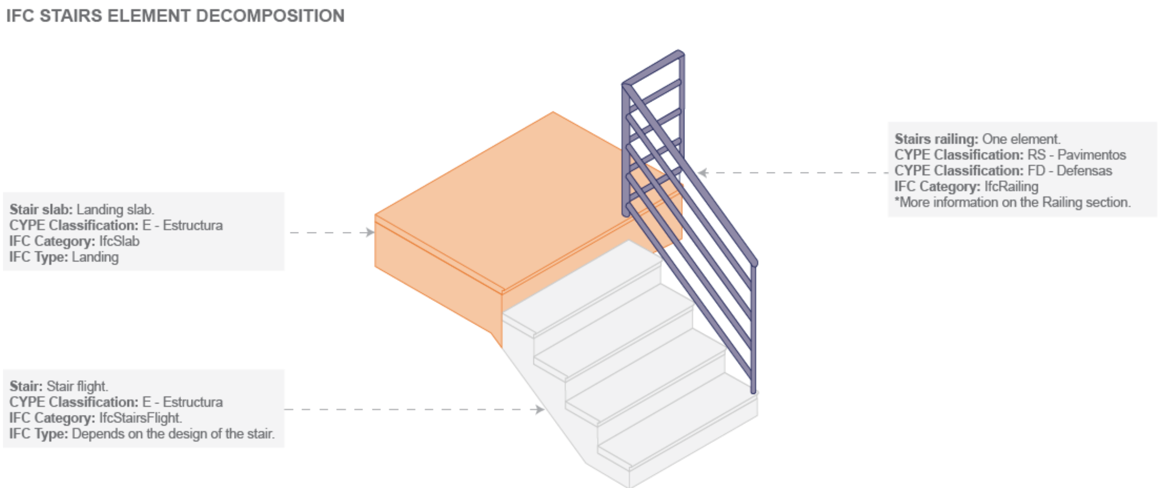


Figure 42 – Stairs decomposition according to IFC schema.

The quantity take-off for the stairs requires a two step process that has to be done in the software for the cost estimation phase, as shown in Figure 43. This is required by the WBS since it divides the stairs in finish, measured by unit and the whole structure (not divided by slab and stairs flight as in the IFC schema), measured by m^2. The first step consists on calculating the area of the stairs flight, to do so, the stairs flight QTO property set includes the width and the length. The second step is to calculate the area of the slab, which is separated from the rest of the stairs when using IFC, for this is necessary that the volume and slab thickness are included in the export, even if it means to manually map them. Both calculations requires a manual procedure done through formulas in the QTO software.

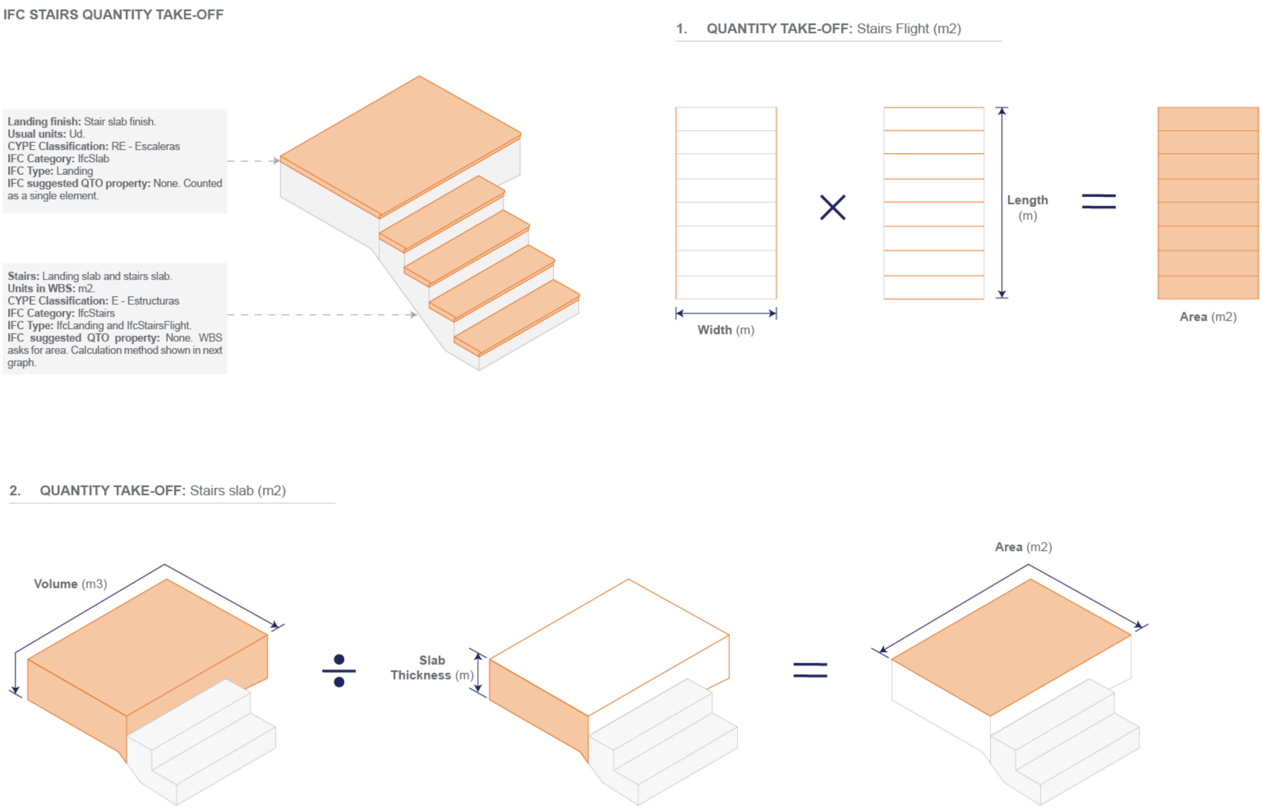


Figure 43 – Stairs quantity take-off procedure.

Each of the parts has a defined category according to the WBS used in this work. This is shown in the Table 32, in which is described by following their respective division according to the IFC schema.

Table 32 - Stairs WBS attributes.

WBS properties – Stairs						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
1.	**Landing Slab**	Landing slab	m²	IfcSlab	Volume and thickness.	E - Estructuras
2.	**Stair**	Stair flight	m²	IfcStairsFlight	Width and length.	E - Estructuras
3.	**Stair's railing**	One element	m	IfcRailing	Length	FD - Defensas
4.	**Stairs Finish**	Stair finish	Ud.	IfcStairsFlight	None. Counted as single element.	RE - Escaleras

Definition of level of information need.

The level of information need of the stairs has one difference compared to other non-layered elements, its appearance on the Table 33 is set as consisted colors. This is because this element requires a special process for its quantity take-off and it's easier for surveyors to understand its components through the colors of the materials.

Table 33 – Stairs level of information need.

Object	**Stairs**
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Detailed
Dimensionality	3D
Location	Not applicable
Appearance	Consistent colors
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 34

As shown on the Table 34, the information content defined for the stairs is composed by the four elements mentioned in the explanation of the modelling procedure of the element. Each element's type definition is exported automatically when the IFC schema is applied to the object.

Table 34 – Information content for Stairs.

Information content - Stairs							
Property Set		**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_SlabBaseQuantities	1	Landing Slab	Landing slab	IfcSlab	Landing*	Volume and thickness.	m²
Qto_StairFlightBaseQuantities	2	Stair	Stair flight	IfcStairsFlight	Straight*	Width and length.	m²
	3	Stairs Finish	Stair finish			None. Counted as single element.	Ud.
Qto_RailingBaseQuantities	4	Stair's railing	One element	IfcRailing	Handrail*	Length	m

Important note: In the authoring tool the stairs type is defined by the typology of the stairs used in the project, this table represents the type of each element when divided at the IFC export.

3.3.4.9. Railing

The railing can be an independent element or a nested family on the stairs. In both cases, the WBS category is the same, as shown in the Table 35. To do a proper QTO, when modelling a railing be aware of repetition of some elements, especially the posts. To avoid duplicated post QTO, railings should be modelled as one element, it doesn't have to be divided into segments. Also, define the style that assimilates the project's railings design in the WBS database, not necessarily in the modelling tool.

Table 35 - Railing WBS attributes.

WBS properties – Railing						
	Name	**Layer**	**Unit**	**IFC Category**	**IFC suggested QTO property**	**WBS Category**
1.	**Railing**	One element	m	IfcRailing	Length	FD - Defensas

As shown in Figure 44, the railing shall be represented as just one element and according to the WBS it measured in meters, so even if its just one element their entire length must be quantified.

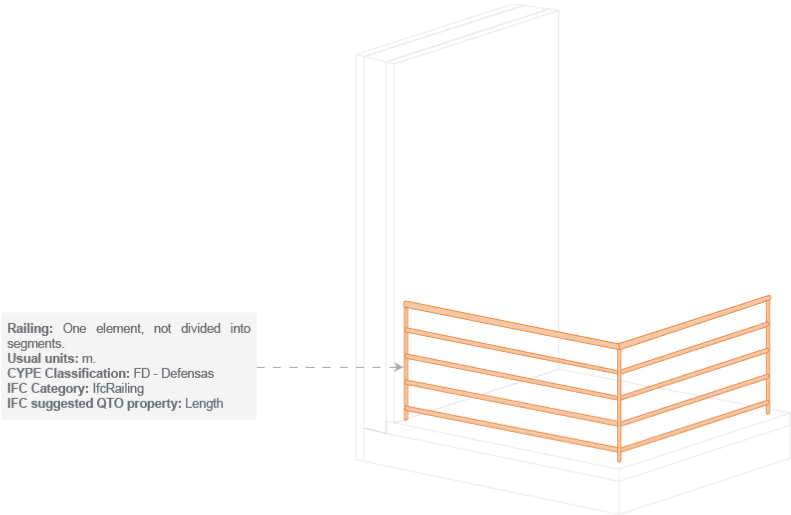


Figure 44 - Railing geometrical representation.

Definition of level of information need.

The floor's attributes to establish its level of information need are defined on Table 36. Complementing the information required for the QTO process of the floor the Table 37 defines its information content.

Table 36 – Railings level of information need.

Object	**Railing**
Purpose	Quantity Take-off
Geometrical Information	
Detail Scale	Simplified
Dimensionality	3D
Location	Not applicable
Appearance	Symbolic
Parametric Behavior	Not applicable
Alphanumerical Information	
Identification	WBS Code
Information Content	Table 37

Table 37 – Information content for Railings.

Information content - Railings						
Property Set	**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Qto_RailingBaseQuantities	Railing	One element	IfcRailing	Handrail	Length	m

3.3.5. Modelling procedure

The modelling procedure consists of generating a 3D model suitable enough for a quantity take-off. This process is mainly composed by two main steps: generation of 3D model and set up of the elements. To show the process, an example was generated according to the WBS stated in Table 6.

First, model the elements according to the stated modelling rules in section 3.3.2. It is easier to start modelling the project when all the instances are already created and modified according to what was established on the WBS of the building and to the level of information need per element. Also, for a clearer and organize process, it is important to set a naming system for all the elements, in this study the naming convention was settle according to the NBS BIM object standard shown in the Figure 45.

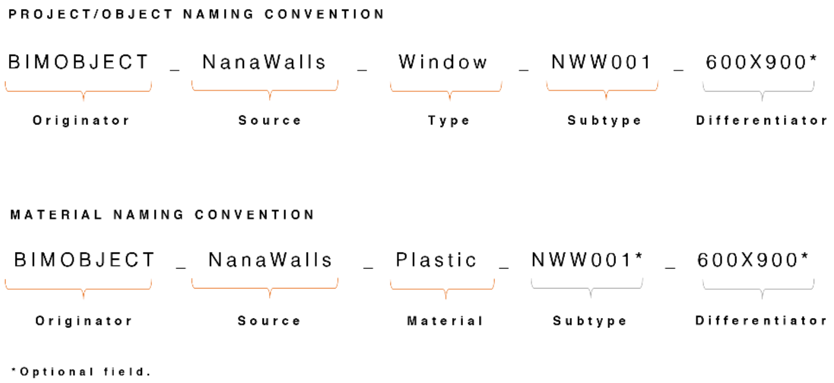


Figure 45 – Naming convention.

In this phase is important to add all the materials needed per instance. As defined in the level of information need section, the layered elements should include a coloring system. It is important to mention that to be exported correctly into the IFC file, all the colors should be set up as RGB colors into the appearance section, as shown in the red square of the Figure 46.

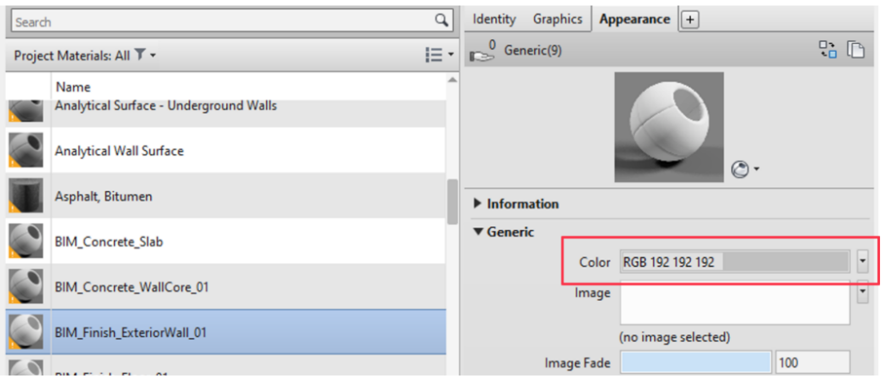


Figure 46 – Example of set up of RGB colors.

Second, assign the correct categories to all the elements in the project, this includes to assign the IFC category according to the selected element and integrate all the WBS codes into their properties. The IFC category can be selected in the properties tab or depending on the authoring software it automatically selected by the type of instance the user selected (ex: CYPE Architecture).

On the other hand, to integrate the work breakdown structure to the elements, a project parameter has to be created and defined as "WBS_Code" and applied to all the instances that are going to be used in the project. This parameter has to be created as an instance parameter under the text type and added to the Identity Data group.

If the element has more than one code another category named "WBS_Code_2" should be added. A clear example is shown on the Figure 47, when the skirting board (a non-modelled element) uses the perimeter of the floor (a modelled element) for its quantity take-off.

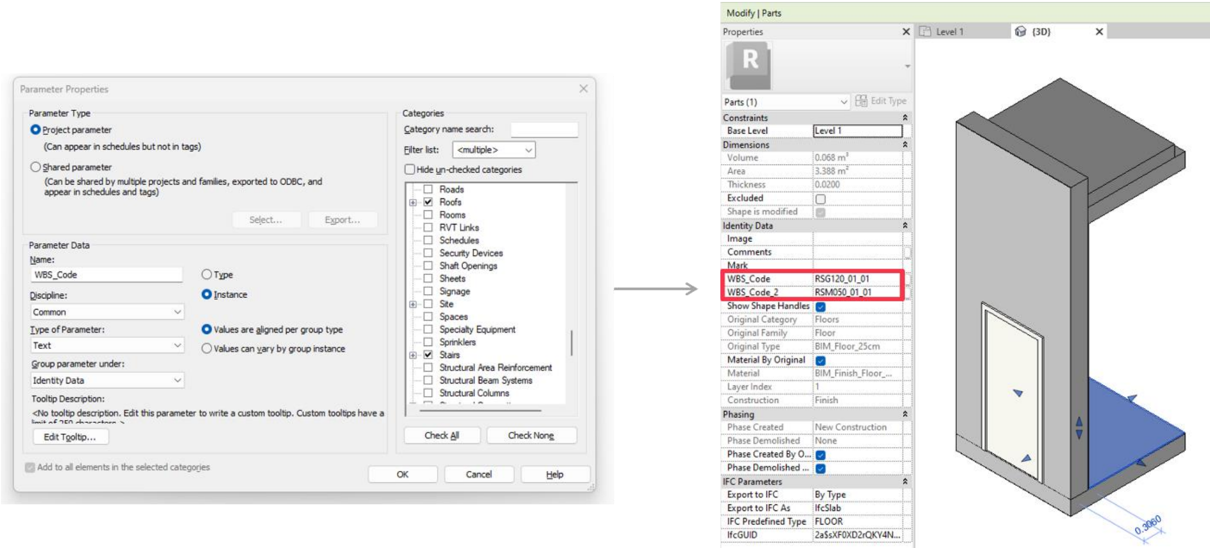


Figure 47 – WBS Code project parameter.

3.3.6. IFC export

The IFC export set up depends on the authoring tool that the user selects. As mentioned before, through this study several tests were generated in three authoring tools: Revit, CYPE Architecture and ArchiCAD. Each of them has a different set up and were tested mainly to determine which properties per element needed a mapping procedure.

The following section is going to be divided in two parts. The first one consists of an explanation of the IFC trials and the second one, how to export an IFC file from the authoring tool used in this study, Autodesk Revit.

3.3.6.1. IFC export trials

To explain the IFC export of each authoring tool, one instance will serve as an example of how the information is exported, in this case a wall in a small project. Since the wall is a layered element the export test includes how the data is presented when the object is extracted with or without the parts tool.

The first authoring tool export to be explained is going to be Revit. For these trials the IFC export was settle with and IFC version 4 Reference View, with the IFC common property sets and base quantities are selected.

When the parts are not exported, the properties are defined as a whole, not per layer; meaning, it only displays the compound element quantities instead of showing them for every element, just as shown in Figure 48. The only property that is usually individually included in this export is the width of the layers.

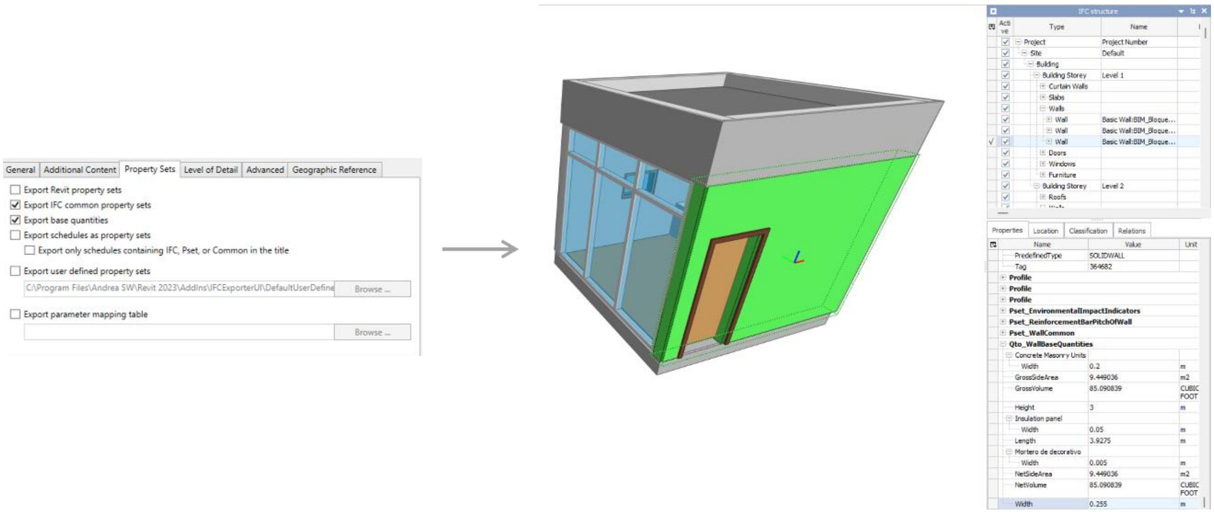


Figure 48 – IFC Revit export without parts.

On the contrary, as shown in the Figure 49, by using the “Parts as building elements” in the Advanced tab export, the wall’s IFC attributes are exported individually not as a whole element. The quantities per layer is what we need to have an accurate quantity take-off process. This approach is more well explained and done in the sub-chapter 3.3.6.2.

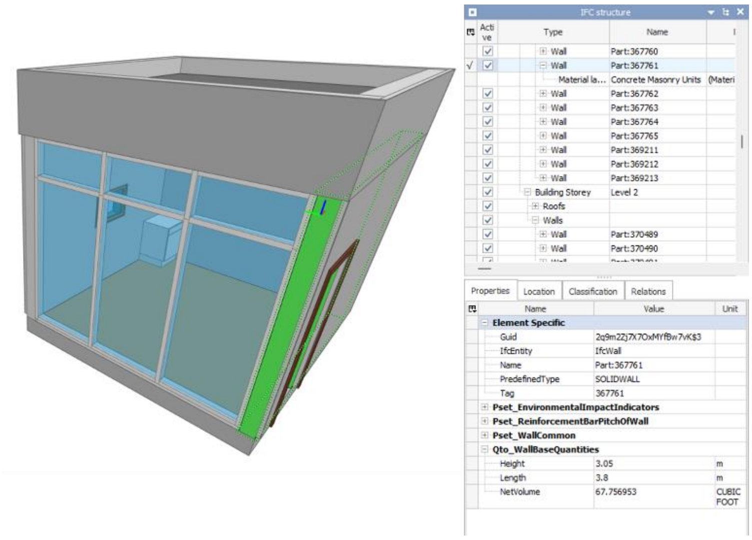


Figure 49 – IFC Revit export as parts.

The second authoring software is CYPE Architecture. Since this software doesn’t have the parts tool, the objects work only as compund elements. The IFC export is through CYPE’s cloud-based system, BIMserver.center. The IFC export is automatically linked to the IFC schema by using the architecture categories available in the software. To export the file a project has to be created in the cloud server, then it has to be shared through the BIMserver.center tab, or it can be directly shared to other software that are part of the CYPE suite (ex: Bill of quantities, structural analysis, etc.).

As shown in Figure 50, the wall's extracted quantities show the total amount of materials of the element, not divided by layer. The export includes all the materials of the wall and the properties of the IFC QTO property in a well-structured way.

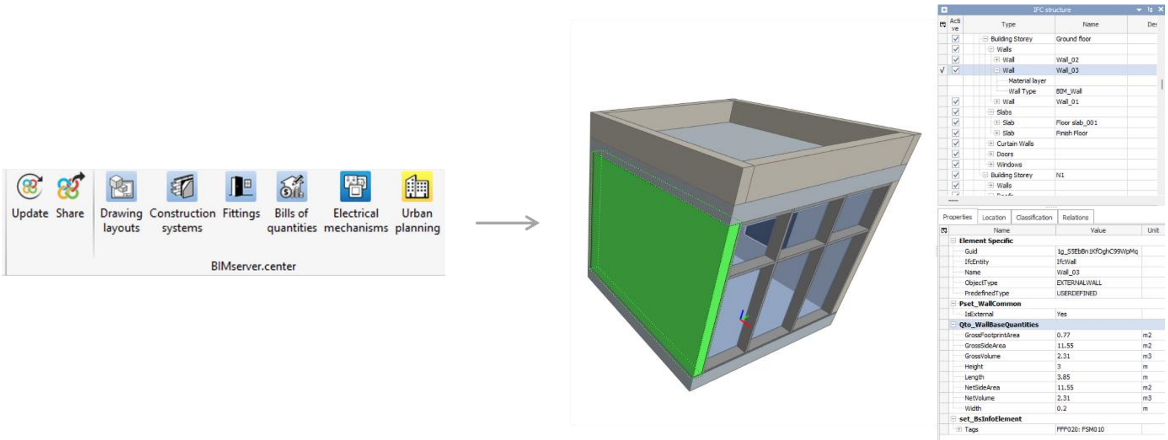


Figure 50 – CYPE Architecture IFC export.

The third authoring software explored in this study is ArchiCAD. ArchiCAD offers a wide range of setup options to export an IFC file. The "Type mapping" section was setup following the IFC4 schema with a geometry defined by the Reference model view. Also, the Building material properties along with the classification and IFC base quantities were selected for the QTO procedure.

As shown in the Figure 51, ArchiCAD applies the IFC QTO property set to the general geometry of the wall, giving just general quantities of the object. The only way to get specific layered quantity material take-off when using compound elements is by using the "Compound Quantities" property set, already included in the file export. The only issue of using this property set is that don't follow the IFC schema. The only exported individual property under the IFC schema applied to the wall is the width, just as the Revit export.

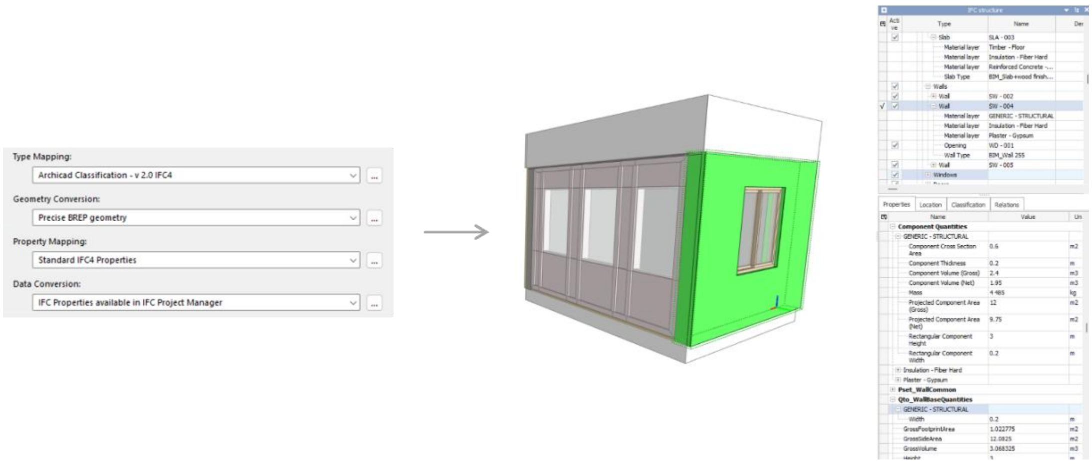


Figure 51 – IFC ArchiCAD export without parts.

The second trial on ArchiCAD is to export the layered elements as parts. As shown in Figure 53, when exporting the layered elements with the parts specification in the export setup, the IFC properties sets disappear, but the quantities of the layers could be found under ArchiCAD's component quantities property set. It is important to mention that the Property sets of the IFC schema only appears if all the parts of the layered elements are selected altogether.

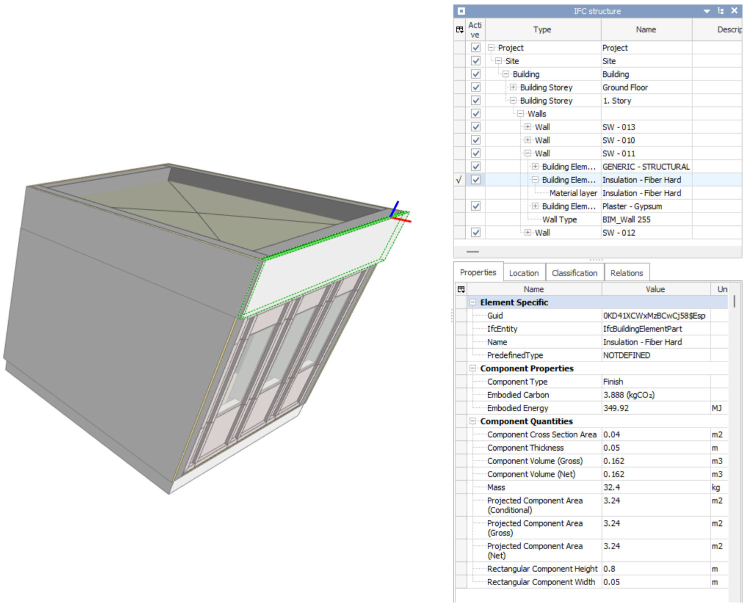


Figure 52 – IFC ArchiCAD export as parts.

The Table 38 shows all the properties that are part of the QTO property set of the walls. The table includes the properties classified by the parts or no parts export option and it shows how many of them were included in the export process. This table gives a glance of which properties should be mapped manually depending on the authoring software. More tables that show the same information but using all the other architecture elements studied in this work can be found on the Appendix 4.

Table 38 – IFC export of quantities properties - Wall.

Object: Wall	**Revit**			**ArchiCAD**			**CYPE Architecture**	
	No Parts	**Parts**		**No Parts**	**Parts**		**No Parts**	**Parts**
Qto_WallBaseQuantities		**Whole**	**Single**		**Whole**	**Single**		
Length		**						-
Width		**				*		-
Height		**				*		-
GrossFootprintArea		**						-
NetFootprintArea		**						-
GrossSideArea		**				*		-
NetSideArea		**				*		-
GrossVolume		**				*		-
NetVolume		**				*		-
GrossWeight	x	x	x	x	x	x	x	-
NetWeight	x	x	x	x	x	x	x	-
Material Layer	Whole	**	Per layer	Per layer	Whole	Per layer	Not included	-
Notes: * Not displayed as IFC schema. **Displayed as parts at all times.								

3.3.6.2. Revit's IFC export

The Revit export to IFC option can be found in the File tab with the name IFC. By default, Revit will choose the IFC 2x3 Coordination View, this has to be changed to IFC4 Reference View with the Architectural Reference Exchange as the exchange requirement.

On the Additional Content tab, the only option that can be checked, depending on the user's needs, is the "Export only elements visible in view". If this option is marked make sure all the elements that are going to be exported are visible, a good practice for this is to duplicate a view and set visibility filters to choose which elements are going to be exported.

Then, as shown in the Figure 53, the property sets that should be exported is the IFC common property sets and the base quantities, which includes the QTO property sets of each element. Also, since there are properties that are not exported, ex: the property of the WBS, a mapping procedure has to be done though a .txt file.

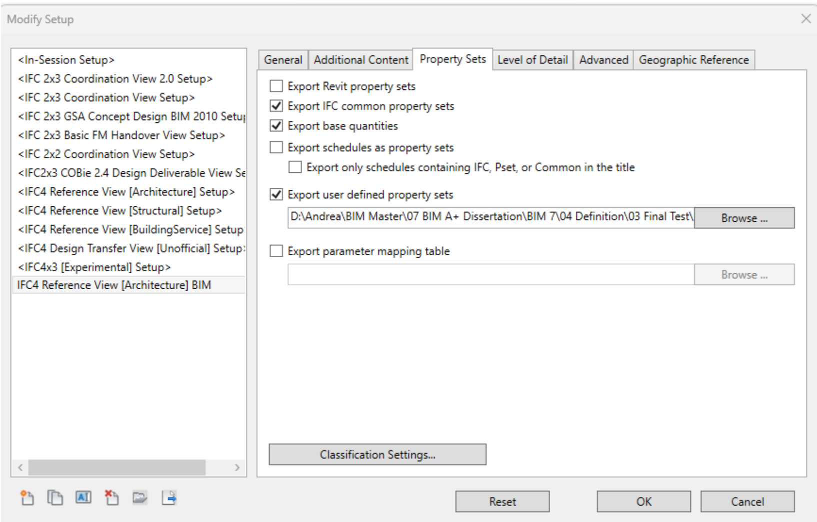


Figure 53 – Revit IFC export set up.

Finally, in order for the parts works as individual elements and not compound elements two main steps should be followed: first, the option in the graphics view the Parts Visibility property has to be set as "Show parts" and second, on the IFC export setup, on the advanced tab, the option of "Export parts as building elements" should be selected. As shown in the Figure 54, the wall has all the needed attributes needed for the QTO process.

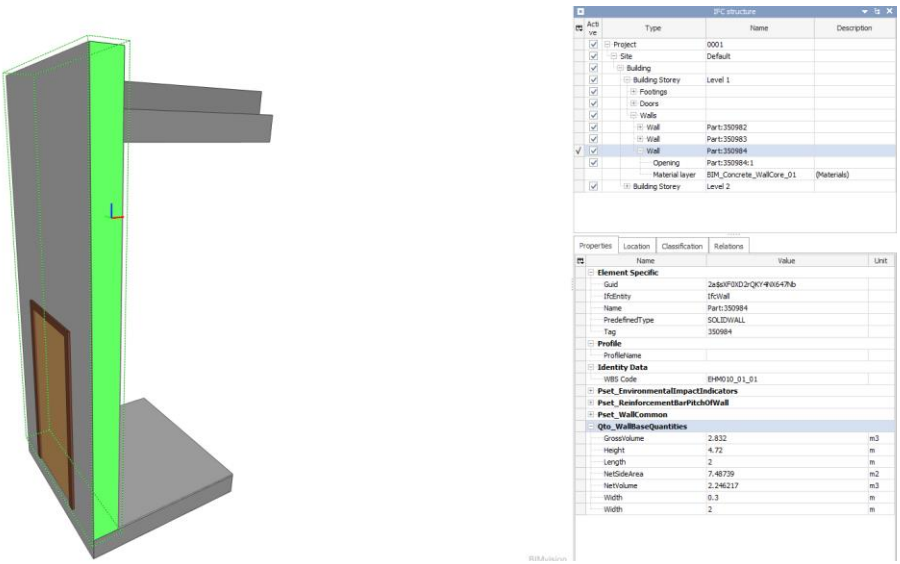


Figure 54 – Revit IFC export.

3.4. Model verification

The third step of the proposed workflow consists of the model verification, previously exported as an IFC file, in terms of geometry and information. This process is very important to ensure the accuracy and reliability of the 3D model. As shown in the Figure 55, this verification procedure is composed of two main steps: geometric verification, which analyses the volumetric reliability of the project; and the information verification, which makes sure that all the properties required for the QTO process were exported correctly into the IFC file.

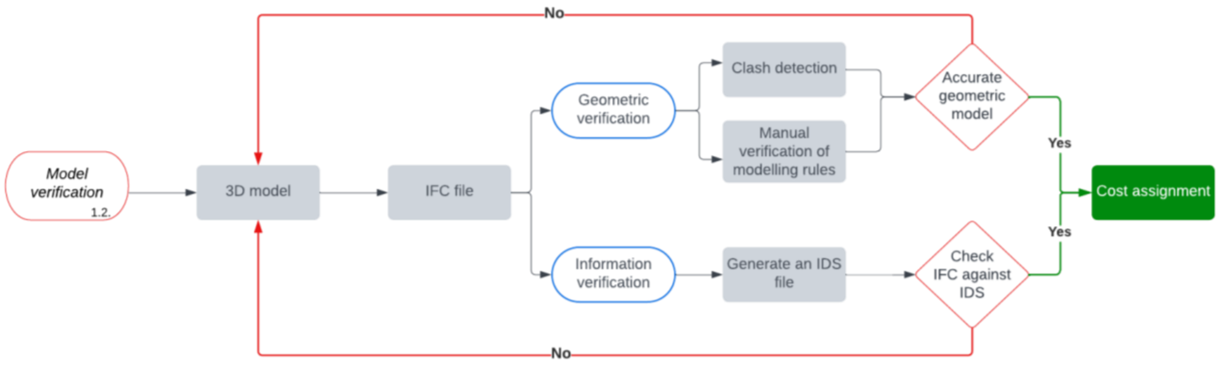


Figure 55 – Model verification workflow.

If the geometric and information verification presents negative results, the problem has to be fixed in the 3D model authoring software and repeat the following steps, as previously explained in the chapter 3.1, Figure 28. If the process shows no main issues the IFC file can be uploaded to the Bills of Quantities of CYPE to generate the quantity take-off process.

3.4.1. Geometrical information

The geometrical information is checked through two different filters. The first one is to check the IFC file against a clash detection between the model elements. The second one consists of checking that the model has been done according to the modelling rules.

Clash detection is a process where different building elements or systems intersect or interfere with each other, and they are properly identified and solved. Generating a clash detection study ensures accuracy and reliability of a quantity take-off process because when clashes are resolved the QTO calculations become a more realistic representation of the project. This process leads to avoid overestimation or underestimation of the required materials, works and costs.

The first geometric check procedure is to manually check that all the modelling rules are being properly applied to the model. This process has to rely on manual methods since at this moment the there is a limitation of software that addresses this type of verification and the difficulty of automatization that causes a lack of research on the topic. The verification of each element according to the modelling rules are the following:

- Geometrically, the user has to check that each element is divided into parts and that each of them has the color code mentioned in the level of information need.

- Generate different sections of the building to check that all the elements are modelled according to its real-life application. Most of the checking should be done in the walls since it's the component that has more relations with other instances.

- Check that all the elements have the minimum layers need according to what was discussed on the chapter 3.3.4. Also, look out for elements that doesn't need a physical representation and that its quantities can be extracted through other elements model.

- Make sure to add into the IDS a specification for the WBS code, proper IFC class and its properties according to the instance.

The second geometry check-up was done through a clash detection procedure in Solibri. When generating the study there are two main clashes that are important for a quantity take-off process: a clash between the geometry of the elements in the project and a repetition of elements.

The first one is to generate a clash detection between Architectural components, this means that even if it's just one IFC or more, all the architecture elements are going to be tested by looking for collisions between their own category and against other categories as well. The second clash type to study is the repetition of elements. This is more common when the project is composed by more than one IFC or that the model was generated by more than one person. This process helps to reduce the overestimation of the elements and reduces some of the costs of the project.

For the scope of this work, only a clash detection procedure is needed. This is because in the study only one model was generated, and it was done by the same person. A simple way to approach this step is to use Solibri rulesets for clash detection. In this case, since the studied elements only belong to an architecture category, a clash detection between the same and different kind of components in the model should be more than enough to find the clashes within the geometry. When a clash is detected by the software, the issue should be addressed and solved, just as shown in the Figure 56.

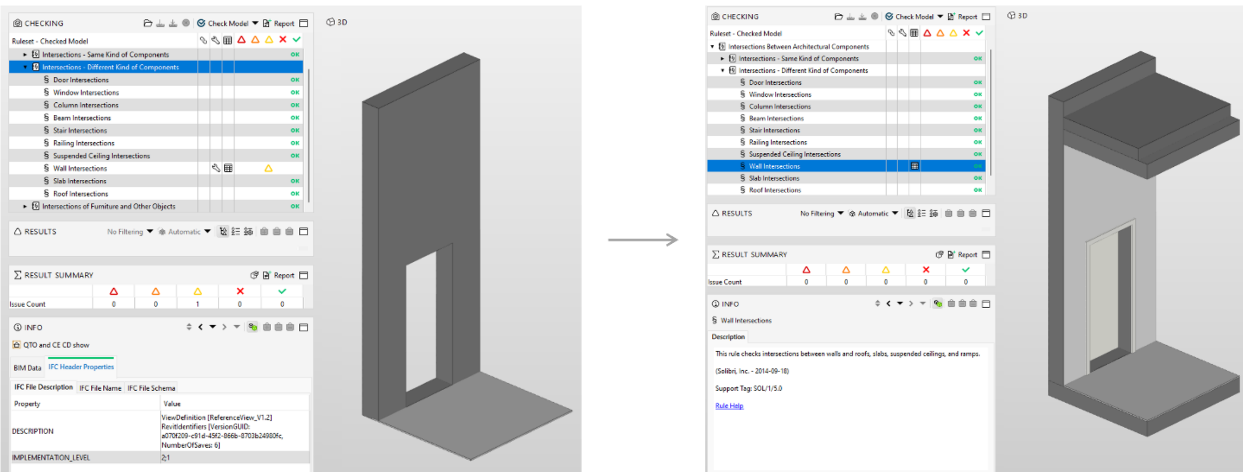


Figure 56 – Clash detection.

3.4.2. Alphanumerical information

The alphanumerical information verification aims to confirm that all the properties established by the level of information need of each element were exported correctly into the IFC file. This process consists of two main steps: the generation of the IDS and the verification against the IFC file.

To properly explain the process, the following chapter will explain each step by generating an IDS verification for the example generated according to the WBS stated in Table 6.

3.4.2.1. Generating an IDS

To generate an IDS, it is important to use a tool that will allow the user to set up all the properties needed for each of the elements in the project through a filtering process, and that allows the export of an IDS that will be human (.pdf) and computer readable (.ids / .xml) files. For this reason, the tool used to create the IDS file for this work is the usBIM.editor.

What the standard asks to do first is to establish the metadata to define and identify the IDS' information that will help the user to understand the purpose and the general aspects (described on Table 39) of the IDS. This could be included in the General Data tab when creating the IDS file in the usBIM.editor.

Table 39 – IDS metadata definition.

Name	Description	Example
Title	Document title	Minimum QTO and CE requirements
Copyright	Owner of the IDS	Andrea Roldan
Version	Version of IDS, to keep track of changes.	1.0 or 2.0
Author	The author provided as an email address	ar27@gmail.com
Date	Date it was published	14/07/2023
Description	One or two sentences. Describes purpose, application, etc.	"Minimum requirements for the project to ensure an accurate and reliable quantity take-off process…"
Purpose	Short sentence of what IDS achieves	Minimum requirements for the quantity take-off process.
Milestone	Project milestone	Desing, Construction or Commissioning

The following step is to generate requirements for each of the elements that are being used in the project and specify all the characteristics and properties needed for the quantity take-off process. For the scope of this work, the properties that have to be added into the IDS are the ones defined by Level of Information Need per instance and the WBS Code. Other properties can be added according to the users and project need (ex: materials, properties needed for QTO for non-modelled elements, etc.)

According to the Figure 57, the next step is to define the elements and the properties needed for the QTO. To start is important to create a specification by object and map it according to the IFC class, in this case an IfcWall, Then, the user has to specify the requirements, in this section all the properties previously discussed have to be integrated under the "having" mode. A suggested order to add these properties is to first add the attributes, then the WBS code and lastly the material.

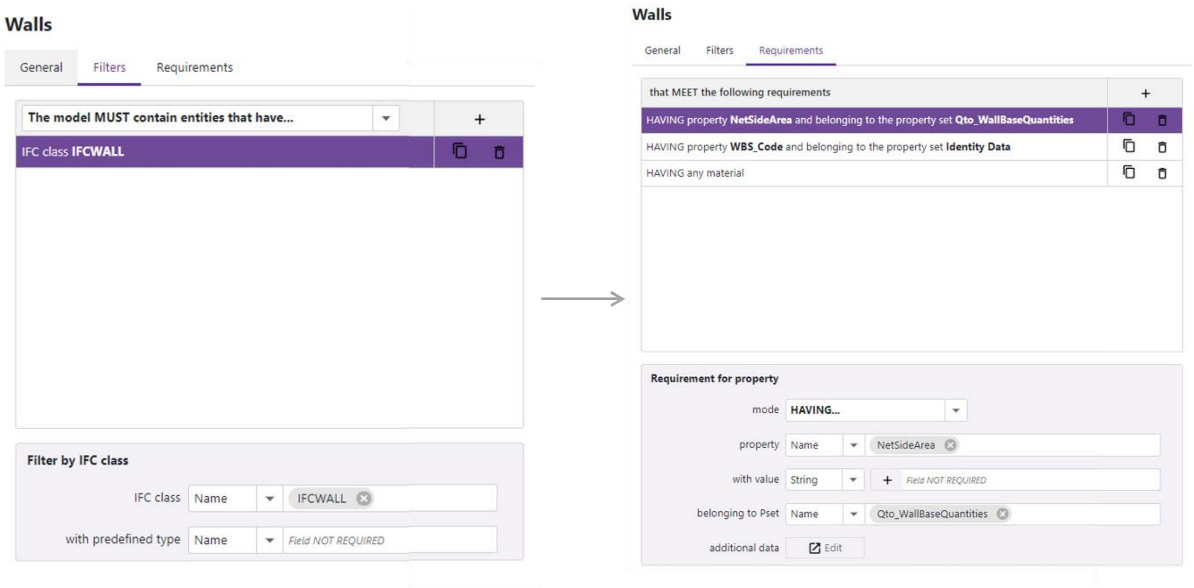


Figure 57 – IDS property filter generation.

When all the categories are defined with their respective properties, the user can download both the .ids, which will be used for the alphanumeric verification; and the human readable report as a pdf file. As shown in the Figure 58, the report includes all the metadata established at the beginning of the process and the instances with specifications about their attributes and the IFC version that should be used for the project. Even though this report does not directly affect the workflow for the QTO, it is important to deliver this type of documentation to the quantity surveyor, so they can have a better understanding of what is expected from the IDS.

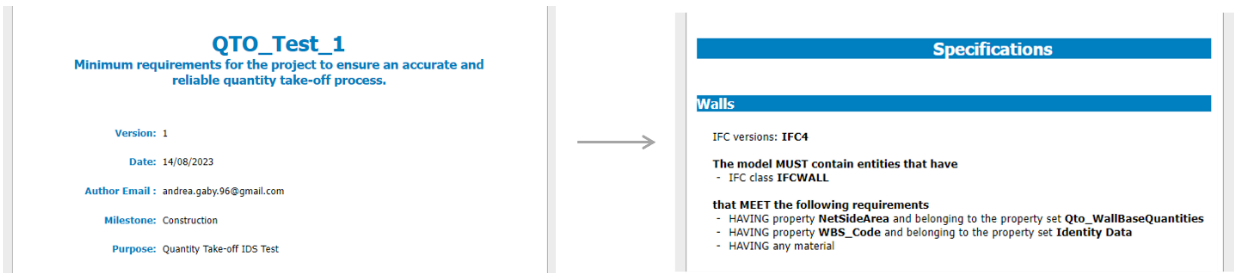


Figure 58 – IDS property setup.

3.4.2.2. Verification through IDS

The next step is to generate an evaluation between the generated IDS file and the IFC of the 3D model. For the scope of this work, the IDS evaluation was generated using Blender with the add-in BlenderBIM. This was selected because the process is simple and user friendly, also everyone can use it since it's a free software.

As shown in the Figure 59, BlenderBIM provides a tab to add an IFC model and another for the IDS file. When both files are selected and uploaded properly, the user just needs to generate the test by clicking on the "Execute Ifc Tester".

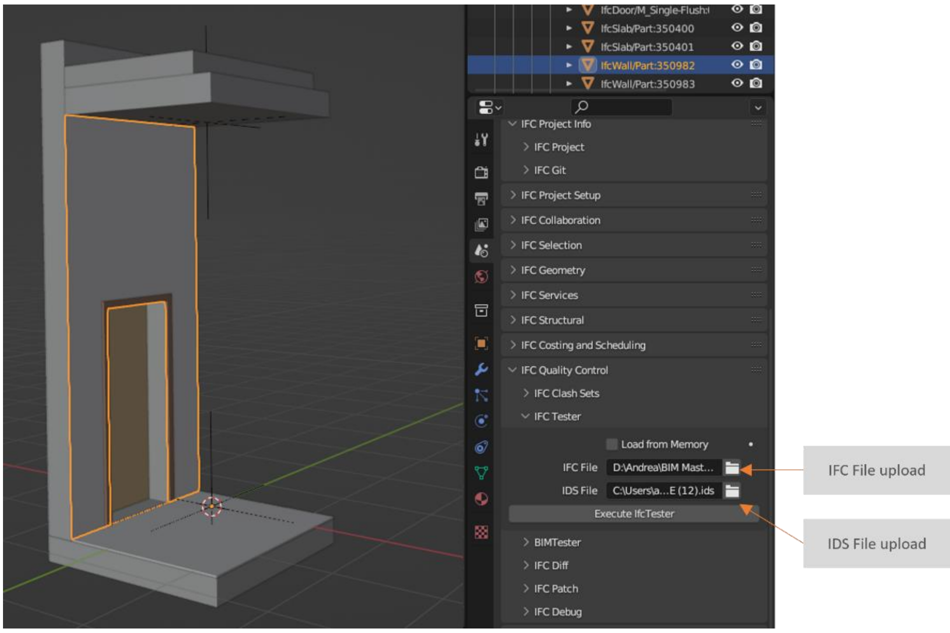


Figure 59 – BlenderBIM setup.

When the user clicks the "Execute Ifc Tester" the program automatically generates a report where it shows all the categories defined in the IDS and then all the properties of the elements as subdivisions of the class. It also generates an .html file of the report of the test, in the same folder where the IDS file is located.

The display shows which properties are exported correctly in green and the ones that are missing or not exported properly in red, as shown in the Figure 60. It also includes a counter under each instance and tells how many of the elements of each class have all the requirements established in the IDS correctly. The user has to go back to the model to solve the issues in order to continue to the next step, add all the cost to the elements and generate a cost estimation report.

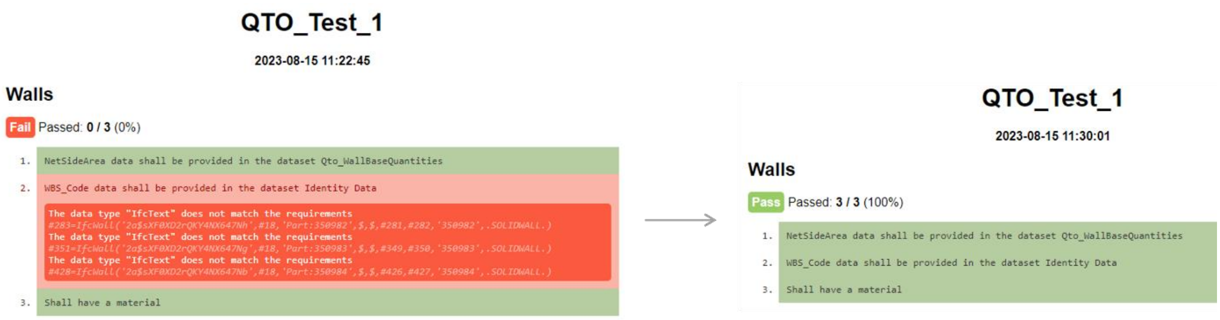


Figure 60 – IDS report.

3.5. Assign cost procedure

The assignment of cost to each individual architectural element involves adding the correspondent financial value according to what the WBS structure specifies. This process can be done when the IFC file is correctly exported, and its geometrical and alphanumerical information is properly checked. The expected outcome of this procedure is that all the elements in the project have all their relative cost and ready to generate a cost estimation for the project.

The presented workflow proposes a systematic approach that involves the integration of financial values to each specific architectural instances based on a standardized coding framework extracted and modified according to the WBS code system already explained on the chapter 3.2. This is why it's important that each element has their code already properly assign at the moment of exporting the IFC file from the authoring tool.

The WBS used in this project is composed by three different types of costs: the materials, works involved and indirect costs. The first one includes all the materials to either create the object (ex: concrete or steel reinforcements to cast a wall) or the object itself (ex: frame and sheet of a door) and complementary materials for its installation. The second includes all the manpower needed to build the instance. The third cost includes the appliances needed for the work (machinery, tools, scaffold, etc.) and it can represent between 1% - 3% out of the final cost.

The Open BIM quantities software of CYPE will be used in the assign cost procedure. To accomplish this task is necessary to follow two main steps: generate a cost database and set rules for the measurement of each element.

Generating a cost database through the Open BIM Quantities is a simple process. Each of the elements selected from the project should be open in a web browser. In the export tab of each element, simply grab the "Arquimedes" icon, shown in the red square at the left on Figure 61, and drag it to the cost database in the Open Bim Quantities. When integrating each element is important to add the suffix to the coding system according to their corresponding object. Repeat this process until all the WBS works are integrated into the cost database.

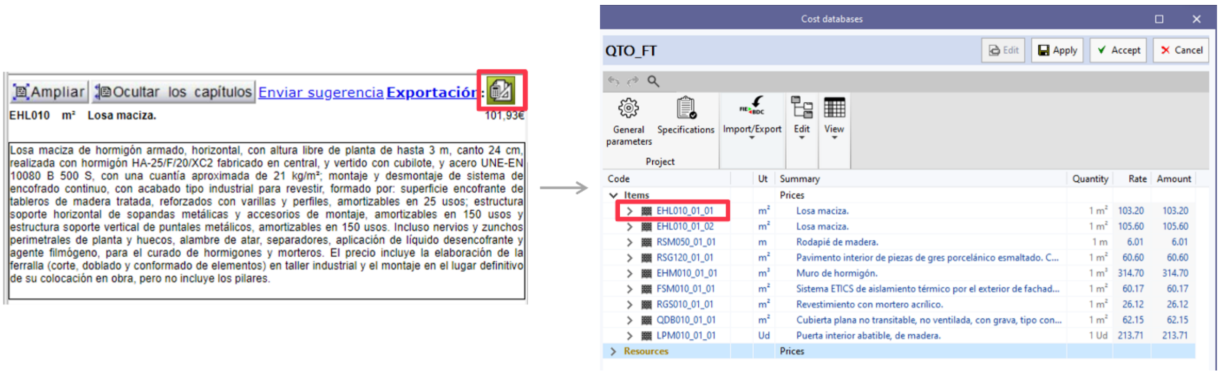


Figure 61 – Generation of a cost database.

The second step is to set rules of measurement per element. This process means to map the all the costs in the database to their respective element. To do so, it is important to first select one element of the model and filter it according to its WBS code on the Selection tab, then connect it to its cost in the database through the Item tab shown on the Figure 62.

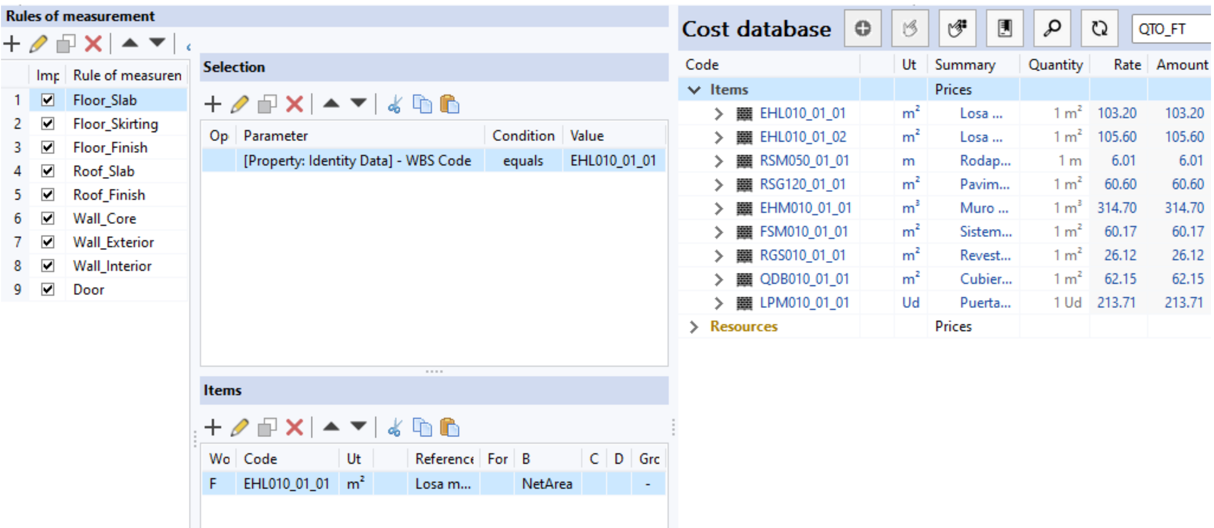


Figure 62 – Mapping quantities procedure.

The quantities attributes have to be mapped according to each element's unit of measurement. For example, if the rules are being set for a wall, the quantity property that has to be selected in this section is the NetSideArea (m^2), which represents its QTO attribute on the IFC schema, as shown in the Figure 63. It also has a formula tab which enables the user to generate calculations between the element's properties.

To make sure that the mapping procedure was done correctly, the user has to check on the main sheet that the element that was being settled has a green square next to it. If the square is orange means that it doesn't have any cost assigned. This process has to be repeated with all the elements that are part of the cost estimation of the project.

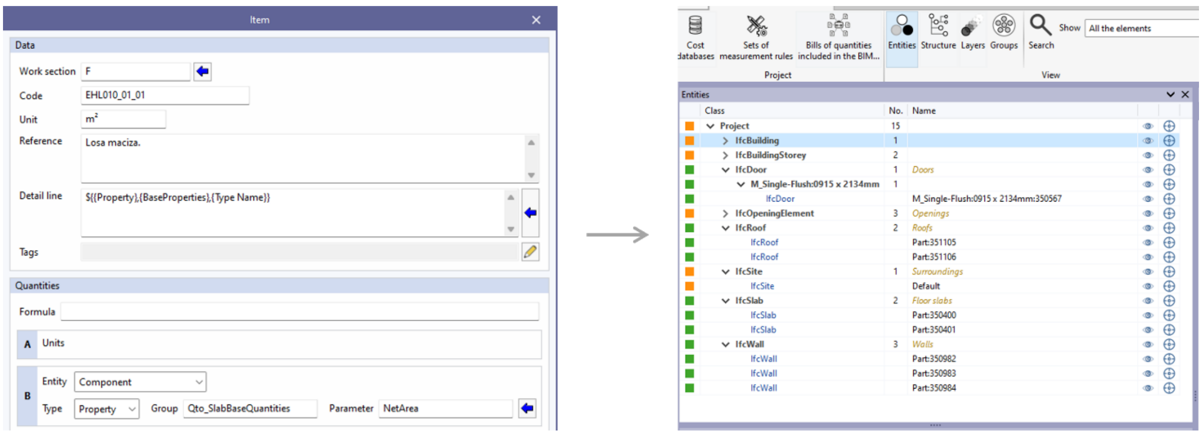


Figure 63 – Setting quantities properties procedure.

3.6. Cost estimation report

The final step of the presented workflow is the cost estimation report. This process involves the integration of all the financial values of the materials, works and equipment needed of each element in the project. Usually, the cost estimation of a project involves all the construction disciplines, but in this case, for the scope of the work, the cost estimation will focus on the architecture discipline. The outcome of this phase is to generate a pdf file with all the costs of the elements that compose the project.

To generate a cost estimation on the Open BIM Quantities is necessary to have all the elements already mapped according to its WBS code, as explained in the previous sub-chapter. When all the elements are ready, in the Bill of Quantities by pressing "Update the quantities" button, the software will automatically create a bill of quantities that can be exported into a pdf file.

The structure of the cost estimation report should be the following: frontpage, index, description of the bill of quantities of the project. Make sure that the report starts with a frontpage that includes important information of the project. For this work it is recommended that at least this information should be added: the name of the project, location, who is responsible (here it can include the name of the company that is doing the cost estimation), and the date. On the other hand, the index, following the nature of a deliverable based WBS stated at the beginning of this work, should be divided into all the categories of the instances used on the project.

Finally, the cost estimation should include all the categories involved in the project (walls, floors, doors, etc.) with their final price and WBS code. Also, below each element a description of all the materials, works and complementary cost should be included, specifying their unitary financial value and quantities in the project, as shown in the Figure 64. Also, the price already applied to their respective amount in the project should be added to the final quotation, in this case it wasn't integrated due to software limitations.

Project: Cost Estimation Report
Location: Portugal
Developer: Andrea Roldan

1. FLOORS

Code	Ut		Description	Rate ()	Amount ()
EHL010_01_01		m²	**Losamaciza.**		103.20
mt08eft030a	0.044	m²	*Tablero de madera tratada, de 22 mm de espesor, reforzado con varillas y perfiles.*	45.50	2.00
mt08eva030	0.007	m²	*Estructura soporte para encofrado recuperable, compuesta de: sopandas metálicas y accesorios de montaje.*	102.00	0.71
mt50spa081a	0.027	Ud	*Puntal metálico telescópico, de hasta 3 m de altura.*	19.25	0.52
mt08cim030b	0.003	m³	*Madera de pino.*	355.50	1.07
mt08var060	0.040	kg	*Puntas de acero de 20x100 mm.*	8.75	0.35
mt08dba010d	0.030	l	*Agente desmoldeante, a base de aceites especiales, emulsionable en agua, para encofrados metálicos, fenólicos o de madera.*	1.80	0.05
mt07aco020h	3.000	Ud	*Separador homologado para losas macizas.*	0.09	0.27
mt07aco010c	21.000	kg	*Ferralla elaborada en taller industrial con acero en barras corrugadas, UNE-EN 10080 B 500 S, de varios diámetros.*	1.60	33.60
mt08var050	0.252	kg	*Alambre galvanizado para atar, de 1,30 mm de diámetro.*	1.50	0.38
mt10haf010ctms	0.263	m³	*Hormigón HA-25/F/20/XC2, fabricado en central.*	92.20	24.25
mt08cur020a	0.150	l	*Agente filmógeno, para el curado de hormigones y morteros.*	1.56	0.23
mq06bhe010	0.024	h	*Camión bomba estacionado en obra, para bombeo de hormigón.*	190.40	4.57
mo044	0.500	h	*Oficial 1ª encofrador.*	22.27	11.14
mo091	0.500	h	*Ayudante encofrador.*	21.15	10.58
mo043	0.252	h	*Oficial 1ª ferrallista.*	22.27	5.61
mo090	0.210	h	*Ayudante ferrallista.*	21.15	4.44
mo045	0.013	h	*Oficial 1ª estructurista, en trabajos de puesta en obra del hormigón.*	22.27	0.29
mo092	0.053	h	*Ayudante estructurista, en trabajos de puesta en obra del hormigón.*	21.15	1.12
%	2.000	%	*Costes directos complementarios*	101.18	2.02

Figure 64 – Cost report.

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4. CASE STUDY

The following case study serves as a demonstration of the proposed quantity take-off and cost estimation workflow into a real-world application project. Through the chapter the study aims to showcase how the workflow contributes to estimating the material quantities, labor costs, and overall project expenses. The expected outcome is to generate a 3D model by following the proposed modelling rules and generate a cost estimate for all the project architectural instances along with their specifications by following the WBS structure used in this study (Generador de Precios of CYPE).

For the scope of this work, the case study, The Lagoa House, was provided by Marta Campos architecture office, one of the partnerships of the BIM A+ master. The project is a real case scenario of a new construction for a single-familiy located in Portugal, which as shown in Figure 65, it is composed by two buildings and exterior areas. It is presented as a good example of how to apply the proposed workflow since the project is composed by many of the architectural instances presented on the chapter 3.3.4. Also, each of this elements, specially the walls, are composed of different materials between instances, which represents an opportunity to use and explain how the coding system should be applied.

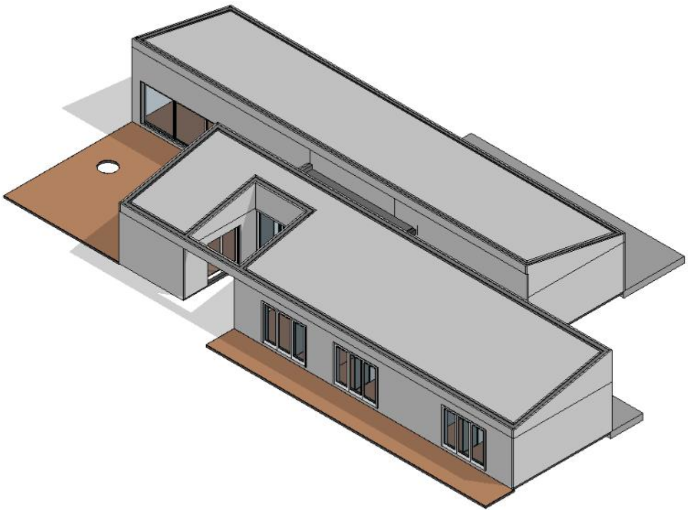

Figure 65 – Lagoa House.

The upcoming chapter will present a comprehensive breakdown of all the steps involved to get an accurate quantity take-off and cost estimation. This process will not only explain the workflow applied to the entire building and its architectural components, but it also addresses a singular element of the project for a more profound understanding of the procedure. In this case, the chosen element is the only type of window within the project. The item was selected because even if its just one instance, it embodies a dual codiging system: one for the frame (depending on the object's overall geometry) and another for the glass panel (focused only on the glass panel measurement).

4.1. Modelling process and considerations

To generate the 3D model it was necessary to define all the types of elements that are integrated in the project according to their type of object, function and materiality. All the elements used in the project can be found on Appendix 5, with their respective WBS codes and their unit of measurement.

When applying all the modelling rules it is important to have order and consistency while generating the model. To accomplish this, all the instances were modelled in the following order: (1) exterior walls, (2) interior walls, (3) floors, (4) roofs, (5) ceilings, (6) doors and (7) windows, as shown in Figure 66. By following this procedure it was easier to have control on applying the modelling rules to each instance and to connect all the elements without generating any type of issue between them.

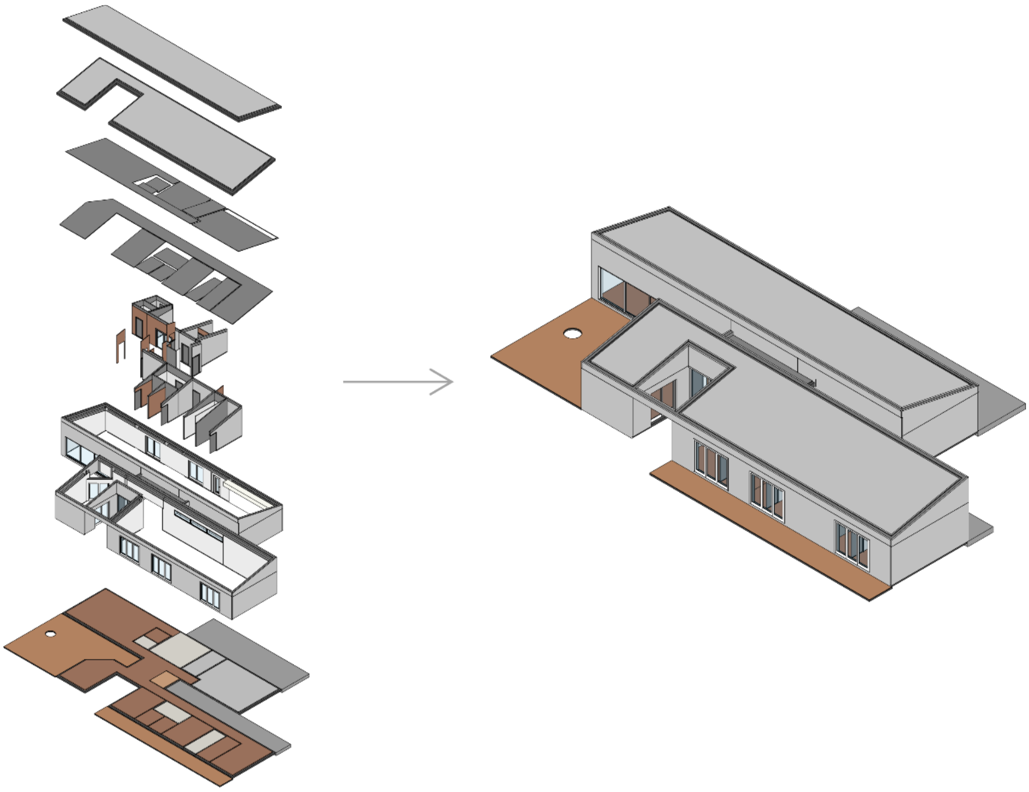

Figure 66 – Modelling process of Lagoa House.

When generating each of the instances types, it was necessary to define three main aspects: layering, dimensions, and materiality. The layering process was defined per family type by following the modelling rules and level of information need per element shown in the chapter 3.3.4. Also, it follows the naming conventions for both the layers and materials according to the NBS standard. After defyning how the element was going to be composed, its respective material (RGB color and material name) was assigned to each of their respective layers. As mentioned before, the texture is not necessary for this process. The layered elements should be defined by different colors, as shown in the sectioned wall on Figure 68. Finally, each element was modelled according to their real-world dimensions, which in the case of the walls, was finished when adding the roofs and ceilings.

When all the elements were modelled, several sections were created to check mainly the heights of the walls. Usually, each part of the wall should have different height and different shape depending on its function. This was settled by turning off the “Parts view”, and attaching the element to its respective covering (ceiling or roof), so that when turning it on, the parts would remain with the correct height. When this method didn’t work, the area that was not needed was divided and excluded from the part of the model by the “Division and Exclude parts” tool. The main idea of this step was to generate a model with precise heights to have accurate quantities, as shown in Figure 67.

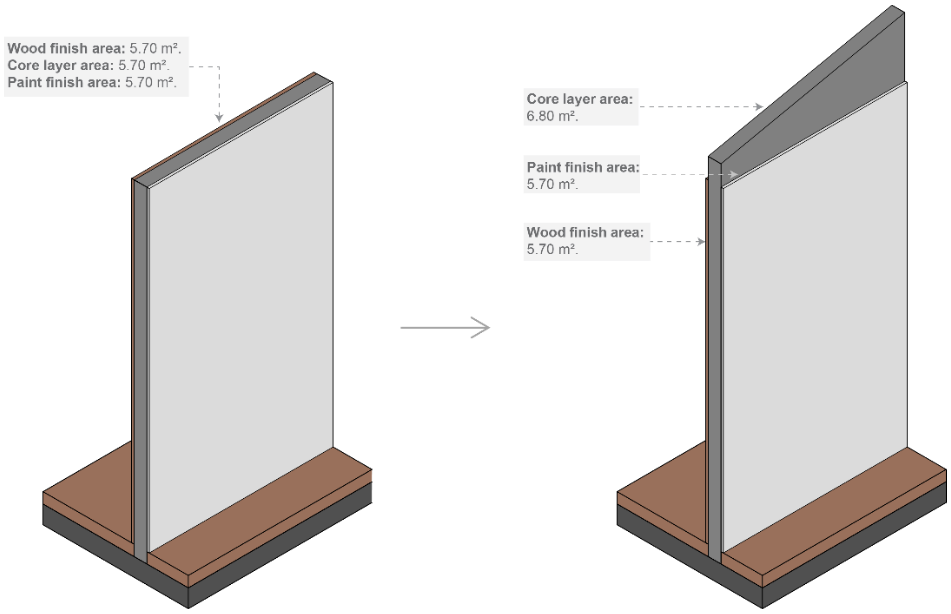

Figure 67 – Modelling setup per parts.

The next step was assigning each of the objects their WBS code and IFC category. The categories were applied per layer and object. When the object only had one WBS code, the second code was defined as "n/a", as stated in the NBS standard. In case of the window, as mentioned in the previous chapter, the user can define a code to assure an accurate definition of the materials by using the glass panel as a nested family, as shown in the Figure 68, which let the extraction of the exact glass area.

A good practice before exporting the model to IFC, is checking if all the elements have their code assigned in the object and most importantly, if they are correctly placed. To accomplish this, the strategy used in this case study was to generate a schedule per instance. In the schedule the type of family, material and WBS coding system should be added. This helped to check that all the codes were properly assigned and that all the names involved are correctly applied and following the naming standard of the NBS.

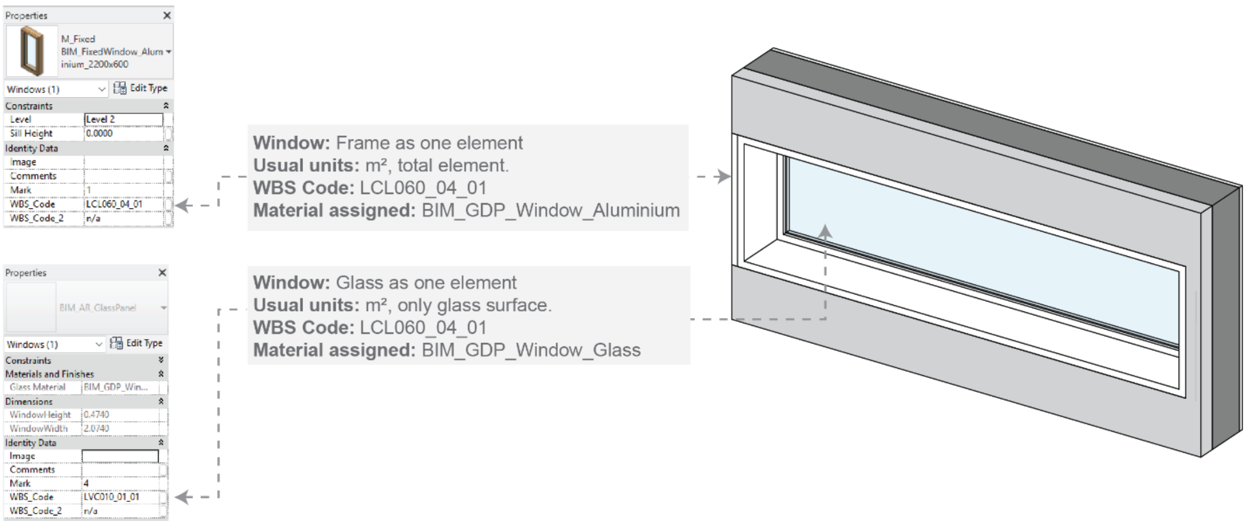

Figure 68 – Modelling process and code assign.

4.2. IFC set up and export configuration

After finishing the modelling with their respective coding system applied and IFC schema defined, the project can be exported as an IFC file. As mentioned in the previous chapter, setting the configuration as an IFC4 Reference View with the base quantities and the “Export parts as building elements” included is important to have a correct export.

One more step that is included in this process is the generation of an user defined property set. The main reason to generate a user property set is to map the properties that won’t be exported when generating the IFC file. A clear example of this is the WBS code, which the only way to export it automatically is checking the Revit’s properties at the configuration panel, which may lead to fill the file with information that is not needed on the project. A better and more organized way to export it, is to include it in a .txt file to define the user property set along with the properties that may not be exported by Revit that are necessary for the cost assignment process.

4.3. Verification process

The verification process was divided into two main procedures: geometrical and alphanumerical verification. The geometrical verification process was carried out through a clash detection study and manual check-up, meanwhile, the alphanumerical verification was done using IDS.

The first step for the geometrical verification was to manual check-up if the modelling rules were applied. This was done through several 3D sections of the project in BIMVision, which allowed to have a clearer view of the elements since it’s easier to be aware of issues not only in the sectioned area but also in the surrounding area. Some corrections were made, mostly to the layered elements, to achieve a more realistic model.

The second step consisted of a clash detection done through Solibri clash detection by using its clash study between same and different kind of components rule set. Some modifications were done to the categories for a more accurate quantity take-off. As an example, the tolerance for layered elements (walls, floors, roofs, and ceilings) was changed from 2” centimetres to at least 1”. As shown in Figure 69, this helped to detect most of the clashes, which thanks to the manual verification, weren’t that much.

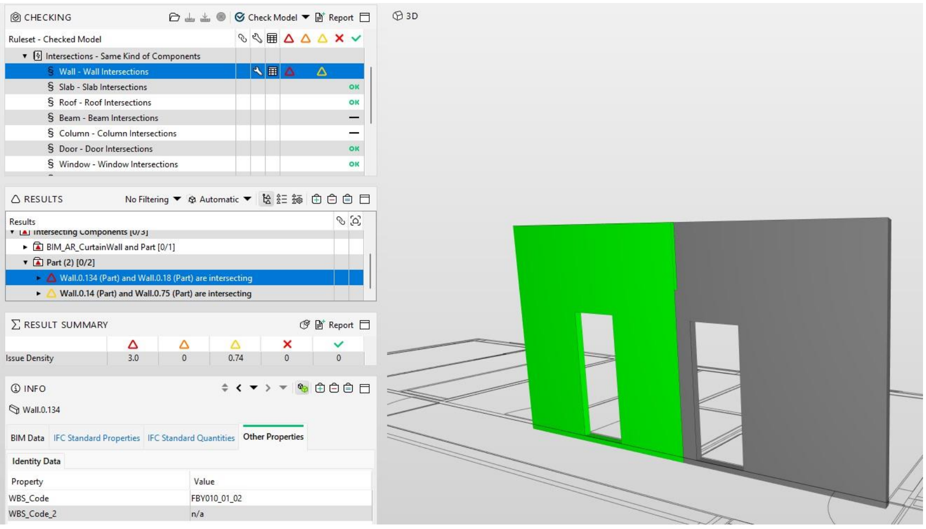

Figure 69 – Clash detection study

The alphanumerical information check-up was done through the generation and practice of an IDS file. To generate an IDS, it was necessary to consider the level of information need of each architecture element in the model and other properties that were needed for the quantity extraction of a non-modelled elements. This process was divided in two steps: setting the information for the project required by the IDS standard and defining the properties needed per architectural instance.

The first step included the definition of all the information required by the IDS standard, previously explained on the Table 39. As shown in Figure 70, the provided information gives a brief description of the IDS and what is intended to accomplish by making this study. It is important to be concise on what is included in this step, since it is what gives a general idea of the purpose and the expected outcome against the generated IFC file.

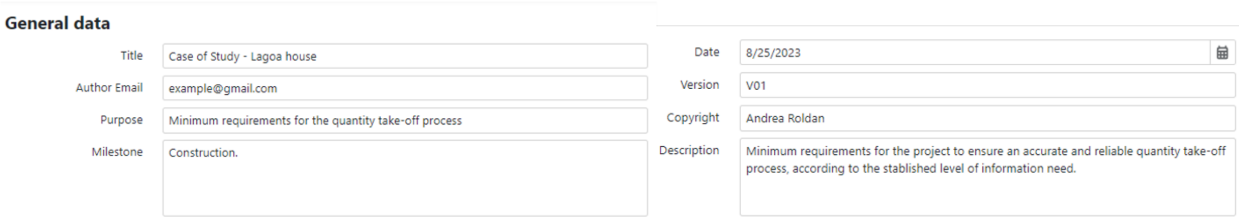

Figure 70 –IDS case study metadata

The study included the definition of two different approaches on the required information of the elements that compose the project. The first one is to generate an IDS that only reviews that the required information is part of each element, regardless of the needed value. An example of this approach is shown in the general approach of the Figure 71. This type of setup asks for the software to check if all the properties are filled with information. Meanwhile, the other approach, looks for a more specific definition of what property is needed and their respective value according to its IFC schema, WBS code and level of information need definition.

A more specific approach is better than a general approach since it correctly defines each value of the properties of the project. For the purpose of the case study, all the elements were done using the general approach and the specific approach was applied to the selected window, discussed earlier in this chapter. As shown in the Figure 71, each property has its own established value, which in most of the cases was exported as “optionally having”, because it generated issues on the check-up analysis since the same properties asked for different values (ex: the materials).

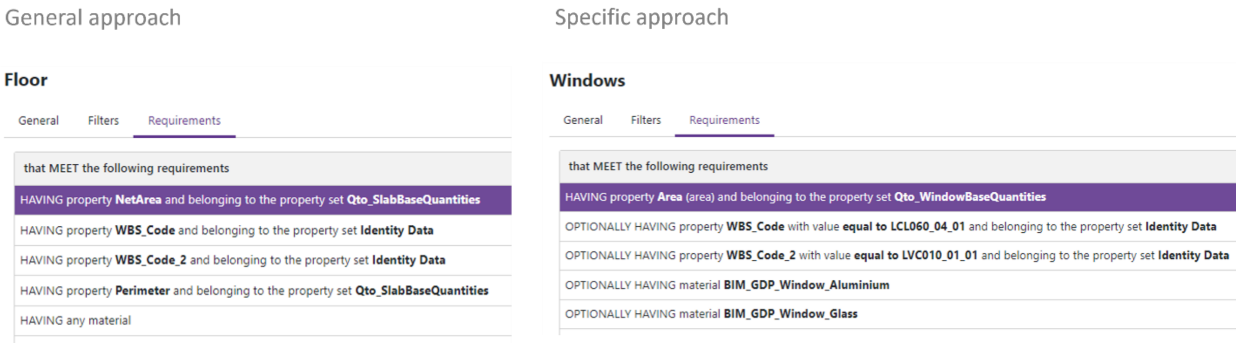

Figure 71 – IDS description defintion.

The last part of the IDS procedure consisted of generating a checkup between the IDS and the IFC file. The entire process was done in the same way as the example explained in the chapter 3.4.2. In this case, as shown in the Figure 72, most of the errors displayed in the study were mainly about missing properties and their respective values. This was because of two main reasons: first, a value was missing because it wasn't filled, or second, the property had to be mapped and it wasn't included in the user defined property set. In any case, each of the issues were addressed by finding the element and add the needed value.

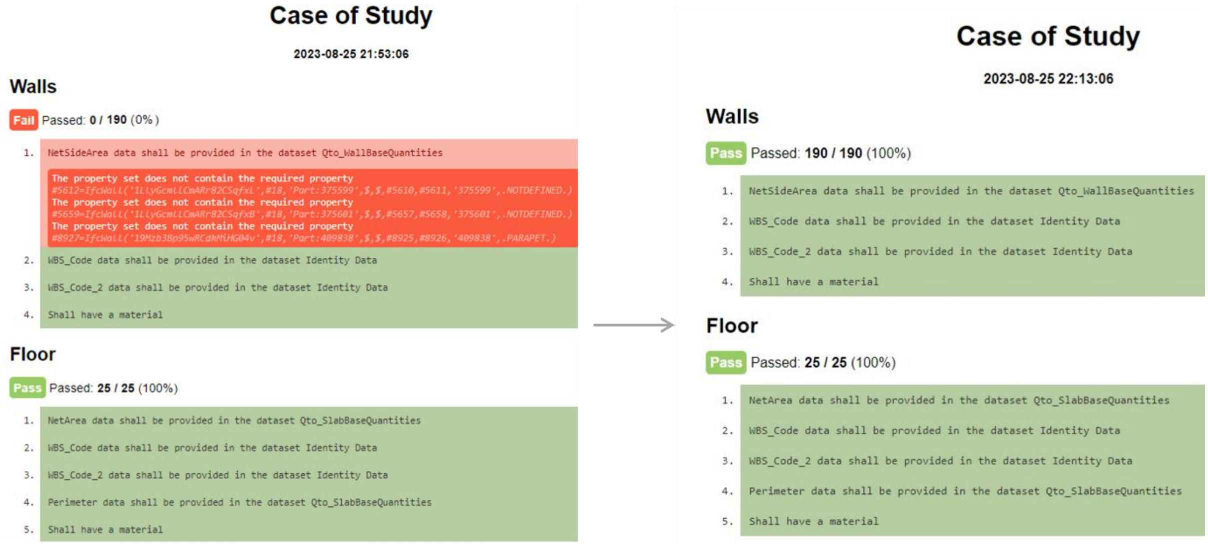

Figure 72 – IDS checking.

4.4. Cost database and cost estimation process

Now that the IFC was tested and checked through several filters, the next step is to assign the costs to their respective instance. To do so, the IFC was already uploaded to the BIMServer.Center of CYPE, then with that file, a project was created on the OpenBIM Quantities software. To generate the final cost estimation, all the codes were integrated into a Cost Database inside the OpenBIM Quantities software following the steps described in chapter Assign cost procedure3.5. Through this step all the financial values, description of each work and tools needed for each job were integrated in the file.

As shown in the Figure 73, the codes were structured as a deliverable-based work breakdown structure when added to the Cost Database, this means, each category was divided according to the different types of instances that composed the project, then subdivided according to its main fuction or type of object. As an example, the door category was divided by types: sliding, foldable, pocket, hinged, etc.

An additional important aspect in this phase was adding the suffix to each of the WBS codes within the Cost Database. This practice was implemented whenever a new code was incorporated into the database from the Generador de Precios website. After several tests done through the entirety of the project, it was decided to add this suffix as soon as the item was integrated on the database. This measure aimed to avoid any potential confussion or incomplete codes that may lead to issues when generating the cost estimate study.

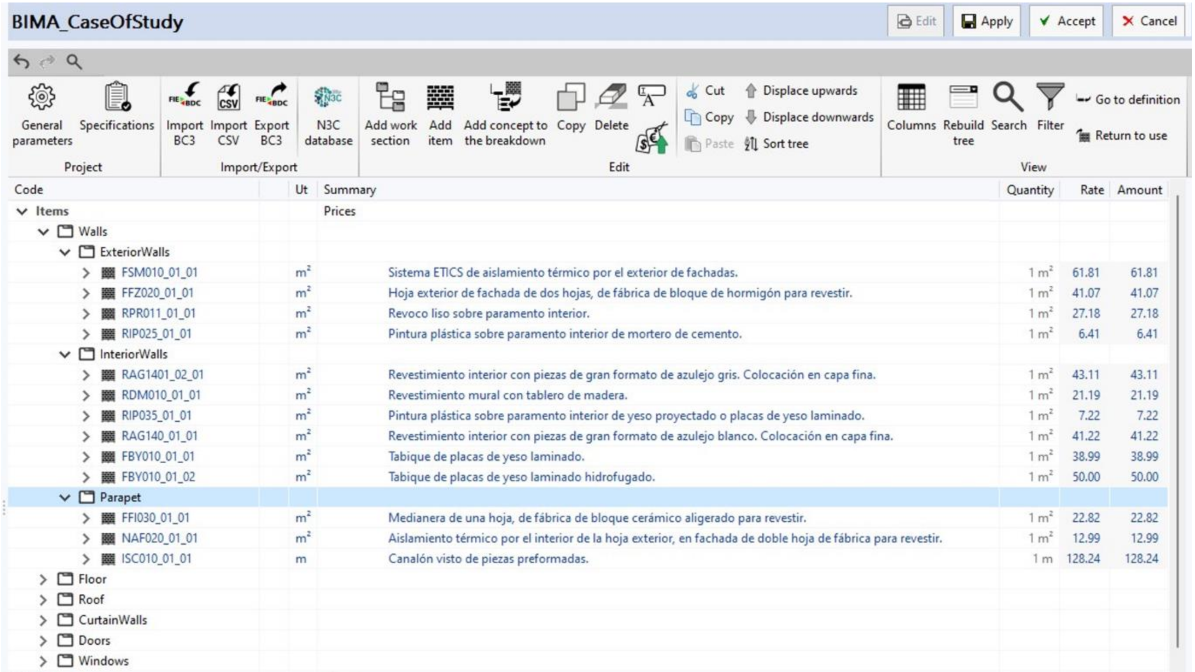

Figure 73 – Case study code structure

The next step, according to what is stated in the in chapter Assign cost procedure3.5, is to generate a set of Rules of measurement to each instance according to the WBS code and unit of measurement. This process is important since it determines the relationship between the financial values of the elements and the objects in the 3D model and their respective quantities.

When creating this set of rules, the same work breakdown structure settled before was followed. This step is important since it determined how the elements were grouped and presented on the cost estimate report. This can be settled when adding elements in the Items tab and it can be checked under the Work section tab of each element shown in the Figure 74.

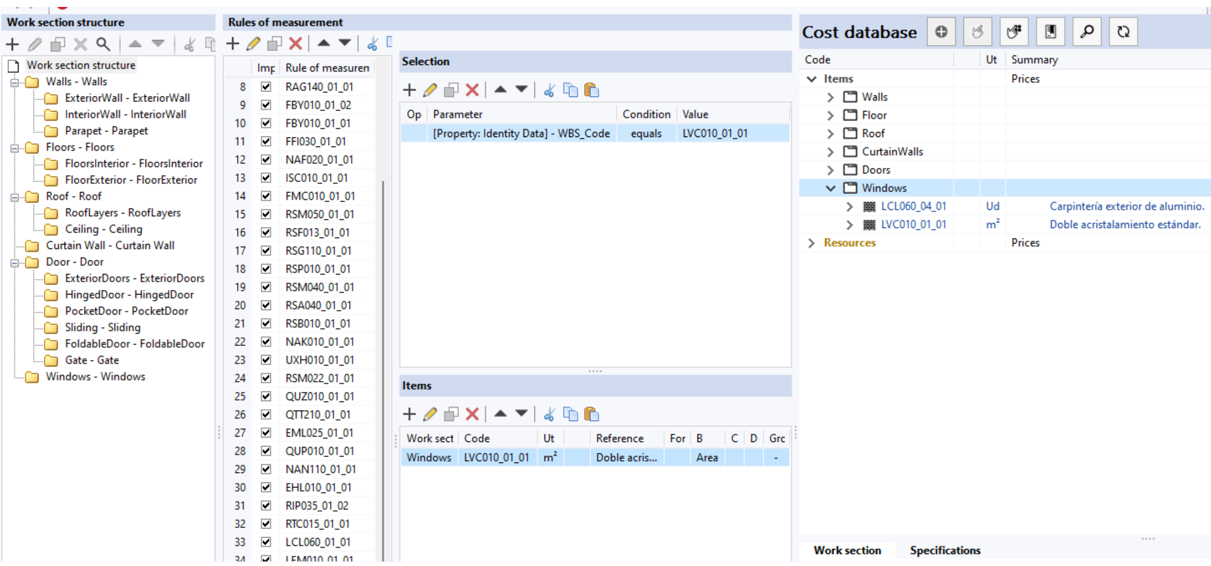

Figure 74 – Case study rules of measurement

The final step was to generate a cost estimate report that includes all the elements in the project, both modelled and non modelled. As shown in the Figure 75, the bill of quantities represents all the elements integrated in the modelled ordered by: first, a category classification defined by a deliverable-based WBS and second, a coding system that defines the element and its respective financial values.

Also, its important to note that the elements marked with a yellow circle (the circle is not part of the automatic graphic display of the software, it was added for clarification purposes) are non-modelled elements which quantities depends on other modelled elements properties. An example of one of this elements, is the roof gutter. The roof gutter uses the perimeter property of the parapet walls since it covers the same distance. The only considerations for this element was adding its WBS code in the parapet properties and the exclusion of the area that the gutter generates on the roof surface in the 3D model.

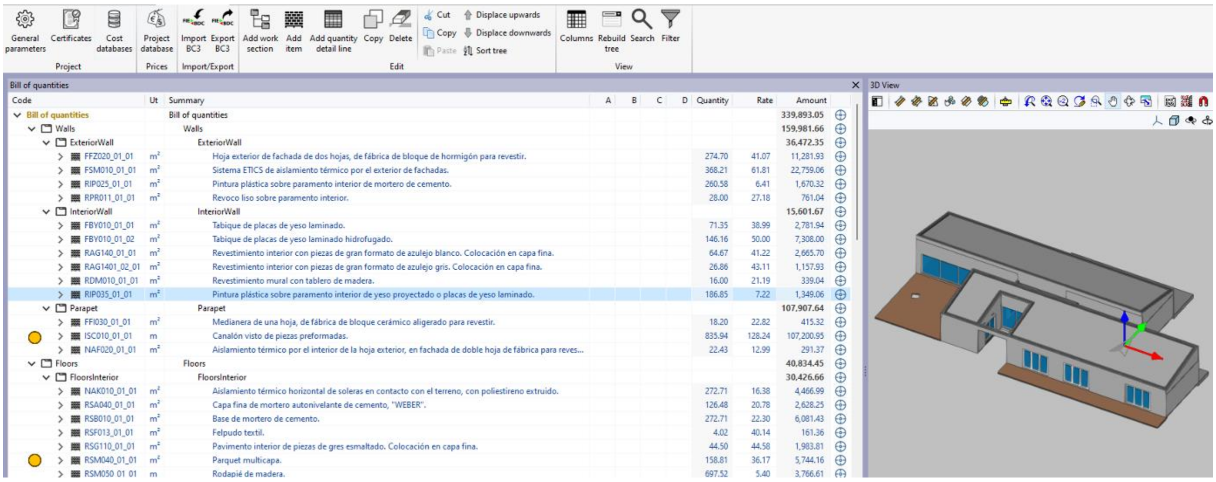

Figure 75 – Case study bill of quantities

4.5. Results

As a final result, the case study plays a significant role since it proves and tests the proposed methodology presented in this work. The study gave a more realistic approach of how the methodology works and the possible challenges that might need to be addressed in the process. It also demonstrates the value of a standardized and simplified process for a quantity take -off procedure in order to achieve accuracy and consistency by selecting a level of information need and setting modelling rules before generating the model. The final outcome of this process can be divided into two main results: a simplified 3D model and a final quotation of the project.

The 3D model was composed by a simplified version of its own elements and allowed a complete quantity take-off and cost estimation. What was important during its generation was to make sure that all the elements were created with the correct dimensions, following the established modelling rules and level of information need, to avoid the following: (1) integrating geometric instances that could be quantified without a graphical representation in the model, (2) adding non-useful alphanumerical information and (3) overestimation or underestimation of quantities.

The other final result for this study is the final cost estimate report generated by the OpenBIM Quantities. This document reflects all the modelled and non-modelled elements integrated in the project with their respective: (1) WBS code identification extracted from the Generador de Precios, (2) unitary and total costs grouped according to their categories, (3) defined works and materials needed and (4) respective quantities according to the unit of measurement defined by the WBS.

All the aspects mentioned above can be seen in the cost estimate for the windows shown in the Figure 76. In this case, due to software limitation, only the individual costs, quantities and final cost are shown in the final report; missing the description of what is included in the financial value of each element.

5. WINDOWS

Code	Ut	Description	A	B	Quantity	Rate ()	Amount ()
LCL060_04_01	Ud	**Carpintería exterior de aluminio.**			3.00	336.18	**1,008.54**
		M_Fixed:BIM_FixedWindow_Aluminium_2200x600	1.00		1.00		
		M_Fixed:BIM_FixedWindow_Aluminium_2200x600	1.00		1.00		
		M_Fixed:BIM_FixedWindow_Aluminium_2200x600	1.00		1.00		
LVC010_01_01	m²	**Doble acristalamiento estándar.**			3.03	41.78	**126.59**
		BIM_AR_GlassPanel:BIM_AR_GlassPanel	1.00	1.01	1.01		
		BIM_AR_GlassPanel:BIM_AR_GlassPanel	1.00	1.01	1.01		
		BIM_AR_GlassPanel:BIM_AR_GlassPanel	1.00	1.01	1.01		

Figure 76 – Case study cost estimation

Also, it is important to mention that this project was previously included as a case study in the thesis of Lucas Viera, mentioned in the state of art of this work. Making a comparisson between both is extremely difficult since they were generated through different approaches, which in his case the QTO and CE for this project was generated and focused on Revit, following a more closed approach. At the contrary, for the scope of this work, the project was tested through the proposed open-based methodology by using IFC.

Ultimately, the case study highlights the adaptability of the presented methodology by showing the capacity to apply it to different types of projects. It also remarks the importance of a well-done data structure that settles how to approach the project and settles the base for the construction of a 3D model and how to achieve as much accuracy as possible.

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5. CONCLUSIONS

The presented dissertation focuses on generating a quantity take-off and cost estimation process by the definition of a work breakdown structure. Through the implementation of a WBS, the project can be divided into a hierarchical breakdown system that facilitates defining the project into smaller and manageable components. This makes it easier to quantify and assign a cost to each individual elements. This is important because it ensures consistency in the QTO process by using a common framework to all the stakeholders by categorizing and organizing the project components.

Considering that generating a cost estimation for a project involves several stakeholders, it was decided to implement an open-based approach by introducing OpenBIM into the methodology. Using IFC as a standardized format for the presented methodology promotes interoperability between different software used by several stakeholders. Establishing this as an objective is crucial because encourages collaboration between all the actors involved in the project and ensures data integrity by following the IFC schema.

Another significant objective for this work was generating modelling rules for a quantity take-off process. Following a common set of rules when generating a 3D model ensures consistency through a structured framework that allows accurate and reliable quantities extraction. Its purpose aims that all the involved stakeholders could adopt the same baselines to generate a uniform and standardized 3D model.

The presented workflow main achievement corresponds to all the above-mentioned objectives by generating a quantity take-off and cost estimation process based on the Generador de Precios, a WBS provided by the involved company TOP Informatica. The entire procedure was fully generated using an IFC file as the main source of the information to generate the cost estimate for the project, which was done through an automated process using a coding system extracted from the Generador de Precios and modified for clearer cost assign. The process ensured an accurate quantity extraction by following the presented modelling rules; and using the Generador de Precios to have a complete cost estimation.

Complementing the final result of the dissertation, the presented work established a level of information need for a quantity take-off of an architectural design. Each of the presented architectural instances was studied through several test that helped determine the information, both geometrical and alphanumerical, necessary to generate a quantity take-off. This is an important outcome since provides a clearer understanding of the project’s purpose and the information required according to the stage of the project lifecycle: a construction phase for the architectural elements.

One valuable result of the project was the development of modelling rules. They were established by following the proposed WBS and their main function was to create a baseline to unify the modelling process among different actors. Along with the modelling guidelines for each architectural instance presented on this work, they ensure modelling consistency, real-world accuracy, and a simplified approach to avoid overloading information in the model.

An interesting material produced after establishing the 3D model, was the comparison of the IFC exporter between different authoring tools. This gives an idea of how each authoring tool manages the IFC export and what properties are going to be included. Through this study it was proved that Revit faces some limitations when extracting layered elements. As an example, in ArchiCAD the quantities of each layer that integrates a composed element are exported and found in the IFC file even though they belong to an ArchiCAD property set and do not follow the IFC schema. In Revit, the “parts” tool has to be used in order to get each layer’s exact quantities, not only in the IFC file but also in the traditional schedule of the software, which sometimes generate issues, that even though they are not incredibly relevant, they might need some time to fix.

Another significant aspect of the presented methodology was the verification of the IFC file that targets different types of data. Both geometrical and alphanumerical verification are dependent on each other. While geometrical verification ensures that the 3D model correctly represents the physical geometry of the components, the alphanumerical verification focuses on the correctness of the data associated with those components. This filtering process guarantees a good-quality IFC that allows an accurate and reliable cost estimate of the project.

Even though the verification process is a key step on the proposed methodology is necessary to mention that there are two main limitations regarding this procedure: the manual check process and the difficulty of IDS. Although checking the IFC model manually is a good method to approach this step, an automated check is usually better. Addressing this issue requires a complicated process that at this time not a lot of people are trying to solve or investigating this issue because of its complexity. On the other hand, the issue with IDS is mainly caused by its complexity to new users. In this case, the main reason resides on the lack of a visual demonstration of the elements that are reflecting the issue on the study, and it just displays through a text the possible errors found in the project.

As a final conclusion, it is important to note that even if the presented methodology may require several steps, it generates a more consistent, standardized, and simplified approach for a quantity take-off and cost estimation process. The process ensures consistency by using a WBS and by establishing modelling rules as a starting point for all actors. Also, it offers a more standardized approach due to the use of IFC and its schema definition and by generating a workflow that can be applied in different projects. Finally, the process turns out to be simpler since the model gives just the information that is requested for the project by establishing an adequate level of information need.

5.1. Future developments

Currently there are not too many studies that involve quantity take-off and cost estimation through an open-based approach and most of them are outdated by using a previous version of the IFC schema. It is presumed that this study will open the doors to other researchers to generate more studies involving more updated material and that it serves as a reference for more material generation.

Since buildingSMART is constantly evolving it opens the opportunity of integrating standards that are currently on development to this study. Some of the candidate standards that buildingSMART are developing at this moment approaches quantity take off (as an example: quantity take-off MVD) and it will represent a good opportunity to generate a study similar to the one presented in this work considering these new standards and compare both results to understand their impact.

The presented study generated a workflow based on an architecture approach for a quantity take-off and cost estimation process. Is more than known that to generate a project not only an architecture study is necessary, to complete a project other disciplines should be integrated as well. This study opens two different paths as future developments: first, generate a similar study for other disciplines and test how the workflow and modelling rules should be adapted for each of them; and second, generating a QTO and CE merging at least two disciplines following the presented workflow and test how IFC allows full interoperability between different actors, which wasn’t included in the scope of this study.

One of the main challenges faced during this study was using the Revit’s “parts” tool to extract the exact quantity of each layer that compose the compound elements. This generated some issues that even though they were not critical, they require time to fix. It opens the possibility of testing this study in other modelling software that may have a better approach to this issue, or even testing the presented methodology when the “parts” tool from Revit is more developed by the software.

This study established a level of information need for quantity take-off of an architectural design. This generates two possibilities to complement a quantity take-off process’ level of information need: first, generate the same information for other disciplines that integrates the AEC industry; and second, establish a level of information need for other stages of an architecture project stage.

There were two significant limitations during the verification process, the manual verification of the modelling rules and the complexity of IDS. When generating a verification of a project, a manual process doesn’t fully guarantee that the checkup was done properly. One possibility to approach this issue is to generate this study by using an automated process, that could allow the user to set rules per instances and verify them automatically, something similar to the process that the user has to do when generating a clash detection study.

Meanwhile, the IDS may be hard to understand, especially to new users, since it is a relatively new standard. Developing a graphic display that shows the issues on the model, similar to the one presented in the clash detection, is a good idea to help new users to understand what components on the project are displaying the errors.

The adoption of an open-based approach represents an important step to achieve full interoperability and accessibility through stakeholders, minimizing data silos and improving construction outcomes. During the study several processes were generated that looked for a more accountable and simple approach that can be explored in the future with the help of new improvements, standards, and tools. Finally, quantity take-off and cost estimation are broad topics that are open to new possibilities and further developments.

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LIST OF ACRONYMS AND ABBREVIATIONS

BIM	Building Information Modelling
QTO	Quantity Take-off
CE	Cost Estimation
WBS	Work Breakdown Structure
DT	Database
RICS	Royal Institution of Chartered Surveyors
MVD	Model View Definition
IFC	Industry Foundation Classes
IDS	Information Delivery Specification
BCF	BIM Collaboration Format
GP	Generador de Precios

APPENDICES

APPENDIX 1: WORK BREAKDOWN STRUCTURES

RIBA project Stages			RICS formal cost estimating and cost planning stages	RICS information stages (RICS Cost prediction PS)	OGC Gateways	
Plan of Work 2020		Digital Plan of Work (DPoW)				
0	Strategic Definition	Strategy	**Rough order of cost estimate**	**Level 1 Estimate**	1	Business Justification
1	Preparation and Briefing	Brief	**Order of cost estimate(s)** (option costs) **Elemental cost estimate**	**Level 2 Estimate**	2	Delivery Strategy
					3A	Design Brief and Concept Approval[1]
2	Concept Design	Definition	**Formal cost plan 1**	**Level 3 Estimate**		
3	Spatial Coordination		**Formal cost plan 2**[2]	**Level 4 Estimate**	3B	Detailed Design Approval[1]
4	Technical Design	Design	**Formal cost plan 3**[2]	**Level 5 Estimate**	3C	Investment Decision[1]
	Contractor Engagement	Contractor Engagement	**Pre-tender estimate**[3] **Pricing documents**[3] (for obtaining tender prices) **Post-tender estimate**[4]	**Level 5 Estimate(s)**		
5	Manufacturing and Construction	Build and Commission				
6	Handover	Handover and Closeout	**Formal cost plan 4**[5] (renew/maintain) (measured in accordance with NRM 3)	**Level 6 Estimate**	4	Readiness for Service
7	Use	Operation			5	Operations Review and Benefits Realisation
		End of Life				

Figure 77 – NRM relationship with RIBA stages

APPENDIX 2: INFORMATION CONTENT FOR QTO.

Table 40 – Information content for quantity take-off- Source: Self-generated.

Information content per object							
Property Set		**Objects**	**Type of layer**	**IFC Category**	**IFC Type**	**IFC QTO property**	**Unit**
Walls							
Qto_WallBaseQuantities		Wall	All included	IfcWall	Defined by user.	NetSideArea	m²
Floor							
Qto_SlabBaseQuantities	1	Floor finish	Finish layer	IfcSlab	Floor	NetArea	m²
	2	Slab	Core layer		Baseslab		
Roof							
Qto_RoofBaseQuantities		Roof	All included	IfcRoof	Defined by user	NetArea	m²
Window							
Qto_WindowBaseQuantities		Window	One element	IfcWindow	Window	Area / Unit	m² / Ud
Door							
Qto_DoorBaseQuantities		Door	One element or family.	IfcDoor	Door	None. Counted as single element.	Ud.
Ceiling							
Qto_CoveringBaseQuantities		Ceiling	Core layer	IfcCovering	Ceiling	NetArea	m²
Stairs							
Qto_SlabBaseQuantities	1	Landing Slab	Landing slab	IfcSlab	Landing*	Volume and thickness.	m²
Qto_StairFlightBaseQuantities	2	Stair	Stair flight	IfcStairsFlight	Straight*	Width and length.	m²
	3	Stairs Finish	Stair finish			None. Counted as single element.	Ud.
Qto_RailingBaseQuantities	4	Stairs railing	One element	IfcRailing	Handrail*	Length	m
Railing							
Qto_RailingBaseQuantities		Railing	One element	IfcRailing	Handrail	Length	m
Curtain Wall							
Qto_CurtainWallQuantities		Curtain Wall	Structure and panels	IfcCurtainWall	Userdefined	NetArea	m²

Important note: In the authoring tool the stairs type is defined by the typology of the stairs used in the project, this table represents the type of each element when divided at the IFC export.

APPENDIX 3: WBS CATEGORY FOR QTO PER ELEMENTS

Table 41- WBS attributes per architectural elements. Source: Self-generated

WBS Category and IFC properties per architectural element						
	Name	Layer	Unit	IFC Category	IFC suggested QTO property	WBS Category
			Walls			
1.	**Insulation and Finish**	Exterior layer	m²	IfcWall	NetSideArea	F - Fachadas
2.	**Main structure**	Core layer	m²			E - Estructuras
3.	**Interior finish**	Interior layer	m²			R - Revestimientos
			Floor			
1.	**Finish**	Finish layer	m²	IfcSlab	NetArea	RS - Pavimentos
2.	**Main Structure**	Core layer	m²			E - Estructuras
			Roof			
1.	**Insulation and Finish**	Exterior layer	m²	IfcRoof	NetArea	Q - Cubiertas
2.	**Main structure**	Core layer	m²			E - Estructuras
			Window			
1.	**Window frame**	One element or family.	m²	IfcWindow	Area	L - Carpinteria y Vidrios
2.	**Glass**	Nested element.	m²			LE - Vidrios
			Door			
1.	**Door**	One element or family.	Ud.	IfcDoor	None. Counted as single element.	L - Carpinteria y Vidrios
			Ceiling			
1.	**Main structure**	Core layer	m²	IfcCovering.Ceiling	NetArea	RT - Revestimientos
2.	**Interior finish** (if not included in the WBS)	Interior layer	m²	IfcCovering.Ceiling	NetArea	RI - Revestimientos
			Stairs			
1.	**Landing Slab**	Landing slab	m²	IfcSlab	Volume and thickness.	E - Estructuras
2.	**Stair**	Stair flight	m²	IfcStairsFlight	Width and length.	E - Estructuras
3.	**Stair's railing**	One element	m	IfcRailing	Length	FD - Defensas
4.	**Stairs Finish**	Stair finish	Ud.	IfcStairsFlight	None. Counted as single element.	RE - Escaleras
			Railing			
1.	**Railing**	One element	m	IfcRailing	Length	FD - Defensas
			Curtain Wall			
1.	**Curtain Wall**	Structure and panels	m²	IfcCurtainWall	NetArea	FM - Muros cortina

APPENDIX 4: IFC EXPORT OF QUANTITIES PROPERTIES

Table 42– IFC export of quantities properties - Slab. Source: Self-generated.

Object: Slab	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_SlabBaseQuantities		Whole	Single		Whole	Single		
Width		**						-
Length		**						-
Depth		**						-
Perimeter		**						-
GrossArea		**				*		-
NetArea		**				*		-
GrossVolume		**				*		-
NetVolume		**				*		-
GrossWeight	x	x	x	x	x	x	x	-
NetWeight	x	x	x	x	x	x	x	-
Material Layer	Whole	**	Per layer	Per layer	Whole	Per layer	Not included	-
Notes: * Not displayed as IFC schema. **Displayed as parts at all times.								

Table 43 – IFC export of quantities properties - Roof. Source: Self-generated.

Object: Roof	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_RoofBaseQuantities		Whole	Single		Whole	Parts		
GrossArea		**				*		-
NetArea		**				*		-
ProjectedArea		**						-
Material Layer	Whole	**	Per layer	Whole	Whole	Per layer	Not included	-
Notes: * Not displayed as IFC schema. **Displayed as parts at all times.								

Table 44 – IFC export of quantities properties - Door. Source: Self-generated.

Object: Door	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_DoorBaseQuantities		Whole	Single		Whole	Parts		
Width								-
Height								-
Area								-
Perimeter								-
Material Layer	Whole			Whole			Not included	-

Table 45 – IFC export of quantities properties - Windows. Source: Self-generated.

Object: Window	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_WindowBaseQuantities		Whole	Single		Whole	Parts		
Width								-
Height								-
Area								-
Perimeter								-
Material Layer	Whole			Whole			Not included	-

Table 46– IFC export of quantities properties – Curtain Wall. Source: Self-generated.

Object: Curtain Wall	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_CurtainWallQuantities		Whole	Single		Whole	Parts		
Length			*					-
Width			*					-
Height			*					-
GrossArea			*					-
NetArea			*					-
Material Layer	Whole	Not included	Per layer	Whole	Whole		Not included	-

Notes: *Per element (mullion and glass panel).

Table 47 – IFC export of quantities properties - Ceiling. Source: Self-generated.

Object: Ceiling	Revit			Archicad			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_CoveringBaseQuantities		Whole	Single		Whole	Parts		
GrossArea		**				*		-
NetArea						*		-
Width		**				*		-
Material Layer	Whole	**		Whole	Whole	Per layer	Not included	-

Notes: * Not displayed as IFC schema. **Displayed as parts at all times.

Table 48 – IFC export of quantities properties - Stairs. Source: Self-generated.

Object: Stairs	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_StairFlightBaseQuantities		Whole	Single		Whole	Parts		
Length	***							-
GrossVolume	***			*		*		-
NetVolume	***			*		*		-
Material Layer	Per element	Per element		Per element	Per element	Per element	General	

Notes: * Not displayed as IFC schema. **Displayed as parts at all times. ***Divided into stair flight and landing, properties displayed on this table represent the Stair Flight properties. X= Parts not available for the element.

Table 49 – IFC export of quantities properties - Railing. Source: Self-generated.

Object: Railing	Revit			ArchiCAD			CYPE Architecture	
	No Parts	Parts		No Parts	Parts		No Parts	Parts
Qto_RailingBaseQuantities		Whole	Single		Whole	Parts		
Length						**		-
Material Layer	Per element	Per element		Per element	Whole	Per element	General	

Notes: * Not displayed as IFC schema. **Displayed as parts at all times. ***Top rail exported as railing, but balusters are turned into IFCMember category.

APPENDIX 5: CASE STUDY WBS

Table 50 – WBS for the Lagoa House. Source: Self-generated.

WBS Case Study				
Code	**Suffix**	**Item**	**Layer**	**Unit**
		Wall		
		Exterior		
FSM010	_01_01	Sistema ETICS de aislamiento térmico por el exterior de fachadas	Exterior layer	m2
FFZ020	_01_01	Hoja exterior de fachada de dos hojas, de fábrica de bloque de hormigón para revestir	Core layer	m2
RPR011	_01_01	Revoco liso sobre paramento interior	Finish layer	m2
RIP025	_01_01	Pintura plástica sobre paramento interior de mortero de cemento		m2
		Interior		
RAG140	_02_01	Revestimiento interior con piezas de gran formato de azulejo gris. En capa fina.		m2
RDM010	_01_01	Revestimiento mural con tablero de madera	Finish layer	m2
RIP035	_01_01	Pintura plástica sobre paramento interior de yeso proyectado o placas de yeso laminado		m2
RAG140	_01_01	Revestimiento interior con piezas de gran formato de azulejo blanco. Colocación en capa fina		m2
FBY010	_01_02	Tabique de placas de yeso laminado hidrofugado	Core layer	m2
FBY010	_01_01	Tabique de placas de yeso laminado		m2
		Parapet		
FFI030	_01_01	Medianera de una hoja, de fábrica de bloque cerámico para revestir	Core layer	m2
NAF020	_01_01	Aislamiento térmico por el interior de la hoja exterior, en fachada de doble hoja de fábrica para revestir.	Finish layer	m2
ISC010	_01_01	Canalón visto de piezas preformadas	Gutter	m
		Curtain Wall		
FMC010	_01_01	Muro cortina de aluminio	-	m2
		Floor		
		Interior		
RSM050	_01_01	Rodapié de madera	Skirting	m
RSF013	_01_01	Felpudo textil		m2
RSG110	_01_01	Pavimento interior de piezas de gres esmaltado. Colocación en capa fina		m2
RSP010	_01_01	Solado de piedra natural sobre una superficie plana, con adhesivo.	Finish layer	m2
RSM040	_01_01	Parquet multicapa		m2
RSA040	_01_01	Capa fina de mortero autonivelante de cemento, "WEBER"		m2
RSB010	_01_01	Base de mortero de cemento		m2
NAK010	_01_01	Aislamiento horizontal de soleras en contacto con el terreno, con poliestireno extruido	Core layer	m2
		Exterior		
UXH010	_01_01	Solado de baldosas de hormigón	Core layer	m2
RSM022	_01_01	Tarima de madera para exterior	Finish layer	m2
		Roof		
QUZ010	_01_01	Cobertura de bandejas de zinc	Finish	m2

QTT210	_01_01	Cubierta inclinada de tejas		m2
EML025	_01_01	Forjado de cubierta de entramado ligero de madera		m2
QUP010	_01_01	Cobertura de placas de policarbonato		m2
NAN110	_01_01	Aislamiento térmico por el interior de cubiertas inclinadas de estructura de madera, sobre espacio habitable	Core layer	m2
EHL010	_01_01	Losa maciza		m2
		Ceiling		
RIP035	_01_02	Pintura plástica sobre paramento interior de yeso proyectado o placas de yeso laminado	Finish layer	m2
RTC015	_01_01	Falso techo continuo de placas de yeso laminado	Core layer	m2
		Doors		
		Exterior		
LCL060	_01_01	Carpintería exterior de aluminio	-	Ud
LEM010	_01_01	Puerta interior de entrada a vivienda, de madera	-	Ud
		Hinged		
LPM010	_01_01	Puerta interior abatible, de madera (tablero macizo)	-	Ud
LPM010	_02_01	Puerta interior abatible, de madera (tablero MDF)	-	Ud
LCL060	_01_02	Carpintería exterior de aluminio (Puerta ingreso a vivienda).	-	Ud
LPM010	_03_01	Puerta interior abatible, de madera (tablero aglomerado)	-	Ud
		Pocket		
LPM021	_01_01	Puerta interior corredera, de madera (tablero aglomerado)	-	Ud
LPM021	_02_01	Puerta interior corredera, de madera (dos hojas).	-	Ud
LPM021	_03_01	Puerta interior corredera, de madera (tablero macizo)	-	Ud
		Sliding		
LCY010	_01_01	Carpintería exterior de aluminio "CORTIZO"	-	Ud
		Foldable/Exterior		
LCL060	_02_01	Carpintería exterior de aluminio (tres hojas plegables)	-	Ud
LCL060	_03_01	Carpintería exterior de aluminio (dos hojas abatibles, 2000x2100)	-	Ud
LCL060	_03_02	Carpintería exterior de aluminio (dos hojas abatibles, 1800x2100)	-	Ud
		Gate		
LGL040	_01_01	Puerta enrollable para garaje, de aluminio	-	Ud
		Windows		
LCL060	_04_01	Carpintería exterior de aluminio	Frame	Ud
LVC010	_01_01	Doble acristalamiento estándar	Glass	m2