

Article

# BIM in Structural Project: Interoperability Analyses and Data Management

Augusto M. Gomes <sup>1,2</sup>, Gonçalo Azevedo <sup>1</sup>, Alcínia Zita Sampaio <sup>1,2,\*</sup>  and Alberto Sánchez Lite <sup>3</sup> <sup>1</sup> Department of Civil Engineering, Higher Technical Institute, University of Lisbon, 1649-004 Lisbon, Portugal<sup>2</sup> CERIS—Civil Engineering Research and Innovation for Sustainability, IST, 1649-004 Lisbon, Portugal<sup>3</sup> Department of Mechanical Engineering, School of Industrial Engineering, Universidad de Valladolid, 47011 Valladolid, Spain

\* Correspondence: zita.sampaio@tecnico.ulisboa.pt

**Abstract:** Building Information Modelling (BIM) is a methodology supported on technological evolution achievements, and consists of a set of processes and tools that allows the creation of a digital three-dimensional model. The model centralizes information, in an organized database, facilitating the data access and the exchange between the collaborators and enterprises along all life cycle of a building. The study is focused on the application of BIM within the framework of a structural design, identifying the benefits and limitations verified in the process and indicating strategies allowing to improve the quality of the project and construction. A structural BIM model of a study case was created; using BIM based platforms, followed by its transfer to the calculation software, where the structural analysis and design were carried out. After, using the structural BIM model complemented with the reinforcements, several applications and tasks were performed, namely, the coordination and collaboration procedures, detection of conflicts analyses, production of dynamic drawings, budget estimation and environmental impact simulation of the structural framework concerning the CO<sub>2</sub> emission. In the structural domain, the interoperability is the main problem that must be understood and the present study contributes to clarify the recurrent limitations. The research also presents the capacity of BIM methodology of using the database of the BIM model to achieve several types of tasks that normally are associated to the structural design. The study demonstrates the significant improvement in the quality of the structural design and the wide applicability of the BIM model, when compared with the current traditional sequential and fragmented process.

**Keywords:** Building Information Modelling (BIM); implementation; interoperability; structural design; reinforced concrete; BIM dimensions



**Citation:** Gomes, A.M.; Azevedo, G.; Sampaio, A.Z.; Lite, A.S. BIM in Structural Project: Interoperability Analyses and Data Management. *Appl. Sci.* **2022**, *12*, 8814. <https://doi.org/10.3390/app12178814>

Academic Editors: Haijiang Li and Guoqian Ren

Received: 11 August 2022

Accepted: 31 August 2022

Published: 1 September 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

One of the main objectives of the architecture, engineering and construction (AEC) industry is the constant need to produce more efficient workflows, contributing to increase the quality of the final product and reduce cost. To achieve a high level of efficiency, the use of new digital technologies, which have been introduced in the sector, is necessary in order to facilitate communication and to avoid repetitive and exhaustive tasks that cause inconsistencies and productivity loss [1]. The traditional way of using Computer Aided Design (CAD) tools, based on digital drawings, requires a great volume of manual work, and it is susceptible to misunderstandings and irregularities. As referred by Khudhair et al. [2], the evolution of the construction industry is associated with the continuous implementation of new technologies. However, it needs to be supported by new technologies that can embrace digital construction by transforming the construction industry into a dynamic environment. The natural evolution has given rise to a new and more complex generation of building design tools that incorporates advanced modelling technologies [3].

Building Information Modelling (BIM) methodology has been implemented in the sector, with recognized benefits registered worldwide. In recent decades, it has contributed

to the agility of the project development, replacing the CAD traditional design process. BIM concept is based on the generation of a digital three-dimensional (3D) model, containing the information related to all project disciplines, in a centralized and accessible database, allowing an easy data sharing among all collaborators. Modelling buildings in fully parametric 3D BIM systems offer numerous benefits in terms of productivity, the ability to quickly generate design alternatives at different levels and the reduction of errors of inconsistencies between the design drawings [4]. In this perspective, BIM has revolutionized the collaboration and data sharing processes in the AEC sector.

However, the knowledge about what BIM is and what are the potentialities of it, is still not enough disseminated. Nowadays, around the world there is an agreement that BIM is not just software. BIM is a methodology supported in an integrated and collaborative platform that allows professionals to generate and maintain a data enriched source, easily accessed to perform all life-cycle processes, concerning design, construction and building occupation [5]. Currently, BIM is considered as the process of creating and using digital models, based on the use of advanced technologies based in parametric objects, for design, construction and operations of buildings.

The BIM process involves participants from the entire project life-cycle sectors (architect, engineer, contractor, owner or facilities management) that contribute to create, update and manage the BIM model. The model contains a well-organized database of the virtual building, providing a centralized and integrated source for all information associated with the building designing and performance [6]. The BIM adoption promotes collaboration and an accurate detection of inconsistency at the design stage, which naturally leads to less effort and lower costs associated with eventual corrections. Although this methodology is promising, there is still some resistance to its implementation, not only due to the high investment that offices have to make in equipment, software and training, but also due to the knowledge restrictions that still exist in the use of the available BIM based systems [7]. The present study intends to bring some clarity and knowledge to this limitation.

BIM is a leading technology for AEC practices playing an important role in facilitating projects, delivery through a 3D virtual model with information associated. It allows a real-time track of the project adjustments and progress in different stages of the building life-cycle [8]. Based on the centralized data in the model, the construction process planning, the estimation of costs in an early project stage [9], and the achieving of a better buildings' performances in aspects related with comfort, efficiency and sustainability [10], can be easily elaborated. As the amount of data in BIM is rising exponentially, the value-relevant design information has not yet been widely utilized for property valuation or application. Su et al. [11] present a system that allows to improve information exchange between multi-projects, and automates specific workflows for property valuation. The present work intends to enlarge knowledge on the use of BIM model on the development with accuracy of several tasks.

The ability of an enterprise to perform a task, deliver a service, or generate a product can be defined in distinct phases: Pre-BIM, BIM phase 1, BIM phase 2, BIM phase 3 and Post-BIM. These BIM phases or stages define the main goals to be achieved by teams and organizations as they adopt the BIM concept and associated technologies. Each BIM phase is defined based on establishing minimum requirements [12]. In this context, the term maturity corresponds to the adoption of admissible measures relative to a structure that encourages repeatable, stable, well-defined, and quality results. The maturity corresponds to the ability to differentiate the execution of tasks or delivery of BIM services or products, and it is defined as the degree to which business processes and activities are performed according to acceptable bases [13]. The structural design is an activity that requires a well-known management of the available software, concerning both the modelling process and the analyses practice [14].

The structural design process, supported in BIM software, have been widely studied, having in common the identification of the interoperability capacity of the systems, as the principal limitation on BIM implementation in this construction segment [15–17].

Ren et al. [18] conducted a literature review in order to identify topics and trends on BIM interoperability problem with a focus on the structural analysis domain, from theoretic and application perspectives, identifying the most relevant interoperability problems and proposing possible solutions. A survey of 2014, promoted by Shinler and Nelson, evaluates the structural projects percentage, where BIM software is used, showing an average of 50%, in tasks concerning coordination (inter-disciplines), documentation prediction (drawings), analyses and design (using exterior analyses software) [19].

As interoperability is an inevitable step to take and analyze with care in project design offices, the present study aims to contribute to the investigation of the methodology implementation, in order to promote BIM adoption in this specific domain. Thus, the main objective of the work is to analyze, through a practical case, the implementation of the BIM methodology in structural design, complemented with the extraction of information supporting the development of a diverse type of tasks [20]:

- Evaluating the efficiency of the BIM tools used in the elaboration of distinct phases of the structural design process (design, analysis and structural dimensioning);
- Exploring the various applications that the BIM model database can support related to different dimensions of the methodology (coordination, drawing production, construction planning, risk analyses, estimation costs, and sustainability simulation).

In structural domain, the interoperability is the main problem that must be understood and the present study contributes to clarify the most recurrent limitations. The research also presents the capacity of BIM methodology of using the database of the BIM model to achieve several types of tasks that normally are associated to the structural design. For that, the research requires a sequence of several steps:

- First, the modelling of the structural project in analyses, followed by the transfer of the created model to the structural dimensioning software;
- Next, the results of the analyses, including the reinforcements obtain for each structural elements, were transposed to the initial BIM model, in order to obtain a complete structural BIM model;
- Finally, the tasks required in a structural project, namely, the conflict analyze or the construction planning was performed.

The main innovation of the study is supported on the manipulation of the complete structural model to obtain the necessary drawings, tables or cost estimation.

## 2. BIM in Structural Design

The generation of a BIM model is supported on a parametric modelling process that consists on the use of 3D object-oriented associated with parameters that can be manipulated by the designer, in terms of their geometry, applied material and physical properties [5]. The BIM model is then composed of a set of parametric objects that contains a large collection of data, which can be used as input for further tasks, such as extracting quantities of material to support budgeting or to carry out structural or sustainability analyses. Based on the quantitative assessment allowed by the BIM model, a wide range of data extraction scheme and integration can be performed. As mentioned by Ren et al. [21] to extract distinct data types from the BIM model, several specific filters of information can be established, facilitating the quantitative assessment required in structural project. BIM methodology supports the elaboration of a wide range of applications that satisfy different objectives based on the project information contained in the BIM model. These tasks correspond to the distinct BIM dimensions that are frequently designed as nD BIM [7]:

- 3D BIM represents the set of 3D parametric objects referring to all the specialties (geometry, spatial inter-relation, and physical properties of the materials);
- 4D BIM is concerned with the planning of the construction process associating the model to the critical path chain established in each case;
- 5D BIM is related to the project estimation costs supported by the automatic quantity take-off of materials and components;

- 6D BIM supports the performance of sustainability studies, namely the simulation of the energy consumption or the CO<sub>2</sub> emissions;
- 7D BIM is considered in the management and maintenance of the building during its period of use.
- 8D BIM is associated to the safety risks during the construction work supporting to set up preventive action plans.

In order to establish the collaborative capacities in an enterprise, maturity stages were defined, resumed in the Bew–Richards matrix of maturity [22]. Currently, it is easy to obtain the level 2 of maturity, the stage of full collaboration, and the present study demonstrates that it is possible to reach it, as revealed in the building case application. At level 3, a full collaboration and integration (iBIM) is effective, through the central model, where the BIM model is unique and fully integrated managed through a collaborative server. This level has not yet been reached, being a theoretical concept [23]. Every project requires a well-defined strategy for the implement of BIM, where all entities know exactly how to collaborate between partners in every phase of the project. The BIM execution plan (BEP) is the formal document defined before the beginning of the project and contains all the necessary information concerning disciplines, task and responsibilities. The charge of each collaborator is well defined in the document and a BIM manager coordinates it.

Important findings lie in the necessity of understanding how to manage knowledge needs with diverse and variable ways, when BIM maturity levels are advanced. All decisions made would always rely on good, timely and correct data. Then the use of BIM models in terms of Building Information Management can support decision-makers through data gathering, sharing and using across all disciplines and through all life-cycle steps. In particular, it inserts significant improvement in level of life-cycle costing. Experience and knowledge can be stored in the BIM model database, concerning the description of the user requirements, the best practices derived from other projects and the research outputs that can help to understand sustainability of the project development in its complexity and wholeness [24]. The study elaborated by Ren and Zhang [25] presents a review approach to identify the current issues that are affecting value for money assessments and suggests that BIM, functioning throughout the whole life-cycle, could support decision-making in order to satisfy service target.

Within the scope of this study, interviews were carried out, within structural design offices that have been implementing BIM in the project. The survey was carried out on the advantages and limitations of BIM in structures, allowing the identification of some difficulties and benefits found on the application of BIM in the sector:

- The transition to BIM does not result in an immediate improvement of productivity as expected, as initially there will always be a decrease;
- The use of BIM tools contributes to the optimization of structural modelling (conception), coordination (inter-discipline) and documentation (production of drawings);
- Increased quality is achieved due to clash detection tools, consistent drawings, and great accuracy in quantity take-off;
- Insufficient knowledge of BIM by some professionals limits the collaboration potential of the methodology;
- Lack of confidence in the quality of the generated analytical model and in the transferred data process due to the ineffective level of interoperability between the modelling and calculation software, which still subsist.

To guide professionals in the implementation of BIM in the distinct activities associated to the construction industry, some countries developed relevant guides. Is the case of Finland, the country pioneer in the implementation of BIM. The Common BIM Requirement 2012, COBIM, developed in Finland, is based on the requirements identified by owners, software developers, construction companies and software vendors. The BuildingSMART Finland organization participated also in the financing of the project and as a result, the updated series 1–9 were released on 2012 [26]. Concerning the present work the series 5—Structural Design, was consulted and followed. As well the Series 6—Quality Assur-

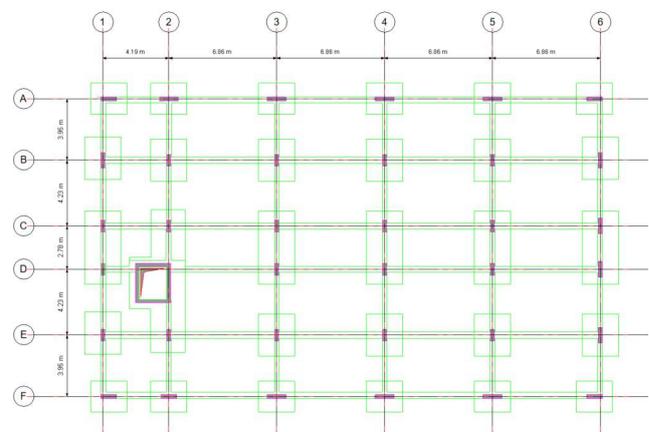
ance [27], namely, the topic concerning the BIM structural building elements. Another guide, the UK BIM Framework Guidance, was consulted [28]. The access of those guides allowed to better define the structural BIM model of the case study.

Currently, the application of BIM technologies for reshaping structural design has been widely embraced by both academic and industry communities. The structural design processes (including modelling, analysis and optimization of structures) are fully investigated with emphases on specific design stages. Chi et al. [29] put efforts on surveying the benefits of BIM in facilitating current structural design, such as systematic modelling processes, powerful interactive visualization platform and standardized exchanging data interfaces. In the structural design Hamidavi et al. [13] provided an automated procedure, to bind architectural models with structural ones for tall buildings, allowing to automatically generate and update alternatives for structural models, based on the input extracted from the architectural model. Nawari et al. [30] explored BIM tools in creating structural analytical models and the use of multiple analytical models to perform various structural analysis and design education tasks.

### 3. Case Study: Generation of the Structural Model

The selected building concerns a four-story residential building located in Lisbon. The established structural solution is a reinforced concrete frame. The structural BIM model was generated based on the available set of drawings of floor plans, sections cuts and details of the structure (Figure 1):

- The structure is composed of an orthogonal frame which supports the floor slabs;
- The isolated foundations are 0.60 m high and are connected to each other by beams placed in both directions.



**Figure 1.** A realistic image of the structural project and the foundation plant [20].

#### 3.1. Physical Model

- The modelling software used was Revit from Autodesk. In the process, several significant distinct ways of working were verified during the conception of the structure:
- Revit enables the introduction of the coordinates in the survey point and project base point allows all objects to have their real coordinate and elevation associated;
- Since the process involves 3D modelling, when the solution is created in a plan view, it will be reflected in all other plans;
- An additional advantage is that the structure can be observed in a 3D perspective, contributing to a clear understood of the solution in progress;
- The project browser, associated to the model, presents an organized directory in order to support collaboration and coordination, avoiding inconsistencies between disciplines or tasks;
- The schedules of material take-off are dynamic tables that can be always be updated, following the solution alternatives or adjustments;

- The project represented in a BIM model form, can be easily examined simplifying the detection of inconsistencies, regarding the type of information associated with each object.

Revit software includes a structural menu with a wide variety of parametric objects representative of the most frequent structural components, facilitating the modelling process of the required structural solution. First, the available CAD drawings, representing each structural plant, were imported and positioned over the correspondent level of the model. After, level by level, the necessary structural elements (columns, beams and slab) were selected, retrieving them from the concrete reinforcement's components library, and then adjusted in order to represent, with correctness, the established structural solution.

Initially, some basic definitions were considered, in particular the work unites and the materials, associated to the adequate mechanical characteristics, namely, the Concrete C30/37 and the Steel A500 NR SD (Table 1). The values of the mechanic properties were introduced with their correct values, as they are later used in the structural analyses stage.

**Table 1.** Properties of design materials.

Materials		Proprieties			
Concrete C30/37	fck (MPa) 30	fcd (MPa) 20	fctm (MPa) 2,9	Ecm (GPa) 33	$\gamma_c$ (kN/m <sup>3</sup> ) 25
Steel A500 NR SD	fyk (MPa) 500	fyd (MPa) 435	Es (GPa) 200	$\gamma_s$ (kN/m <sup>3</sup> ) 78	

The modelling process of the structural solution is then initialized. A floor solution is defined based on the size of the spans between the columns and the presence or absence of beams. All the elements were pre-sizing, were the thickness of the slabs, the cross-section dimensions of the beams and the columns, and finally the dimensions of the foundation elements, were established (Figure 2). The beams and columns were adequately positioned according to the grids outlined. The modelling system allows to replicate the modelled elements from one floor to the others, speeding up all process. Since the upper floors were similar, this feature was used, replicating the structural elements from the level 0 to the other 3 floors.

In addition, the building presents a stair column and an elevator core (Figure 3):

- The stair element was first modelled only as an architectural element and, therefore, it cannot be associated with an analytical element or modelled with reinforcements. To solve this problem, the stair was created as a sloped floor element, which belongs to a structural category. Thus, as it was modelled as a structural element of the category slab, with the geometry of the stair, later, it would be possible to insert reinforcement in it;
- The elevator core is composed of three structural walls with 25 cm thickness and the wall with openings with 25 cm.

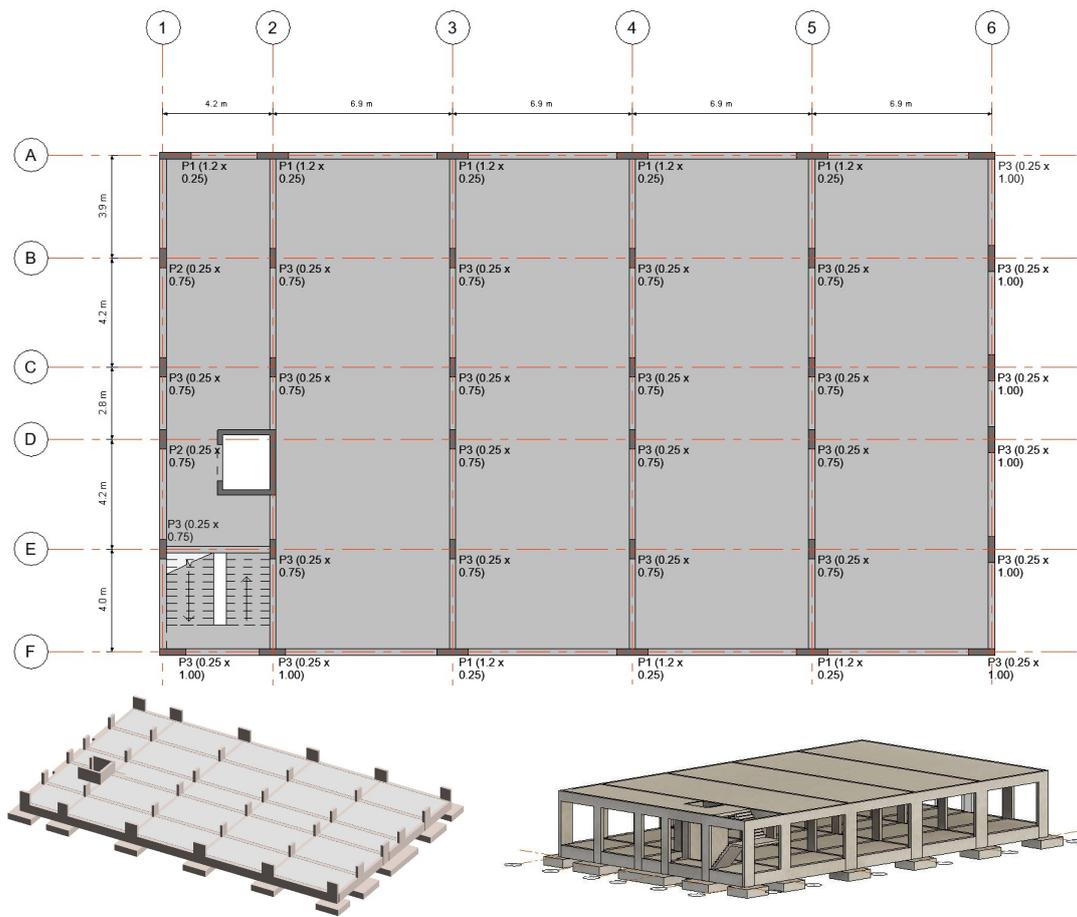


Figure 2. Plant of level 1 and models of the foundations and of the first level.

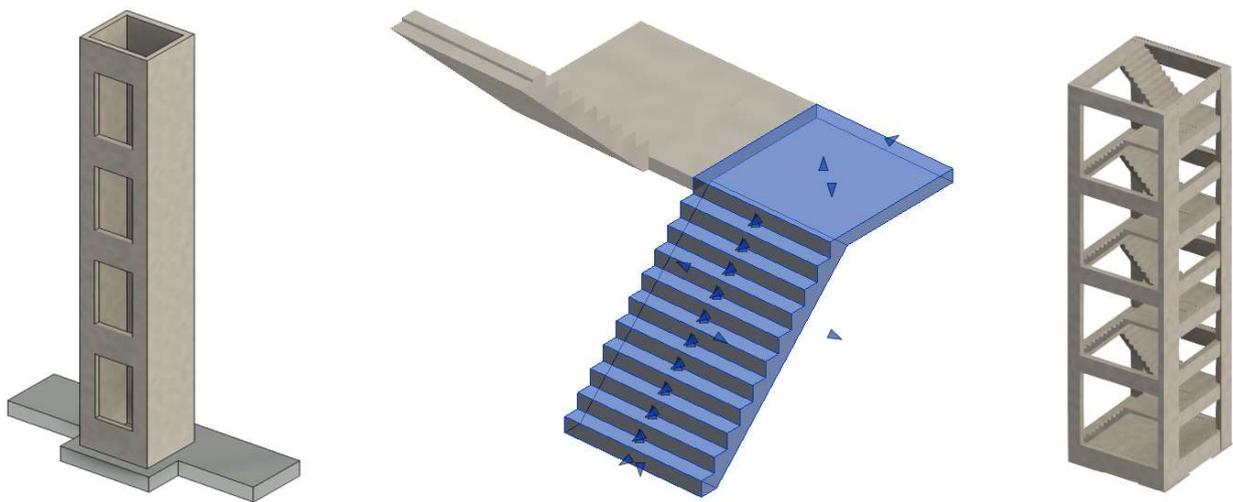
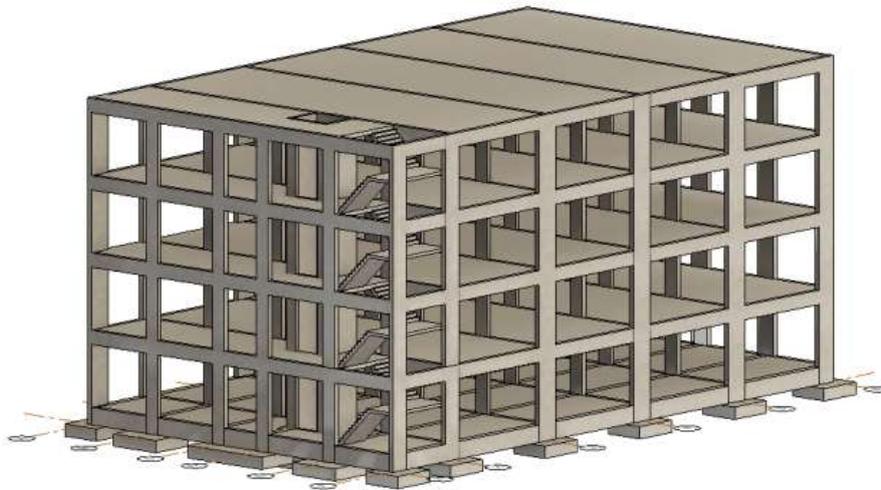


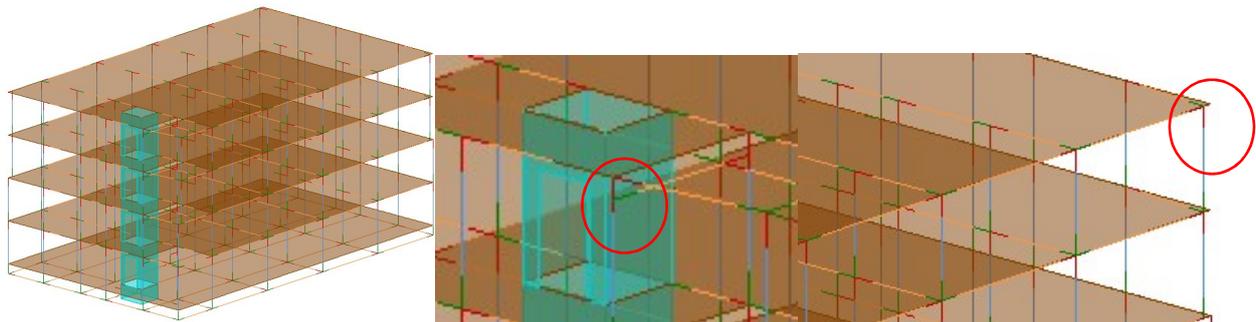
Figure 3. Cont.



**Figure 3.** Model of the elevators core, of the stars and the final structural BIM model.

### 3.2. Analytical Model

After completing the physical modelling of the structural solution, Revit enables the automatic generation of the respective analytical model (Figure 4). Each physical structural objects have attributes associated with finite elements (FEM) and physical properties. Despite the analytical model being generated automatically, the engineer needs to carefully check its consistency.

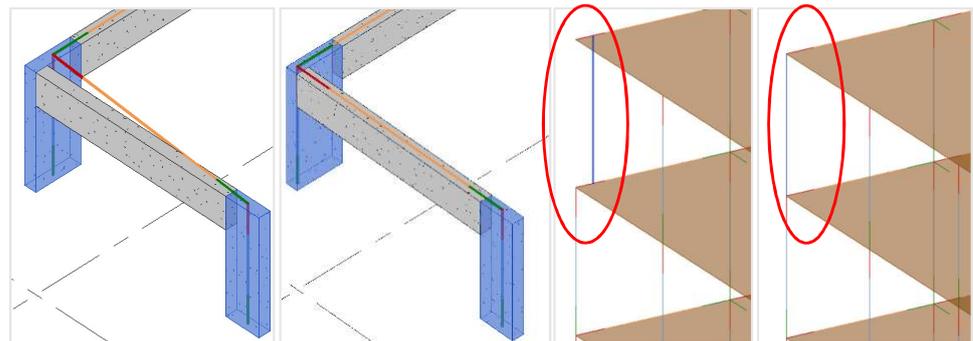


**Figure 4.** Automatic generation of analytical model without adjustments.

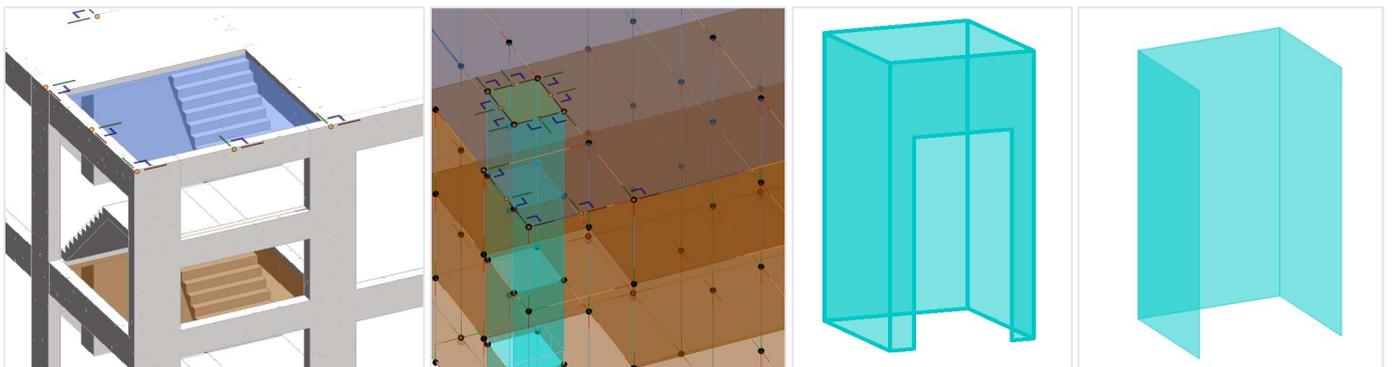
Through the observation of the global analytical model, some inconsistencies were identified. Therefore, the required adjustments were made, before doing the transposition of the analytical model to the structural analysis software:

- Some FEM elements were not placed over the orthogonal axis, which can cause unwanted effects in the structural analyses process. The analytical beams were sloped positioned towards the orthogonal axis, since the analytical representation of the column was located at its geometric center, which does not coincide with the intersection of the beams axis. Thus, the column was positioned on the desired reference line by modifying the *Base* and *Top Alignment* in the analytical alignment function concerning the analytical column elements (Figure 5).
- The ground floor was modelled as a slab element. However, this element does not have a resistant function supporting the stresses to which the structure is subjected. Thus, in the correspondent parametric object the characteristic *Structural* was removed. Whenever it is not possible to adjust the analytical element through its properties, Revit allows manual adjustment, where a node of the analytical model is dragged from one position to other, independently of the physical representation in the model (Figure 6);

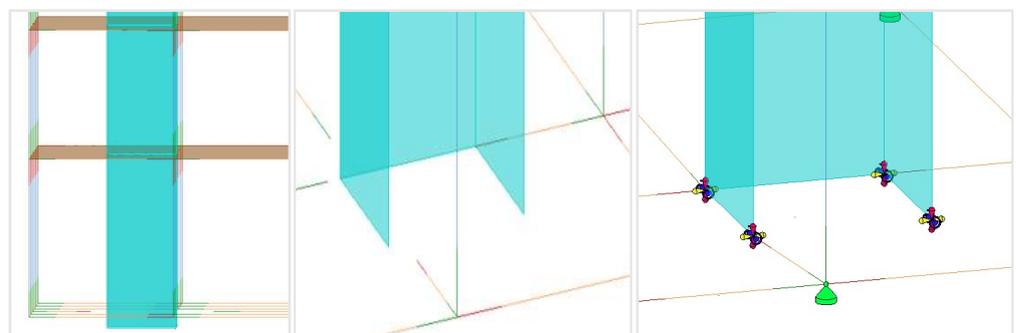
- In Revit, the analytical representation of the foundations corresponds to nodes, which are converted, in Robot, into a clamped support. However, if boundary conditions are applied in Revit, Robot assumes that information. In this case a pinned support was applied at the base of each column;
- The base foundation of the core walls is located at a lower level of the beam elements. The analytical model is a simplification of the reality; therefore, the base level of the shell has changed, but they are positioned at the same level. It is possible to make this kind of modification to the properties of the analytical walls by placing the base extension at the level of the foundations (Figure 7).



**Figure 5.** Adjustment of a beam in the analytical model.

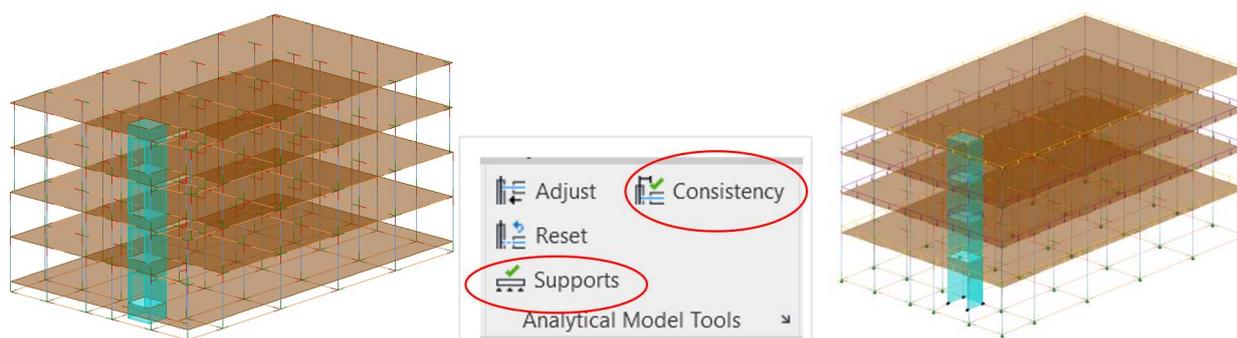


**Figure 6.** Manual adjustment of the analytical model concerning the stairs and the elevator core.



**Figure 7.** Irregular position of the analytical wall and beams connection to the wall.

Once the adjustments have been completed, Revit includes a function that can automatically check the geometric consistency in the analytical model (Figure 8).



**Figure 8.** Analytical model before and after the consistency check process.

#### 4. Structural Analysis and Design

Revit has the ability to communicate directly with Robot structural analysis professional, allowing to send and update the whole model or of a pre-selected part. The Revit model is then, as a whole, transferred to Robot. In Robot, after a consistency check of the transposed model, it was verified that most of the data was transferred correctly, except the value of the spring stiffness of the elastic support, which present an incorrect situation. The application of the standard loads over the structure, as well the loads combinations, were made in Robot. Robot can automatically generate the combinations of loads and apply them effectively (Table 2). The analysis results verify the Ultimate Limit State (ULS) and the Service Limit State (SLS).

**Table 2.** Load combinations.

Combinations	Name	Combination Type	Case Nature	Definition
4 (C)	ULS	ULS	structural	$(1 + 3) \times 1.35 + 2 \times 1.50$
5 (C)	SLS-QP	SLS-QPR	structural	$(1 + 3) \times 1.00 + 2 \times 0.30$
6 (C)	RARA	SLS	structural	$(1 + 3 + 2) \times 1.00$
12 (C) (CQC)	$1 \times 0.3 \times Y$	ULS	seismic	$8 \times 1.00 + 9 \times 0.30$
13 (C) (CQC)	$1 \times (-0.3) \times Y$	ULS	seismic	$8 \times 1.00 + 9 \times (-0.30)$
14 (C) (CQC)	$0.3 \times 1 \times Y$	ULS	seismic	$8 \times 0.30 + 9 \times 1.00$
15 (C) (CQC)	$0.3 \times (-1) \times Y$	ULS	seismic	$8 \times 0.30 + 9 \times (-1.00)$

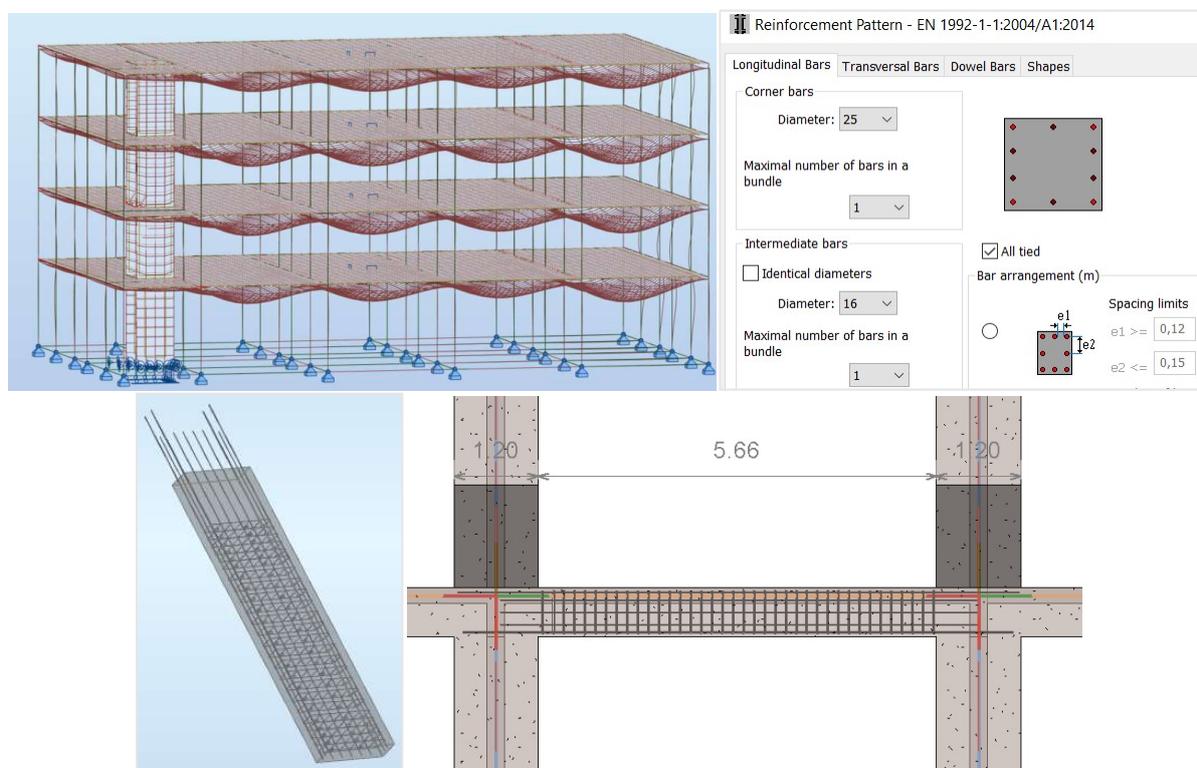
##### 4.1. Reinforcement Design

Robot allows an automatic calculation of the reinforcement according to the Portuguese standard following the Eurocodes 2 and 8 [31–33]. There are two main steps in this process:

- Calculation of the minimal reinforcement ( $A_t$ ), which refers to the required theoretical reinforcement area;
- Definition of the provided reinforcement ( $A_r$ ) which determines the area of reinforcement that is actually placed, which must be greater than  $A_t$ .

In the determination of the provided reinforcement, several parameters were manipulated in order to obtain an adequate solution, accordingly to the engineer knowledge and experience. When the reinforcement is calculated, the Robot displays the solution, representing the reinforcements distribution as plant drawings, but also as a 3D model (Figure 9). In addition, a report is generated with the calculation values. The safety of each resistant element was verified. The software presents a possible solution, but the engineer must conceive properly the most adequate bars distribution. The software introduces an important optimization in time consuming and in finding a better solution, instead of defining alternative distribution and repetitive tasks [30]:

- The slab reinforcements were supported on the moments diagrams generated presented for the most conditioning combination (ELU), and the theoretical reinforcement area,  $A_t$ , is first calculated according to EC2. The Robot allows the calculation to be taken into account when calculating the reduction of peak stresses on pillars, or walls, assuming a redistribution of moments in a predefined width;
- In beam elements, the reinforcements are automatically obtained. It is then possible to modify the diameters of the bars after the first calculation. Moreover, the stirrup spacing can be adjusted, in order to obtain the desired configuration;
- In the case of the columns, it is not possible to calculate a continuous element from the lower to the upper floor. The process is similar to the beams' reinforcement, where, after the calculation of the required reinforcement ( $A_t$ ), the parameters and rules relating to the columns are defined using the available options. The reinforcements were evaluated in accordance with the provisions of EC2 and EC8.

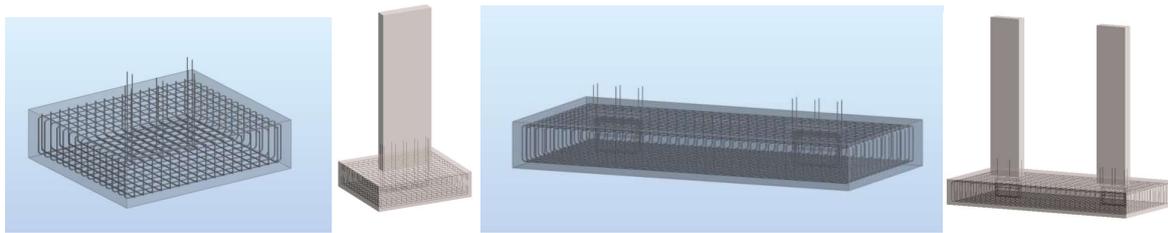


**Figure 9.** Deformation diagram in slabs and the reinforcement in a column and a beam.

#### 4.2. Software Interoperability

After the reinforcement work is completed, it is possible to update the initial Revit model, with the reinforcement details:

- Concerning slabs, it is possible to build an effective reinforcement solution in Robot. However, only the diagrams of forces can be transferred from Robot to Revit. The required reinforcement must be defined in Revit, using its capacities, working over the drawings of bars distribution obtained in Robot. The interoperability capacity is inefficient in this step;
- In the case of the beams, the transfer process is the most efficient. Namely, concerning the transfer of the reinforcements of single multi-span beam;
- Regarding columns and foundations, either the interoperability or the automatic calculation are both done with correction. However, some required manual adjustments must be performed (Figure 10).

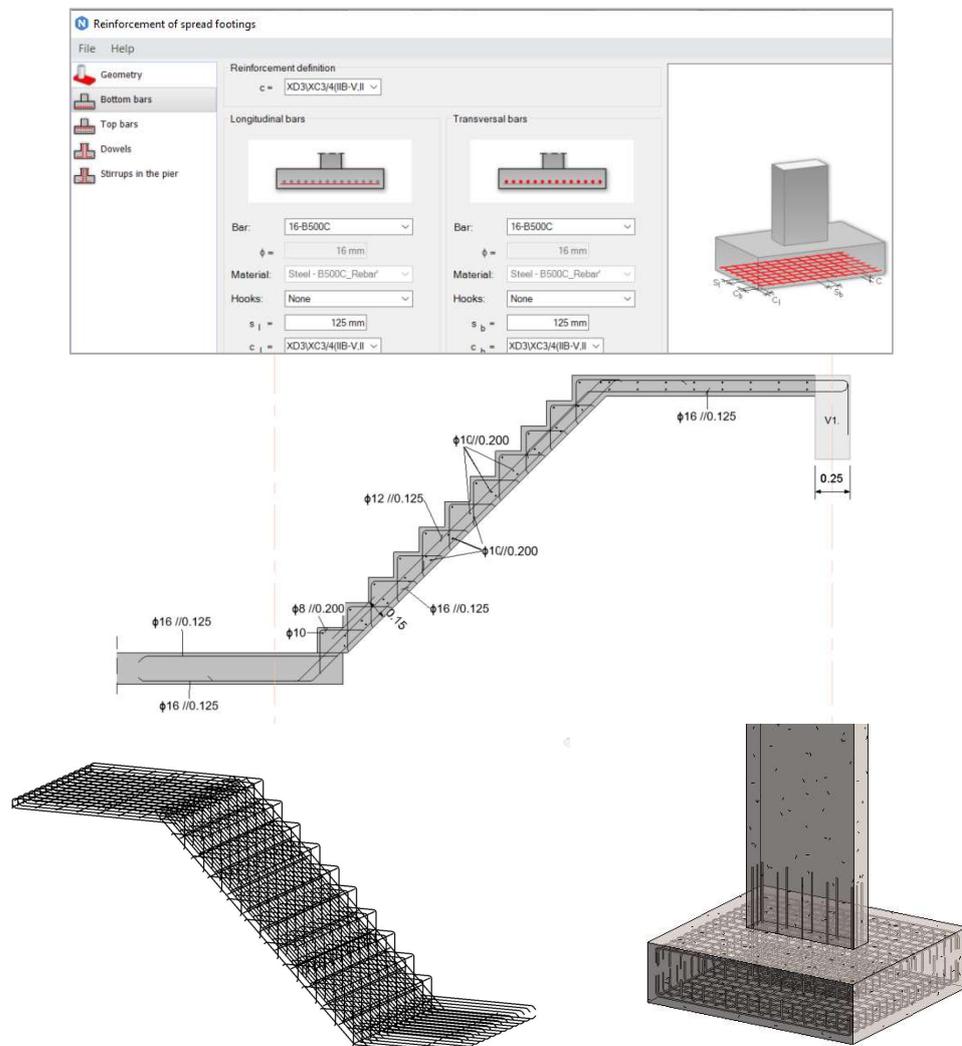


**Figure 10.** Interoperability between Revit and Robot.

The image demonstrates that the transfer of the foundation elements was carried out correctly, both for the insulated and continuous components

#### 4.3. Reinforcement Modelling in Revit

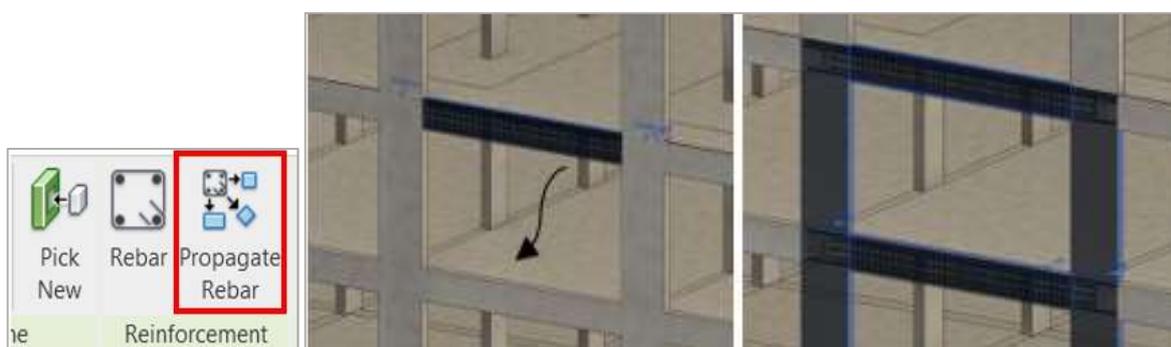
Rebar modelling in Revit is very intuitive using the available interfaces. It allows advantages such as obtaining the reinforcement details with automatic identification and accurate immediate quantity take-off. However, it can be an exhaustive task to model the whole reinforcement of the structure (Figure 11).



**Figure 11.** Reinforcements modelling interface concerning the foundations and the reinforcements in the stair element.

Revit interface is similar to Robot allowing the design to introduce the required parameters in an intuitive way. The detailed solution was performed accordingly to the solution obtained in Robot. The step element was first considered, in Revit, as an architectural element, and after modelled as a floor element, which is a structural category, allowing to introduce the reinforcements.

Software can significantly be improved using specific extensions that perform recurrent tasks, contributing to increase efficiency. Concerning the reinforcement definition, the Rebar Extension, can be applied. The most recent version Revit 2023 has an option referred as *Propagate Rebar* which allows the user to copy a detailed reinforcement from one object to similar elements, avoiding repetition in the modelling process, increasing efficiency (Figure 12).



**Figure 12.** Propagate rebar feature.

In a construction enterprise and along the development of a structural project, the available software should be coordinated and updated, in order to achieve a better performance in time consuming and in the quality of the project.

## 5. Management of the BIM Model

A BIM model is composed of parametric objects that contain multiple information besides the geometric one. The model database enables the development of several applications related to the various dimensions or applicability of BIM.

### 5.1. Coordination and Collaboration

Revit saves the information about the results of the diagrams of forces, displacements and the required reinforcement area of each element from the calculation performed in Robot (Figure 13). The ability to centralize information is quite helpful when, in a reinforcement modelling or design review process, the engineer wants to consult the data of the structural analysis.

In a collaborative process of multiple specialties, elaborated in an enterprise context, there is a sharing functionality the Project Browser, that allows to properly organize the model in progress and establish an efficient communication between the professional team. The Project Browser supports the modelling data, such as the imported auxiliary drawings, the material specifications, the tables of quantities of materials and the drawing sheets properly composed with cuts, details and captions, forming an upgradeable dynamic component of the project.

One of the most used applications, concerning the coordination of a project, is the software capacity to detect conflicts between specialties, in an automatic way. This adaptation is extremely relevant since it is not possible to spot inconsistencies in the project so quickly, that would otherwise only identified and resolved on site. Revit allows the user to check interference in the project itself through the Interference Check feature (Figure 14).

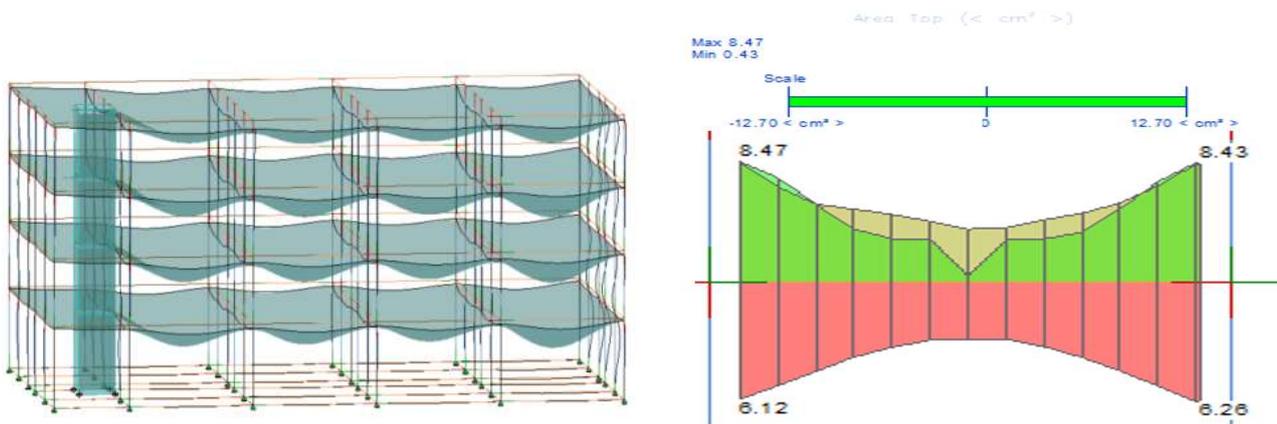


Figure 13. Perspective of a 3D model with deformations and the reinforcement area in a beam.

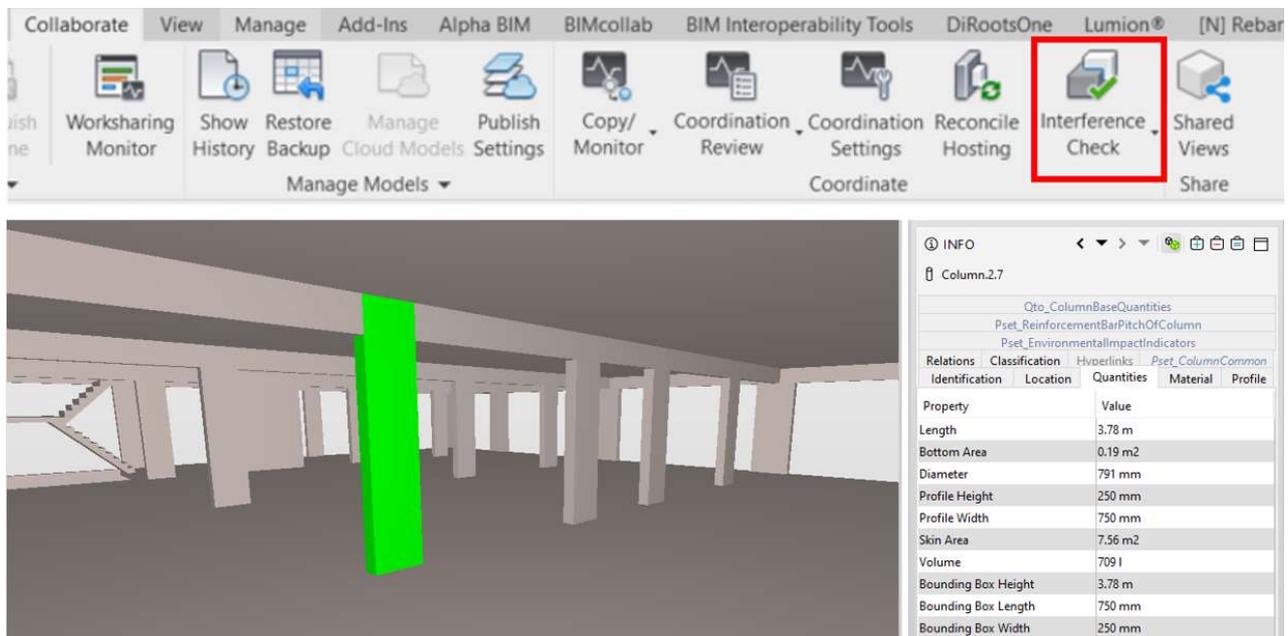


Figure 14. Interference check applied in the intersection of beams and columns.

In order to explore the use of the clash detection tool, a test was performed between using Navisworks manage detective clash option. Thus, it was verified that the transfer of the Revit model to Navisworks was carried out without errors, and all the relevant information for the analysis was transposed.

### 5.2. Drawing Preparation

The great advantage of BIM programs compared to CAD tools is that all sections, plans and details can be generated automatically, from the most actualized model, and there are no inconsistencies between drawings. However, the representation of a drawing, as a cut applied over the components of the model, needs an addition work and some expertise to handling the systems' support functionalities, concerning the technical drawings definition. Formatting drawings is a task that causes a decrease in productivity, as it still requires a repetitive work (Figure 15).

To perform the reinforcement detailing over each element, it is necessary to modify the viewing options in the Visibilities/graphics Overrides menu so that the cut and projected elements have different shades. Over the view, the dimension lines, the labels on the

structural elements and the reinforcements were inserted and some adjustments were made to annotative lines and text.

Through the generation of schedules and legends it is possible to prepare distinct type of elements to be placed in organized drawing sheets. The elements placed on the drawing sheets are all dynamic and therefore they can be upgradeable if changes were required in the project (Figure 16).

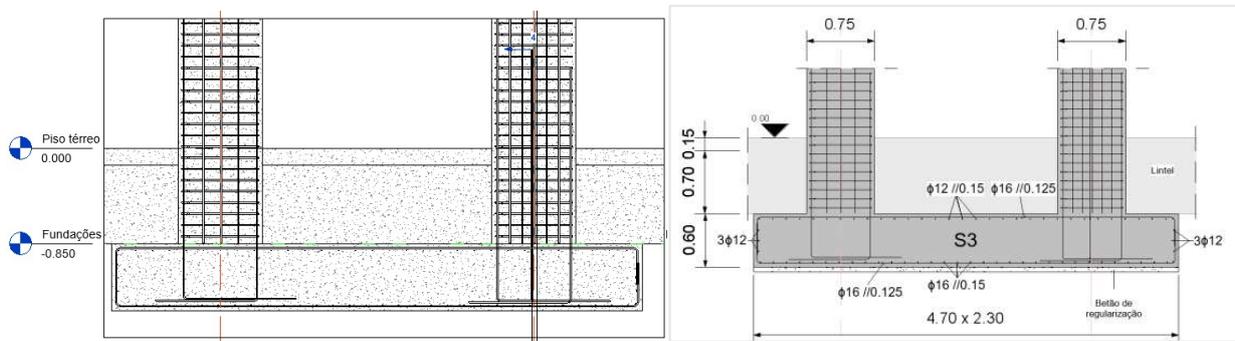


Figure 15. Detailing of a continuous foundation before and after text marks application.

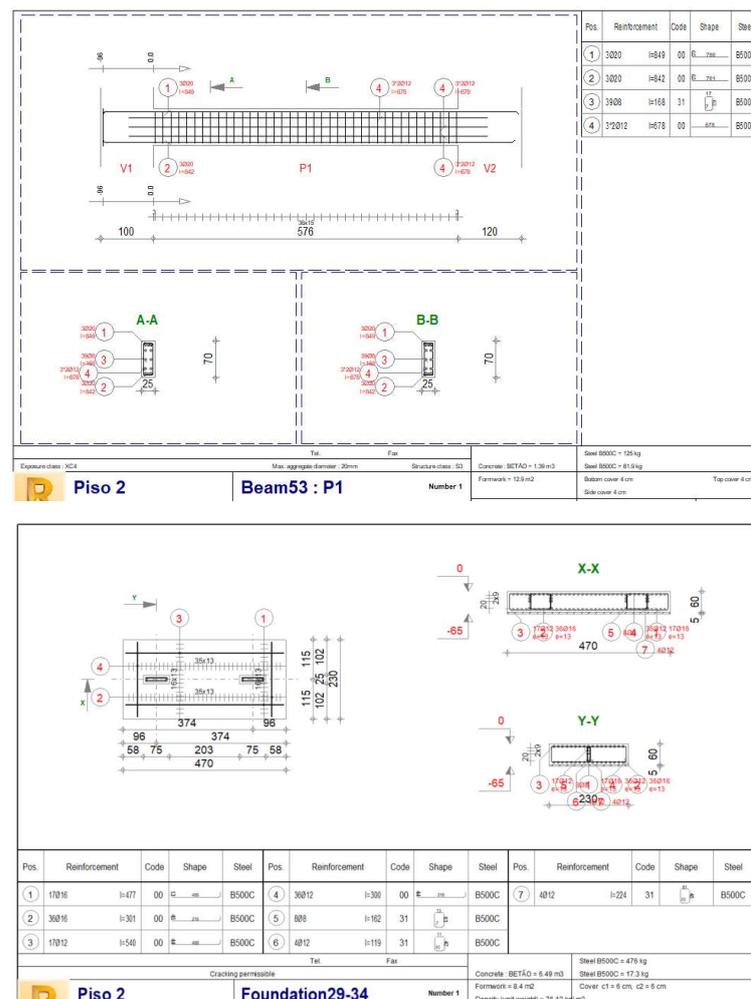
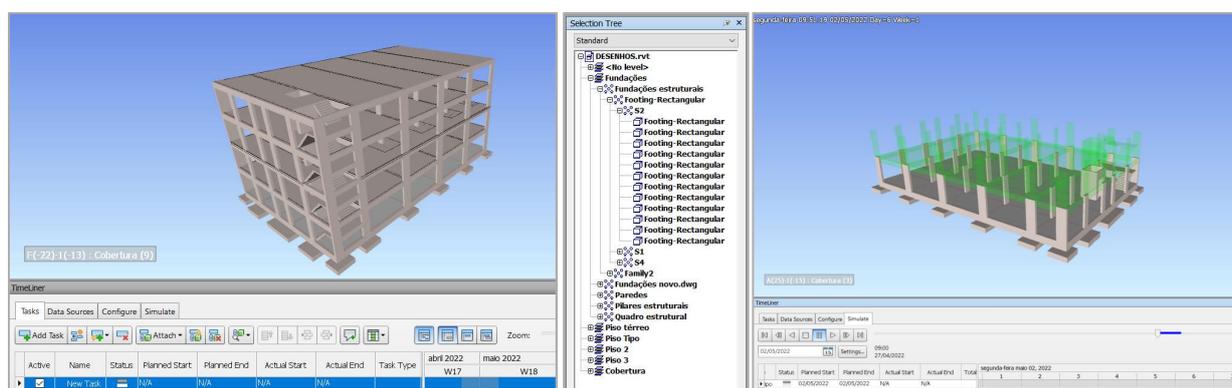


Figure 16. Drawing sheets of beams and foundation with reinforcements and identification of individual bars.

### 5.3. 4D and 8D Dimension of BIM

Associating the time factor to sets of objects of the model, it is possible to simulate the construction phase, supporting the construction planning establishment. The model that links the components of the model to periods of time related to construction activities, is referred to as a 4D model. The simulated representation of the construction also assists in the risk assessment that the worker may experience, as it allows to identify the situations in the construction site, that require special attention in terms of precautions. This other activity, supported also on the BIM model, is mentioned as an 8D model. Exploring the time liner tool of the software Navisworks Manage, tracking properly the building components to the time of the correspondent activity, the construction simulation can be visualized (Figure 17).



**Figure 17.** The Navisworks timeline, sets of objects and an image of the construction simulation.

In order to illustrate the generation of a 4D model, an automatic association of objects was made by floors. Once the 4D model was created, the visual simulation of the construction was started, and a green (in progress) and gray (completed) color can be associated with the development state (Figure 16). This model can also be used in the real construction place, comparing the planned progression with the one that is actually executed. Over the 4D model it is possible to add temporary elements such as formwork and metal anchors, which makes simulation more real.

### 5.4. 5D Dimension

The estimating cost activity, concerning the structural project, was also carried out, operating over the BIM model, by associating a unit cost to each material or object. The extraction of quantity from the model is an automatic task, through the creation of dynamic tables or schedules since every object has the information of its volume. A table concerning the volume of concrete related to the walls of the model was created (Figure 18). It was organized by type of elements, so that the list could be separated by categories and thus be able to obtain partial sums of elements or sets of elements, evaluating the influence of each one in the overall project. The parameters for concrete, C30/37, include the price per  $m^3$ , having been considered the value of  $\text{€}120/m^3$ . In the preparation of the concrete budgeting table, the category, family and type, volume and cost of the material were selected as columns to be presented. A new column was also created to obtain the total cost, associated with the product of the unit price of the material by the volume.



Figure 18. Quantity take-off of concrete and the formwork of a column.

At any stage of the project, the engineer can consult the schedules created to monitor the economic impact of the structure being created. This functionality is crucial when comparing technical-economic studies of alternative solutions. To include formwork in the structural project, a *plug-in* retrieved from *alphabim* was used, which generates the formwork needed for each element based in a set of rules defined by the user. The data generated in schedules can be manipulated and exported to excel in order to create the quantity take-off sheets of the amount of each material used in the structural solution.

5.5. 6D Dimension

A sixth dimension can be included in the project, by attributing the information of the amount of CO<sub>2</sub> incorporated in each element (Figure 19). Through the analyses of the schedules, it is possible to estimate the quantity of carbon emissions of each material used in the structure, supporting the decision making of the solution.

Concrete CO <sub>2</sub> emission				
A	B	C	D	E
Category	Family and Ty	Material: Volume	Material: CO2 incorp	CO2 (Kg)
Walls	Basic Wall: G	1,18 m <sup>3</sup>	252,86	298
Walls	Basic Wall: G	1,18 m <sup>3</sup>	252,86	298
Walls	Basic Wall: G	1,18 m <sup>3</sup>	252,86	298
(...)				
Floors	Floor: Betão i	122,19 m <sup>3</sup>	252,86	30 898
Floors	Floor: Betão i	122,26 m <sup>3</sup>	252,86	30 915
Floors	Floor: Betão i	122,26 m <sup>3</sup>	252,86	30 915
Floors	Floor: Betão i	122,26 m <sup>3</sup>	252,86	30 915
Floors: 19				146 088
Grand total: 442				265 016 kg

Figure 19. Quantity of CO<sub>2</sub> emissions associated to concrete elements of the structure.

Buildings are known to significantly affect the global carbon emissions throughout their whole life-cycle. To mitigate carbon emissions, Kumanayake and Luo [34] investigate the current performance of the materials applied in buildings with regard to carbon emissions in new constructions. According to Habert [35], 80% of the carbon dioxide (CO<sub>2</sub>) associated to the production of cement, and it is harmful to the environment. During the design process, it is relevant to estimate with precision the CO<sub>2</sub> impact, allowing timely changes to the project to be made accordingly. For that, in the model it is possible to associate a parameter in the properties of the materials relative to the amount of associated CO<sub>2</sub> emission. The carbon emission analysis associated with the project was performed in the study through the *Revit* dynamic tables.

Ma et al. [36] present a study concerning the use of fine aggregate sourced from concrete waste, due to abundant existence of hardened old mortar in recycled fine aggregate. An innovative and viable approach is proposed to crush recycled coarse aggregate into recycled manufactured sand, which has high-quality properties similar to the manufactured sand crushed from natural stone, for preparing high-quality recycled mortar with high strength and good durability. This also contributes to the reduction of the CO<sub>2</sub> emission.

## 6. Conclusions

This study identifies several benefits and limitations that should be considered when adopting the methodology in the structural design. It also demonstrated the advantages of having a model that has a high quantity of centralized information, in the elaboration of several applications and tasks.

- BIM tools, due to their 3D geometric feature, enable the conception of an optimized solution, not only due to the 3D visualization capacity, allowing to observe the structure that is being developed, but also due to the facility in analyzing the constraints of the solutions modelled concerning other disciplines;
- The BIM model contains parametric objects with several attributes, and this fact allows the manipulation and organization of information in order to obtain drawings and the extraction of quantities. In addition, whenever there is a change in project, all the information is updated, and no manual modification is required;
- The analytical model can be associated to the BIM model, allowing an integrated structural analysis and design. In this way, the centralized model is coherent with the results of the calculations.

Nevertheless, there are certain bottlenecks that delay a further implementation of BIM in the sector:

- The investment is considerable and there is always a decrease in productivity during the adaptation phase;
- The analytical model is not yet completely independent from the physical one, which prevents the engineer from making the simplifications required;
- Automatic design does not yet allow a solution to be developed with the desired integration and efficiency;
- Interoperability is still limited and may not provide engineers with the necessary confidence.

The study demonstrates that BIM can be used in the development of a structural project, with relevant positive contributions. The analyses of the interoperability limitation associated with the software used, was clearly described and strategic solutions were presented. In addition, the documents and task associated with the design were also described, making use of the software functionalities, contributing to the dissemination of the potentiality of BIM in the structural context, and for that a BIM manager is required in each project.

Despite some limitations, there is, however, some optimism in the adoption of BIM in structural design, either due to competition need in a global world, or because the new generation of engineers is culturally more technological. Technological innovation is

growing exponentially and it is necessary that the industry is aware and open-minded in the search for solutions in order to achieve a more efficient and better-quality construction.

**Author Contributions:** Conceptualization, A.M.G. and A.Z.S.; methodology, A.Z.S.; software, G.A.; validation, G.A. and A.S.L.; formal analysis, A.Z.S.; investigation, G.A.; resources, A.S.L.; data curation, A.S.L.; writing—original draft preparation, A.Z.S. and G.A.; writing—review and editing, A.Z.S. and A.S.L.; visualization, G.A.; supervision, A.M.G. and A.Z.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The study is supported by Azevedo, G. in a Implementation of the BIM methodology in the project of structures: adaptation of procedures and information management, MSc dissertation, Department of Civil Engineering, University of Lisbon, Lisbon, Portugal, 2022. With the institutional link: [https://fenix.tecnico.ulisboa.pt/teacher/thesisDocumentConfirmation.do?thesisID=565303595503566&method=viewThesis&request\\_checksum=6121493cc2247448dd003be602e5d4b1fc4b177b](https://fenix.tecnico.ulisboa.pt/teacher/thesisDocumentConfirmation.do?thesisID=565303595503566&method=viewThesis&request_checksum=6121493cc2247448dd003be602e5d4b1fc4b177b) accessed on 9 August 2022.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Boukara, A.; Aziz, N. A brief introduction to Building Information Modeling (BIM) and its interoperability with TRNSYS. *J. Renew. Energy Sustain. Dev.* **2015**, *1*, 126–130. [CrossRef]
2. Khudhair, A.; Li, H.; Ren, G.; Liu, S. Towards future BIM technology innovations: A bibliometric analysis of the Literature. *Appl. Sci.* **2021**, *11*, 1232. [CrossRef]
3. Sacks, R.; Eastman, C.M.; Lee, G. Parametric 3D modelling in building construction with examples from precast concrete. *Autom. Constr.* **2004**, *13*, 291–312. [CrossRef]
4. Migilinskas, D.; Ustinovichius, L. Computer-aided modelling, evaluation and management of construction project according PLM concept. In *Cooperative Design, Visualization, and Engineering*; CDVE 2006. Lecture Notes in Computer Science; Luo, Y., Ed.; Springer: Berlin/Heidelberg, Germany, 2006; Volume 4101, pp. 242–250. [CrossRef]
5. Eastman, C.; Teicholz, P.; Sacks, R.; Listo, K. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
6. Sampaio, A.Z. BIM as a computer-aided design methodology in civil engineering. *J. Softw. Eng. Appl.* **2017**, *10*, 194–210. [CrossRef]
7. Sampaio, A.Z. Maturity of BIM Implementation in Construction industry: Governmental policies. *Int. J. Eng. Trends Technol.* **2021**, *69*, 92–100. [CrossRef]
8. Aksenova, G.; Kiviniemi, A.; Kocaturk, T.; Lejeune, A. From finnish AEC knowledge ecosystem to business ecosystem: Lessons learned from the national deployment of BIM. *Constr. Manag. Econ.* **2018**, *37*, 317–335. [CrossRef]
9. Capilla, R.; Nava, F.; Montes, J.; Carrillo, C. ADDSS: Architecture Design Decision Support System tool. In Proceedings of the 23rd IEEE/ACM International Conference on Automated Software Engineering, L'Aquila, Italy, 15–19 September 2008; pp. 487–488. [CrossRef]
10. Langdon, D. *BIM Guides for Clients, Getting the Most Out of BIM*; AECOM: London, UK, 2012. Available online: [https://issuu.com/jojowasmydog/docs/davis\\_langdon\\_-\\_bim\\_guide\\_for\\_clients\\_-\\_apri\\_l2012](https://issuu.com/jojowasmydog/docs/davis_langdon_-_bim_guide_for_clients_-_apri_l2012) (accessed on 15 March 2022).
11. Su, T.; Li, H.; An, Y. A BIM and machine learning integration framework for automated property valuation. *J. Build. Eng.* **2021**, *44*, 102636. [CrossRef]
12. Succar, B. Building Information Modelling Maturity Matrix. In *Handbook of Research on Building Information Modelling and Construction Informatics: Concepts and Technologies*; Underwood, J., Isikdag, U., Eds.; Information Science Publishing: Hershey, PA, USA, 2010. [CrossRef]
13. Giel, B.; Issa, R.R.A. Quality and Maturity of BIM Implementation in the AECO Industry, October 2013. *Appl. Mech. Mater.* **2013**, *438–439*, 1621–1627. [CrossRef]
14. Hamidavi, T.; Abrishami, S.; Hosseini, M.R. Towards intelligent structural design of buildings: A BIM-based solution. *J. Build. Eng.* **2020**, *32*, 101685. [CrossRef]
15. Sequeira, P. Structural Design in a BIM Environment: Technological Advances in Information Transfer. Master's Thesis, Department of Civil Engineering, University of Lisbon, Lisbon, Portugal, 2022.
16. Sampaio, A.Z.; Gomes, A.M. BIM interoperability analyses in structure design. *CivilEng* **2021**, *2*, 174–192. [CrossRef]
17. Borges, N. Design of Structures Supported by BIM Methodology: Interoperability Analysis. Master's Thesis, Department of Civil Engineering, University of Lisbon, Lisbon, Portugal, 2019.

18. Ren, R.; Zhang, J.; Dib, H.N. BIM Interoperability for structure analysis. *ASCE Constr. Res. Congr.* **2018**, 470–479. Available online: <https://ascelibrary.org/doi/abs/10.1061/9780784481264.046> (accessed on 9 August 2022).
19. Shinler, D.; Nelson, E. BIM and the structural Engineering Community. 2008. Available online: <https://www.structuremag.org/wp-content/uploads/2014/08/C-Tech-BIM-SchinlerNelson-Dec-08.pdf> (accessed on 15 March 2022).
20. Azevedo, G. Implementation of the BIM Methodology in the Project of Structures: Adaptation of Procedures and Information Management. Master's Thesis, Department of Civil Engineering, University of Lisbon, Lisbon, Portugal, 2022.
21. Ren, G.; Li, H.; Jiao, Y.; Zhang, W. Data exchange requirement analysis for value for money assessment in public-private partnerships. In *Workshop of the European Group for Intelligent Computing in Engineering*; Springer: Cham, Switzerland, 2018; pp. 429–446. [CrossRef]
22. Ayinla, K.O.; Adamu, Z. Bridging the digital divide gap in BIM technology adoption. *Eng. Constr. Archit. Manag.* **2018**, *25*, 1398–1416. [CrossRef]
23. Olawumi, T.O.; Chan, D.W. Development of a benchmarking model for BIM implementation in developing countries. *Benchmarking Int. J.* **2019**, *26*, 1210–1232. Available online: <https://www.emerald.com/insight/content/doi/10.1108/BIJ-05-2018-0138/full/html> (accessed on 15 March 2022). [CrossRef]
24. Nývlt, V.; Prušková, K. Building Information Management as a tool for managing knowledge throughout whole building lifecycle, Published under licence by IOP Publishing Ltd. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *245*, 042070. Available online: <https://iopscience.iop.org/article/10.1088/1757-899X/245/4/042070> (accessed on 9 August 2022). [CrossRef]
25. Ren, G.; Li, H.; Zhang, J. A BIM-based value for money assessment in public-private partnership: An overall review. *Appl. Sci.* **2020**, *10*, 6483. [CrossRef]
26. COBIM Finland. Common BIM Requirements 2012—Series 5—Structural Design. 2012. Available online: [https://buildingsmart.fi/wp-content/uploads/2016/11/cobim\\_5\\_structural\\_design\\_v1.pdf](https://buildingsmart.fi/wp-content/uploads/2016/11/cobim_5_structural_design_v1.pdf) (accessed on 15 March 2022).
27. COBIM Finland. Common BIM Requirements 2012—Series 6—Quality Assurance. 2012. Available online: [https://buildingsmart.fi/wp-content/uploads/2016/11/cobim\\_6\\_quality\\_assurance\\_v1.pdf](https://buildingsmart.fi/wp-content/uploads/2016/11/cobim_6_quality_assurance_v1.pdf) (accessed on 15 March 2022).
28. UK BIM Framework Guidance. 2021. Available online: <https://ukbimframeworkguidance.notion.site/ukbimframeworkguidance/UK-BIM-Framework-Guidance-20a045d01cfb42fea2fef35a7b988dbc> (accessed on 15 March 2022).
29. Chi, H.L.; Wang, X.; Jiao, Y. BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes. *Arch. Comput. Methods Eng.* **2015**, *22*, 135–151. [CrossRef]
30. Nawari, N.O.; Chichugova, T.; Mansoor, S.; Delfin, L. BIM in Structural Design Education. Computing in Civil and Building Engineering ©ASCE 2014. Available online: <https://itc.scix.net/pdfs/w78-2014-paper-266.pdf> (accessed on 15 March 2022).
31. CEN. *Portuguese Standard EN 1992-1-1-Eurocode 2—Concrete Structures Project—Part 1-1: General Rules and Rules For Buildings*; European Committee for Standardization: Brussels, Belgium, 2010.
32. CEN. *Portuguese Standard EN 1998-1-1—Eurocode 8—Design of Structures for Earthquake Resistance; Part 1: General Rules, Seismic Actions and Rules for Buildings*; European Committee for Standardization: Brussels, Belgium, 2009. Available online: <https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-basis-structural-design> (accessed on 9 August 2022).
33. CEN. *Portuguese Standard EN1990—Eurocode 0—Bases for the Design of Structures*; European Committee for Standardization: Brussels, Belgium, 2009; p. 47. Available online: <https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-basis-structural-design> (accessed on 9 August 2022).
34. Kumanayake, R.; Luo, H. Life cycle carbon emission assessment of a multi-purpose university building: A case study of Sri Lanka. *Front. Eng. Manag.* **2018**, *5*, 381–393. [CrossRef]
35. Habert, C.; Billard, P.; Rossi, C.C.; Roussel, N. Cement production technology improvement compared to factor 4 objectives. *J. Cem. Concr. Res.* **2010**, *40*, 820–826. [CrossRef]
36. Ma, Z.; Shen, J.; Wang, C.; Wu, H. Characterization of sustainable mortar containing high-quality recycled manufactured sand crushed from recycled coarse aggregate. *Cem. Concr. Compos.* **2022**, *132*, 104629. [CrossRef]