The project of structures supported on BIM methodology: structural analysis and reinforcement detailing

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Abstract

Building Information Modelling (BIM) is a methodology under development worldwide. BIM is based on the creation of a digital model that contains all the information needed to develop a project, with different specialties working more collaboratively, reducing errors and conflicts, and resulting in reduced costs at different stages of a building's life cycle.

In this work, a structural model was created using the BIM tool (Revit) and transferred to an analytical calculation software (Robot), to perform structural validation and study the occurrence of errors in the interoperability of the software. The study also aimed to detect advantages and disadvantages of applying this methodology directed to structural design and elaborate different solutions or strategies to minimize the existing limitations. Extraction of information, such as material quantity maps, and detail sketches concerning the structural design of real cases were also elaborated.

The study demonstrated that, despite the limitations identified throughout the process, mainly related to interoperability problems, the methodology had clear advantages developing structural designs. As a worldwide evolving methodology, the procedure is believed to lead to considerable improvements in the construction sector.

Keywords: *Building Information Modelling* (BIM), structural design, BIM tools, interoperability, drawings, quantity surveying

Introduction

The Construction sector involves the coordination of multiple specialties to which speed, communication accuracy, and correction of transposed data are required. In order to avoid errors and delays, which lead to an increase in the cost the effectiveness of the process of information exchange is fundamental in an interdisciplinary project. In a construction project, the different specialities usually use a work platform that speeds up the correct transfer of data between stages without omission, repetition or incorrect interpretation of data.

The *Building Information Modelling* (BIM) methodology is a concept that consists of generating a single digital model that aims to contain all organized and easy-to-easily information of the various specialties. The BIM model must monitor all phases of a construction, from design to demolition. The implementation of BIM in companies contributes to an integration of the entire process, minimizing errors, delays and promotes better communication between different stakeholders.

The work aims to explore the use of this methodology in the design of structures. Thus, from a case of the actual study, a BIM model is generated, following the export to the calculation software, in which errors or omissions of transferred information are verified. A structural check is performed, by which exemplifying members are selected for the study of automatic generation of reinforcements and their analytical validation, supported by the Portuguese standard (Eurocodes). As a final phase, it is intended that the model, after a structural validation, represented in the BIM-based software, and then to extract information from the software. It is important to produce more automated and detailed drawn parts and take-off tables than the ones produced by the traditional methodology of structure design. It is also important, when detecting errors or difficulties, finding solutions for the application of alternative strategies.

1. State of art

1.1. BIM Concept

The *Building Information Modelling* (BIM) methodology is based on a three-dimensional

representation (3D) of the construction. The model is created and updated according to the various steps elaborated, throughout the development of a project. The level of detail of the information incorporated into the model is considered by the designer in the elaboration of his specialty. The models are composed of representative parametric objects, such as walls, columns, windows, ventilation systems to which all types of information are associated. The type of information is usually physical, energetic or cost.

The most basic use recognised to BIM model is its realistic visualization component. An important aspect of BIM is its ability to generate technical drawings, obtained automatically from the centralized model of all updated information. The designer can consult the model information, but also get any plan, section or perspective quickly and correctly. The available model and tools check for potential flaws or overlapping errors, allowing for correct models and therefore consistent designs[1]. As data is archived in the model in an organized, compartmentalized manner, and any modification imposed on the building is updated in the model, the drawings (plans and sections), quantity maps, costs, and tables are automatically updated. Drawings and tables thus have a dynamic character, being updated after any changes made to the BIM model. Documentation updates are fast and deliver assured quality, supporting the coordination of different steps. Throughout the building's conception, its construction and use, the BIM model is being incremented with information created by the different actors.

1.2. Maturity levels

The BIM level concept is currently associated with its maturity according to the level of implementation in the sector and the degree of integration into a collaborative project. There are currently three maturity levels associated with different levels of detail, the higher it is the level, the more complex and detailed the model will be. Achieving the most advanced levels of maturity requires a greater investment in training as well as software acquisition, resulting in significant investment costs at an early stage. However, experience has shown that costs are met in the medium term due to increased productivity related by the application of the methodology [2].

The implementation of BIM in companies is translated in terms of maturity [3], [4].

Maturity is classified into three different levels illustrated in Figure 1:
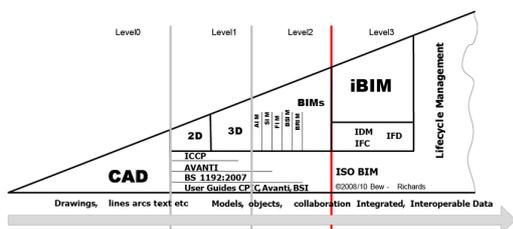

Figure 1 - BIM Maturity Levels [5]

1.3. nDimensions

Tasks that are operated on model information, such as construction planning or budgeting, are assigned multiple dimensions, nD/BIM. The nDimensions refer to the different type of application that is elaborated on the 3D model.

3D Dimension – It is associated with the creation of the geometry component of different specialties, such as architecture, structures and services. The BIM model is unique and is based on the parametric modelling process. The model allows access to the data by various stakeholders, allowing the extraction of all the required information in the different design and construction phases [6].

4D Dimension – it is associated with the time component and is related to the construction process. By associating the constructive tasks, defined by time periods, and 3D model components, a 4D model simulates the process constructed as a function of the time variable [7].

5D Dimension - It is associated with the project cost estimate in different project phases. This dimension is used for the creation and control of the budgets, and the activities related to cost analysis. Allows project participants to view the progress of their activities and related costs over time [8].

6D Dimension - It is associated with the sustainability and environmental component. Parametric objects contain physical and behaviour properties that can be used in energy, acoustic, and environmental impact analysis software [9][10].

7D Dimension - It is associated with project management during its life cycle. Maintenance-related information, such as preventive inspection deadlines or inspection reports, can be added to the model. Embedded information is used by managers and service technicians throughout their life cycle [8].

8D Dimension - It is associated with the safety of construction workers, considers aspects related to safety in construction, supporting a preventive action in the detection of risks in the construction process [11].

1.4. Benefits and challenges

In the design of the different nD/BIM models a high level of added information and more complex content is required. Thus, there may be a broad spectrum of potential BIM users in the construction project involving the full applicability of BIM. Architects apply BIM to the workaround modelling process by producing up-to-date graphical documents with no inconsistency errors and quantity tables. As the technician develops his speciality, he creates the corresponding component of the BIM model and consistently obtains the drawings and tables for his participation. The contractor can use the models created to obtain cost estimates and to analyse construction planning.

To respond to different users, the BIM model features an internal, organized and easily accessible structure, allowing data flow between design phases, supporting collaborative design. BIM's collaborative capability is one of its greatest benefits [12].

1.5.   IFC format and Open BIM

The Industry Foundation Classes (IFC) standard is a specification for an open and neutral data exchange from the software manufacturer. It is a data file format developed for the construction industry and is commonly used in the BIM project to establish interoperability between software platforms. The standard includes definitions that cover the data required for buildings throughout their life cycle [13]. The IFC format was originally developed in 1995 by a group of US and European construction industry companies and software providers through the International Alliance for Interoperability (IAI). Since 2005 it has been maintained through BuldingSmart International [14].

The IFC standard is typically used to exchange information between project steps, using different software. BIM toolboxes provide interfaces that enable IFC format data to be exported, imported and transferred [15].

Currently, the IFC standard is not yet fully effective in direct data exchange. It does not allow, for example, to model in one software, convert to IFC, and continuously modelling in different software, with IFC-based export and import supported. IFC is a mode of archiving content from the template.

Collaboration, based on IFC models, requires the creation of a base model that is shared with different specialties. Participants are inhibited from modifying elements that do not belong to their field of expertise. It is important, however, that in using the IFC model, each discipline remains the author and owner of the content of its component or contribution.

The present study addresses the direct transfer between software from the same provider, Revit and Robot (Autodesk), and a quite satisfactory transfer is verified albeit with some limitations (Chapter 4).

However, the transfer of the Revit model to the calculation software, Robot, is performed based on the native Revit format. The transmitted data is internal. In the market there are several additional applications developed by software manufacturers that appear as an alternative to data transfer, by the IFC format. Transfers between software from the same manufacturer are more efficient because no native language conversion to the IFC standard is required. Several products support BIM on the market, but some do not have the ability to read or save files in IFC format.

1.6.   BIM in structural design

Currently, structural design can already be elaborated using BIM support software, like in the structural modelling and structural designing process. No doubt creating a 3D model is much more efficient than 2D representations. As 2D representation is still required today, the model is merely a more effective mean of producing these drawings, which are shared with other specialties. By the necessary creation of a 3D model for dynamic structure calculation, begins to lose sense the elaboration of two independent documents, one for drawing and one for structural calculation.

The implementation of the BIM model in the design of structures is not easily accepted. The design and calculation software themselves, while supporting BIM formats, require users to gain knowledge of the effective interoperability between different software. In the present study, the Revit and Robot tools are mainly used, and as support, SAP2000, AutoCAD and Excel.

2.   Case of study

The case study selected for the development of the structure project in a BIM environment is a single-family house (category A), located in Tavira, Faro. The owner provided the graphic documentation for the architectural and structural design. The drawn and written parts of the structural design are the basis for the generation of the BIM model through Revit software.

The written project documentation includes the data of the calculation method, the established solution and the design performed. The drawings consist of foundation and floor plans and detailed drawings of reinforcement. The drawings provide the information necessary for the correct model generation. The architecture model used in BIM was provided [9]

Figure 2 - Architecture model [9]

2.1.   Structural solution

Based on the established structural solution plans, the BIM model structures component was generated. The structure modelled in 3D has 4 levels: (i)Foundations (Fundações), (ii) Floor 0 (Piso 0), (iii) Floor 1 (Piso 1), (iv) and Roofing (Cobertura). The considered solution is in reinforced concrete consisting of columns, walls, beams and slabs.

The calculations follow the Portuguese standard (Eurocode): EC0 [16], EC1 [17], EC2 [18], EC7 [19], EC8 [20].

• Slabs have beam solutions with higher height beams on the periphery. The thickness adopted in the consulted project is 0.16 m in all slabs.

• Surrounding the garage area, support walls were laid on and some columns inside that went to higher levels.

• Resistant columns and walls are the vertical resistant elements, which also play a fundamental role in seismic resistance.

• Direct running foundations were placed under the peripheral support walls. In the central areas, under columns, isolated foundations are defined. All foundation elements are locked between them by foundation beams.

• For the foundations' design a soil tension of 200 kN/m^2 was considered.

The loads and load combinations were applied according to the Portuguese standards.

3. Modelling

Based on the previously provided structural design drawings in .dwg format (AutoCAD), the corresponding BIM model was created using the Revit tool. In this case, the software allowed to import the .dwg format and work on it, thus creating the .rvt (Revit) format. The reinforcement detailing drawing, with the different ways to proceed to the design, the validation and the modelling part, are discussed in chapter 6.

The modelling phase requires attention, given that the modelling of the geometric (real) and calculus (analytical) structure must be combined. The geometric model for the use of parametric objects is obtained and the analytical model is automatically associated with the information contained in the family of structural parametric objects used. In this sense, sometimes it is necessary to make some corrections in the analytical model, without compromising the geometric one. Other changes or adjustments to the analytical model may be made after transposition into the calculation software. Incompatibility errors that arise during data transfer between software are interoperability limitations.

3.1. Geometrical and analytical modelling

When a geometric element belonging to a structural family is created, it has analytical information incorporated. Depending on the geometric impositions attributed to the element, the analytical information must adapt to it.

With the unions and intersections of the various structural elements, it is possible to observe the adaptation of both geometric and analytical models (**Figure** 3).
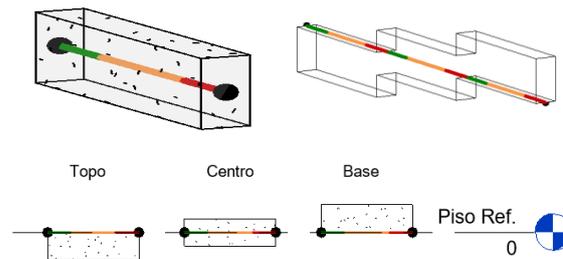

Figure 3 - Analytical adjustment

An important option, in parallel verification of the analytical and geometric model, is to verify that the nodes are correctly connected between the different structural elements. There are display filters options of disconnected nodes. In the creation of geometric elements, their limits may not coincide with the analytical limits causing an analytical disconnection (Figure 5), inciting errors of disconnected structural elements in the calculation software.
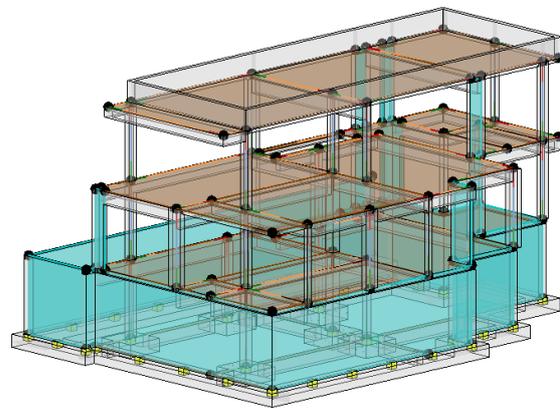

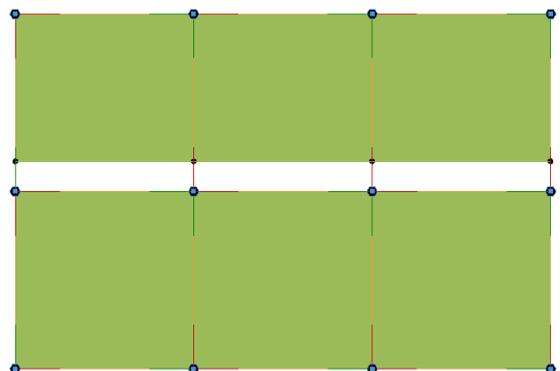Figure 4 - Geometrical and analytical model view

Figure 5 - Analytical inconsistency

At this stage, attention must be paid to the analytical adjustment. Geometrically modelling the slab boundary to the side face of the beams may cause an error where the analytical boundary of the panel is not coincident with the corresponding beam member. Panel boundaries sometimes do not match with the analytical centre of the bars, thus creating an analytical disconnect. Therefore, it is necessary to model geometrically the slab ending at the lateral limit

of the beam and to analytically adjust (Figure 6) the panel nodes to the centre of the beam.
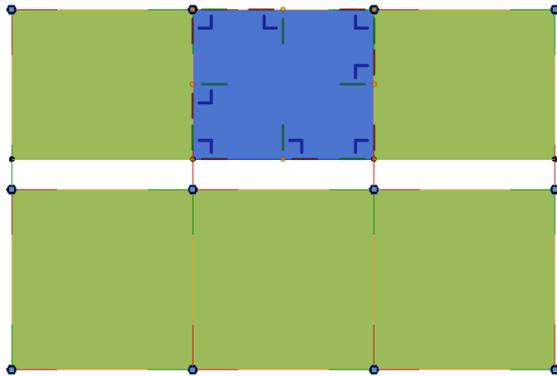

Figure 6 - Analytical adjustment

With the analytical adjustment option, you can change the analytical model without compromising the geometry (Figure 7). This option may be beneficial for minimal adjustments but can sometimes be detrimental in the event of distraction. The analytical model can be completely compromised if the analytical adjustment is not made with the utmost attention to the changes created.
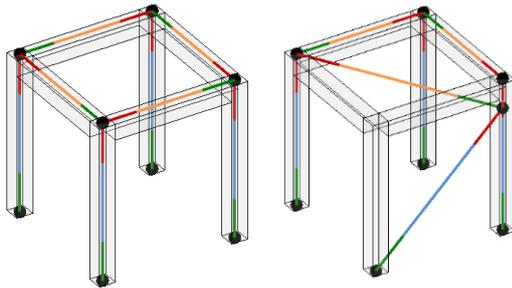
Figure 7 - Independence between models

3.2. Loads and inconsistency verification

It's possible to define the different types of structural actions (dead or alive) and different combinations directly in Revit. Note that the creation of simple load cases and simple combinations are easily inserted and consistent in both Revit and Robot.

However, for seismic analysis, it is only possible to add the correct and detailed action in Robot, defining all data of the respective national annex, such as spectrum and appropriate combinations.

Less complex load and combination information are found to be correctly imported into structural analytical calculation software. However, it is easier to create only loads in the BIM model (Figure 8), and later create all combinations directly in Robot.
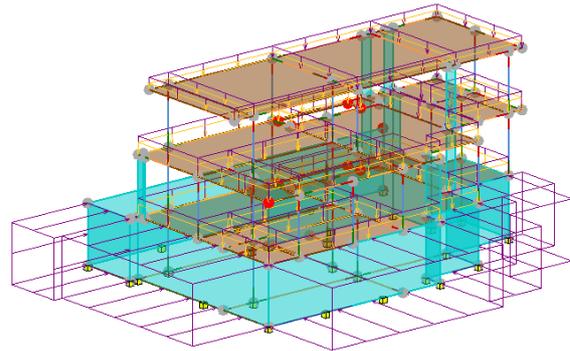

Figure 8 - Analytical loads

4. Software interoperability

In this chapter the errors that arise in both software during data transfer, both Revit - Robot and Robot - Revit, are advanced.

It is possible to keep both software with both files open, and from these make successive updates between the models. However, there is also an independence of create a new file of the identic format, from either of these files individually.

By completing the transfer or update of the model between software, it is needed to check which settings or parameters have not been translated correctly. Upon completion of the transfer between any software, a report box shows up containing warnings and errors. However, some errors are noted in the transfer report box and others are not.

4.1. Inconsistency in Robot

Once transferred to Robot, the report does not indicate the presence of any errors. However, errors have been detected and fixed.

An incongruity in the material was identified. The material presented the same name, but the parametric data did not match those entered in Revit. As Robot has the concrete material in its database with the correct properties, all existing elements were selected, and their material changed to the correct concrete C30/37.

In the verification of the loads, some discrepancies were verified. Even if the values and nomenclature of the load cases were correct, the combinations did not meet the correct safety factors, nor were they correctly associated with the Ultimate Limit State and Service Limit State. The handling, creation or editing of loads in Robot is simple, not imposing an efficiency problem in its correction.

4.2. Inconsistency in Revit

A worse scenario was found when transposing information from Robot to Revit regarding the rebars. Not only were many rebars misaligned, but sometimes they resulted completely outside the host element (Figure 9), invalidating the export.

The behaviour that leads to the reinforcement transition error was detected. In a more logical way and in order to spend less time, Robot allows selecting multiple spans of a beam to calculate and validate its reinforcement. When a rebar set is generated from a multiple selection of beams or columns, it produces the wrong position of rebars when transferred to Revit.
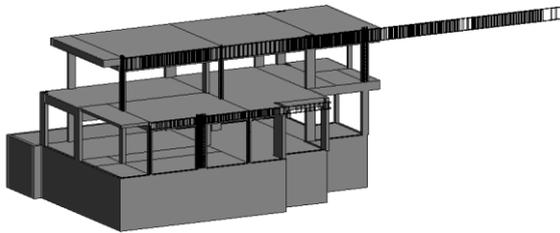

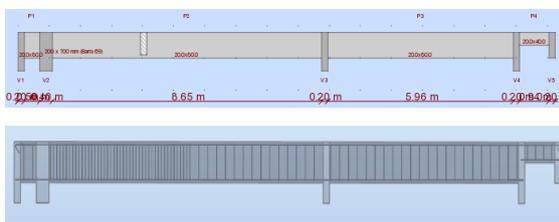**Figure 9 - Rebars completely outside of its host**

Figure 10 - Multiple beam spans selected in Robot

On the other hand, when the element is individually selected and a reinforcement is generated, it will be transferred without problems, not being the most appropriate form of designing. Another solution is to model the beam as a single object instead of being modelled by spans, since this structural analysis is accepted by Robot.

5. Structural analysis

With the previous creation of the model, a greater automation of the software is present in this chapter. However, the user will always have to be careful, with a strong critical spirit, when validating the data provided by the software. Any change, whether in section, material properties or element eccentricity, alters the stress distribution and therefore the overall structure analysis.

A higher evaluation has to be done in the reinforcement, compared with its automatic generation, since the software tries to optimize the design in such a way that sometimes becomes incompatible in terms of execution, increasing the cost of construction (Figure 11). The necessary and suggested reinforcement is verified and therefore adjusted to simplify the design and execution itself.

The entire structure has been validated with the help of advanced analysis tools present in Robot. Making it possible to check bending moments (Figure 12) and deformations (Figure 13).
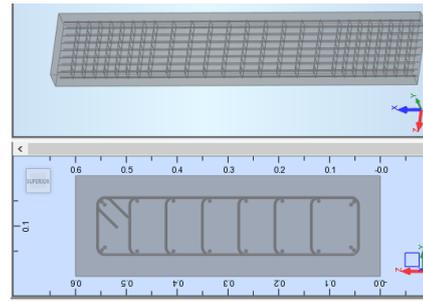

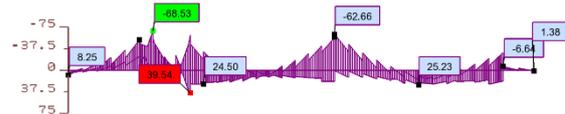**Figure 11 - Automatic reinforcement creation**

Figure 12 - My Bending moment in ULS

Figure 13 - Deformation in SLS

5.1. Reinforcement design

The software allows various forms of reinforcement design procedures. It has a form of automatic generation according to the selected regional standard (in this case the Robot has EC2 - Portuguese Standard). In this way, parameters limiting the optimization can be defined, and, if well calibrated, good results can be obtained extremely quickly and effectively. This tool, in the logistics of a software-experienced designer as well as in the structural design conception itself, can be very productive.

By way of example, this study aims to explore the reinforcement design capabilities of exemplary elements (Figure 14)

In the rebar design process, the various stresses involved were evaluated (Figure 15). However, the beam is oversized due to seismic regulatory requirements. Such warnings appear as soon as the element is checked according to the Standard, indicating exactly which chapter and sub-chapter do not follow (Figure 16).
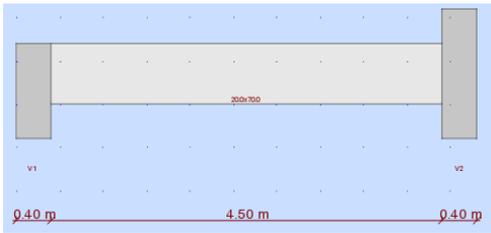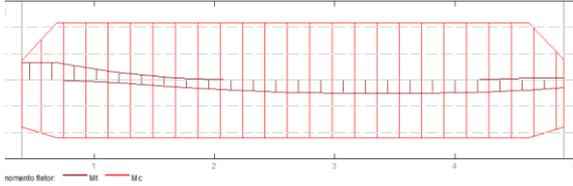
Figure 14 - Selected beam span for reinforcement

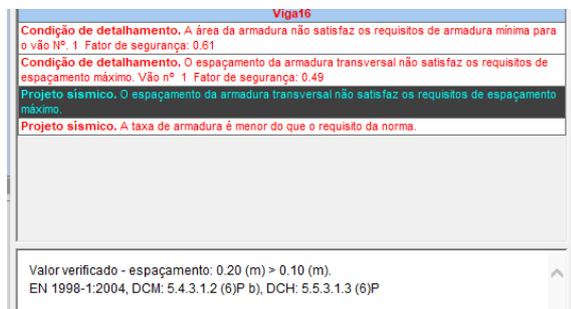**Figure 15 - Actual bending moment and resistant bending moment diagram**

Figure 16 - Warning unsatisfied conditions dialog box

6. Extracting Information

This chapter discusses a feature which, with the proper training and customization of the software by the user, can be extremely cost-effective in terms of designing structures.

The generation of drawings and details in a BIM tool is more efficient than in traditional design, which is mostly composed of 2D drawings without an association between them.

Tables containing various information can be created, showing quantities of structural elements grouped by type, volumes, and analytical loads. These tables update automatically if there is any change or addition of a new element.

Thus, also in the budgeting phase there is an increased ease of material take off. The exact amount in kilograms, or even meters of structural rebars can be detailed in this phase. Getting in more advanced phases prices (5D) labour maps, and runtime schedules (4D) can be added.

From Robot, a structural analysis is performed from several inserted actions to obtain diagrams, resistances, and reinforcement areas among others. Some examples of diagrams were demonstrated in Chapter 5, using the BIM methodology. It is pretended to centralize information into a single database, and

Revit provides a tool to help store strategic analysis graphical information.

The Revit Toolkit tool can be installed as an extension. This extension allows the reading of diagrams of the structural analysis performed in Robot (Figure 17). The extension enhances model information, becoming an useful tool for centralizing analytical information.

The tool is, however, still somewhat limited, allowing to see graphically the information quite roughly as intended. Regarding seismic action or modal analysis, the extension has only load nomenclature information and combinations, without showing the results. A textual information of the load is displayed, but no other information is associated.
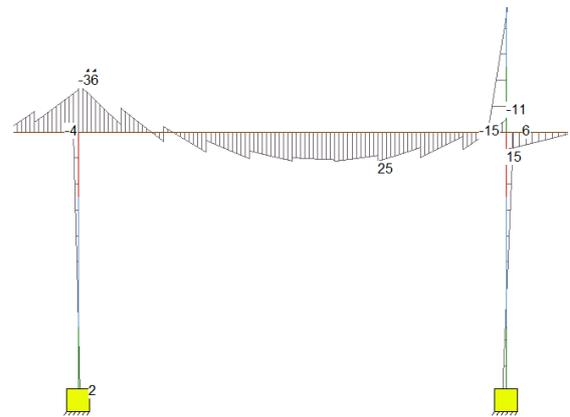

Figure 17 - Bending diagram in Revit

It's possible to use Robot-generated drawings automatically (Figure 18) and attach to Revit. This requires converting the file to .dxf, later to .dwg. Thus, a detailed drawing file can be attached in Revit, automatically generated in Robot with the possibility of editing the generated file using AutoCAD.
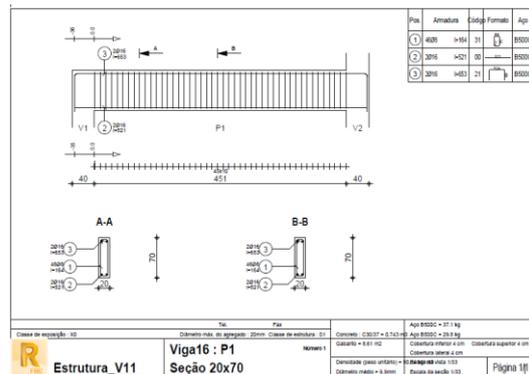

Figure 18 - Automated generated drawing in Robot

In Revit, all objects belong to a family, and sometimes, simple adjustments of lines or text dimensions demonstrate a high complexity in their editing. Families have fixed properties and editing properties. To change the fixed properties of a family, it's needed to change it individually.

A difficulty in the present study was the editing of automatic text boxes for element identifiers such as beams, columns, and especially reinforcement tags. The software has different styles of reinforcement identification (Figure 19), to which none of the ones found was the most suitable for the nomenclature to be adopted.
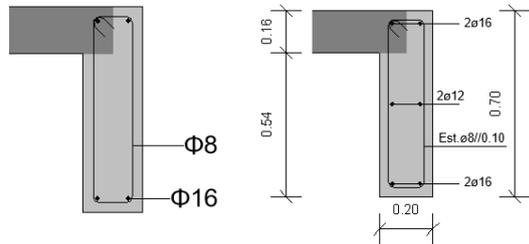

Figure 19 - Rebar detailing

It was possible to create an identification label with correct nomenclature when the reinforcement is grouped by specific spacing. Given the degree of detail that can be done manually, there are some limitations to automatic identification. This tool limits the location of the indicator line as shown in Figure 20.
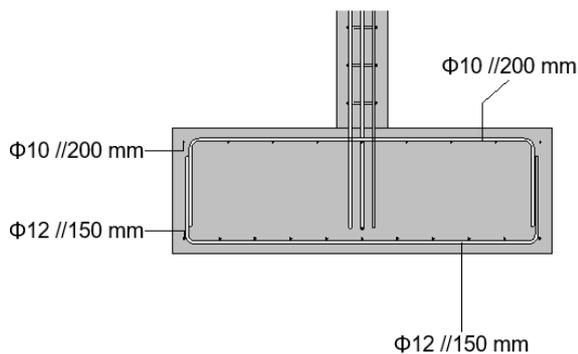

Figure 20 - Improved automatic rebar detailing

It is easy to associate prices by elements in structure designer logistics and in the cost estimate phase of the structure. In these cases, the quantities of the structural elements can be accounted for the materials being based primarily on concrete and reinforcement steel. It was possible to organize all the elements in tables by type and section, and to extract information from their volumes, reinforcement volumes, and their weight (Table 1). Separately, it was possible to obtain a summary table with the quantities of reinforcement organized by diameters (Table 2). Tables can be customized and printed directly from Revit Layout.

Table 1 - Quantity take off

Tipo	Volume Elemento (m³)	Volume armadura (cm³)	Peso Aço (kg)
MS_0.20	34.48	391 841.14	3 075.95
P_0.20	8.23	167 146.46	1 312.10
P20x20	0.81	11 171.50	87.70
P20x40	2.09	21 969.15	172.46

P20x60	2.44	23 238.37	182.42
P30x35	0.3	2 909.11	22.84
P35x40	0.8	5 695.71	44.71
V20x40	0.52	6 243.26	49.01
V20x50	4.8	55 565.42	436.19
V20x70	2.07	28 687.89	225.20
V20x80	9.23	95 922.50	752.99
V30x60	3.84	27 096.67	212.71
VF30x50	2.13	18 487.20	145.12
L16	62.13	811 976.60	6 374.02
S1.5x1.5x0.5	6.75	30 611.68	240.30
SC	70.24	3 253 523.71	25 540.16
Total	**188.27**	**4 720 083.43**	**37 052.65**

Table 2 - Detailed rebar quantity take off

Diâmetro	Volume Elemento (cm3)	Peso (kg)	Comprimento (m)
Ø12	2 977 495.46	23 373.34	4 651
Ø10	1 653 830.19	12 982.57	13 407
Ø8	88 757.78	696.75	1 766
Total	4 720 083.43	37 052.65	19 824.27

Alternatively, by creating partitions in the reinforcement, it was possible to generate automatic tables with the bending formats of the bars (Figure 21) and detailed quantities by elements. Thanks to the creation of partitions, it was also possible to apply visual filters (Figure 22) to perform a more detailed revision of the reinforcement design. In addition, partitions information can be used in construction planning, organized by floors or elements.

Formato dobra	A	B	C	D
	340 mm	140 mm	100 mm	100 mm
	2970 mm	0 mm	0 mm	0 mm
	350 mm	1360 mm	350 mm	0 mm
	350 mm	1390 mm	350 mm	0 mm
	350 mm	1390 mm	350 mm	0 mm
	350 mm	1420 mm	350 mm	0 mm

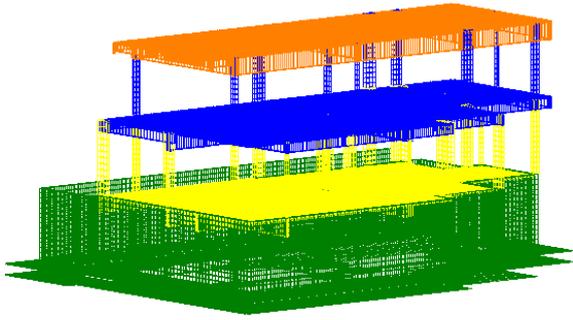**Figure 21 - Rebar bending formats**

Figure 22 - Partition visual filter by floors

7. Conclusions

The study intends to demonstrate that the BIM methodology is valid, and its use brings advantages, even for the design of structures. The objective proposed for the thesis was to analyse the applicability of the methodology in a structural design, based on the development in three phases:

• Creation of structural model in BIM tool.

• Model analysis in structural calculation tool.

• Extraction of information that can be obtained in both software, such as drawings and take off maps.

Therefore, several benefits were detected, which are essentially presented by:

• The capability of parallel modelling of the geometric model (for production of drawings) and analytical model (for structural calculation), avoiding the execution of this task twice.

• Favourable software transfer with simple resolution limitations. Advantage in crossing different specialties and checking interference between them, avoiding overlapping elements of different specialties.

• Easy to create geometric details of sections.

•Production of automatic take off maps with customization of these in various ways directly in the software.

• Possibility of extracting tables for spreadsheet format and later organization and improved presentation.

• By enriching the family library, it's possible to take advantage of these for greater productivity by avoiding repetition of creating common elements across projects.

Although few, some limitations were found, some more severe than others:

• BIM-based software will always require advanced work-based training to benefit from these tools.

• Models transfer still finds some flaws, losing some information associated with it.

• Given the complexity of software working on families, new families must be edited or created for any added information. Thus, simple details such as letter dimensions become complex to edit.

• The software has an automatic subtitle tool, but such a tool contains a lot of customizable information. In the present study, the terminology was greatly improved, but even so, an insufficient nomenclature is presented.

8. References

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