The European Master in Building Information Modelling is a joint initiative of:

Universidade do Minho

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POLITECNICO MILANO 1863

Wilson Zárate

Generative Design of Modular/Industrial Architectural System

BIM A+

UMinho | 2023

Universidade do Minho
Escola de Engenharia

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Generative Design of Modular/Industrial Architectural System

BIM A+ European Master in Building Information Modelling

Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of:
Bruno Acácio Ferreira de Figueiredo
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Co-funded by the Erasmus+ Programme of the European Union

October, 2023

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ACKNOWLEDGMENTS

First of all, I want to thank my supervisor Bruno Figueiredo for his guidance, support, and shared knowledge during the time of developing the dissertation. It was a great experience to be able to receive insights from him, so clear, timely, and of great importance for the development and enjoyment of the work done. Likewise, I want to thank my co-supervisor Filipe Brandão, who with his experience in the topics developed, was very helpful with the methodologies and scripts implemented. I thank both of them for the consistency of the reviews and their continuous participation and involvement.

I also want to express my gratitude to Grupo CASAIS, partner company, for providing the necessary material and knowledge on the topic developed in the case study. Special thanks to Miguel Pires and Pedro Carneiro, who contributed a lot to the development and application of the objectives of the dissertation, through their technical and professional knowledge. Their perseverance and openness were very motivating.

I sincerely thank the consortium for providing me with the Scholarship to be able to participate in the master's degree. And to BIM A+ for the knowledge bases received, as well as the availability of interaction spaces with teachers and classmates. These were catalysts in the research carried out.

I want to thank my family for their constant support and for motivating me to always go in search of my dreams. Thank you for believing in me and for being present in the most necessary moments. I also thank my fellow masters for the shared moments and for the friendships that emerged throughout the course. Their varied backgrounds and perspectives enriched me personally and professionally.

STATEMENT OF INTEGRITY

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

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

RESUMO

Um dos problemas recorrentes na indústria da construção é a sua reconhecida falta de produtividade devido a diversos fatores, entre os quais se destacam a fragmentação do fluxo de informação entre as diferentes fases do ciclo de vida do projeto e a dificuldade de comunicação entre as diferentes partes envolvidas. Para tal, a indústria tem reagido nos últimos tempos através da utilização da pré-fabricação e da implementação de novas tecnologias como a Modelação de Informação na Construção de Edifícios. Isso para melhorar tanto a produtividade por meio da customização em massa quanto o fluxo de informações entre as fases e partes interessadas nos projetos, por meio do uso de softwares e plataformas, que também dão a possibilidade de automação com processos como Projeto Generativo.

A dissertação assenta numa investigação sobre a utilização destas tecnologias na área da pré-fabricação na construção, focando-se na implementação de configuradores e na automatização associada que poderá derivar da sua utilização para o desenvolvimento de projetos. Tomando como caso de estudo um sistema de pré-fabricação híbrido (madeira e betão) atualmente utilizado pela empresa CASAIS, procura-se desenvolver uma metodologia que explore as características modulares destes sistemas, sobretudo na fase de projeto. É nesta fase que é possível tirar partido do número limitado de parâmetros dos elementos pré-fabricados, de forma a automatizar a geração de propostas de projeto, e a obtenção de informação relativa a KPIs (Key Performance Indicators), que por sua vez permitiriam uma análise de viabilidade mais objetiva a partir desta primeira fase do projeto.

A solução indicada é, em primeiro lugar, a proposta de uma metodologia para desenvolver um configurador aplicado ao estudo de caso, que utiliza como elementos constitutivos algumas ferramentas e/ou plataformas, que estão atualmente presentes no mercado relacionadas ao BIM e à construção indústrial. Em seguida, continua-se com o desenvolvimento específico da fase desta metodologia correspondente à geração do modelo computacional, e para o efeito é utilizada a programação visual, tendo como informação inicial os parâmetros e dados relevantes a obter, típicos do sistema de pré-fabricação estudado.

A pesquisa visa contribuir para o atual progresso em termos de produtividade e fluxo de informações que vem sendo desenvolvido na indústria da construção com a implementação da pré-fabricação e do BIM. Com a utilização de configuradores - associados a estas novas tecnologías - propõe-se uma incursão nos métodos de automação, sobretudo nas fases de gestação do projeto através do Projeto Generativo. Assim, aproveitando as possibilidades da customização em massa oferecidas pelos sistemas de pré-fabricação e a integração de agentes não profissionais, enfatizada pela facilidade de manipulação e simplicidade dos dados exigidos por essas metodologias, pode-se alcançar um processo de projeto mais integrado ao nível da participação e um processo decisório mais objetivo, pois é baseado em dados essenciais para avaliar a viabilidade dos projetos.

Palavras chave: (Automação, BIM, Configurador, Projeto Generativo, Pré-fabricação)

ABSTRACT

One of the recurring problems in the construction industry is its recognised lack of productivity due to different factors, among which could be highlighted the fragmentation of the information flow between the different phases of the project life cycle and the difficulty in communication between the different stakeholders. To address this, the industry has reacted through the use of prefabrication and the implementation of new technologies such as Building Information Modelling. The aim is to improve both productivity, through mass customisation, and the flow of information between phases and stakeholders in the projects, through the use of software and platforms, which also give the possibility of automation with processes such as Generative Design.

The dissertation investigates the use of these technologies in the area of prefabrication in construction, focusing on the current implementation of configurators and the associated automation that could be derived from their use for the development of projects. Taking a hybrid prefabrication system (wood and concrete) currently used by CASAIS company as a case study, the research seeks to develop a framework that exploits the modular characteristics of these systems, especially in the design phase. It is in this phase where it is possible to take advantage of the limited number of parameters of the prefabricated elements in automating the generation of design proposals and in obtaining information related to KPIs, which would, in turn, allow a more objective feasibility analysis during this first phase of the project.

The indicated solution is, firstly, the proposal of a methodology to develop a configurator applied to the case study, which uses tools and/or platforms, that are currently present in the market related to BIM and the construction industry. Then the dissertation continues with the specific development of the section of the methodology corresponding to the generation of the computational model, and for this purpose visual programming is used, taking as initial information the relevant parameters and data to be obtained that are typical of the prefabrication system studied.

The research seeks to make a contribution to the current progress in terms of productivity and information flow that has been developed in the construction industry with the implementation of prefabrication and BIM. With the use of configurators, associated with these new technologies, an incursion into automation methods is proposed, especially in the project gestation phases through Generative Design. Thus, by making use of the mass customisation possibilities offered by prefabrication systems and the integration of non-professional agents, (taking advantage of the ease of use of the configurators), a more integrated design process and a more objective decision-making process can be achieved, since it is based on more accurate data related to the feasibility of the projects.

Keywords: (Automation, BIM, Configurator, Generative Design, Prefabrication)

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1. INTRODUCTION

At present, in the area of architecture and construction engineering, it is possible to witness a significant change that has been progressing for some time, mainly related with the objective of promoting greater productivity in the different phases of the projects. From the initial design concepts and construction phases to the maintenance of the building or its deconstruction. This transition is linked to the implementation of prefabrication concepts, which has become increasingly popular in the construction area, thanks to the significant advantages it offers in terms productivity.

Thanks to relatively recent approaches such as Building Information Modelling (BIM), applied to prefabrication in construction, the advance in productivity can be further accentuated, by allowing not only greater continuity and flow of information throughout the different phases of the project but also the possibility of automating processes. Among these processes could be mentioned Generative Design (GD), which makes it possible to establish rules between elements and automate the generation of possible combinations of prefabricated elements. This can be applied within the BIM paradigm (modeling elements with semantics and well-defined parameters and parametric relationships between them) to explore various design solutions. This use GD within BIM permits also the project team and client to have more informed decisions of the project since early stages of development. The potential of this combination (namely GD and BIM) is visible in in the market through configurators, which allow the automatic generation and visualisation of results based on a limited number of inputs.

This dissertation focuses on the use of BIM and GD in prefabrication strategies, developing a methodology to support a construction company in applying a specific modular system at design exploration phases. By clearly defining the modular system's parameters and quickly generating possible solutions, the framework supports decision-making processes based on feasibility and allows the extraction of information for subsequent design phases. To that end, a join system configurator was developed using BIM and GD tools, and applied in the initial design phases of the prefabrication system, focused mainly on the structural elements.

The aim is to contribute to the current progress made in the use of BIM and automation tools, in the area of prefabrication in construction, promoting greater productivity in the gestation phase of a project, where the use of BIM still has a lot to offer. Furthermore, the dissertation intends to make possible the integration of non-professional in the design processes, and improve their communication with design professionals.

1.1. Background and motivation

The construction industry is characterised in many of its phases by a latent lack of productivity, due to a discontinuity in the flow of information from one stage to another, the mismanagement of resources, and the lack of clarity of the repercussions of the decisions made in the initial design phases.

For this reason, the industry is opting for prefabrication systems, which allow the optimization of resources, are capable of increasing the overall efficiency of projects by reducing schedule time, and allow for greater organisation in the construction area. In addition prefabrication allows reducing pollution rates and construction costs, making it a good option towards sustainability and productivity. These factors can be strengthened through BIM technology, which promotes better flow of information and increases process automation at different levels.

The dissertation is framed in the use of this technology, proposing a construction methodology to support the prefabrication processes of CASAIS, a portuguese construction company, based in Braga. This company currently promotes the implementation of a hybrid prefabrication system of laminated wood and concrete, originally developed by the CREE company, which is taken as a case study, to develop the construction methodology. By using BIM tools and Generative Design, the methodology allows obtaining obtaining design proposals, simply and quickly, supporting the design phase of projects.

The aim of the methodology is to make better use of existing BIM technologies in prefabrication which, due to their modular nature and well-defined parameters, allow the application of optimization methodologies since initial stages of design, leading to more objective decisions and greater desing productivity.

1.2. Objectives and methodology

This dissertation seeks to create a methodology that allows the integration of prefabrication systems with BIM technologies in the project conception phase. It also seeks the easy integration and communication of different stakeholders in this stage, allowing an easy-to-use product, with visualisation, and that from a minimum input, relevant results of the project can be obtained in order to take more objective and better-informed decisions, from which the project can continue to be developed by the professionals in charge, in more specific design stages.

Through the analysis and use of tools related to BIM currently available in the market, it seeks to establish a methodology for a configurator, who first uses a set of computational models in an API, linked to the automation of the prefabrication construction system. Then, process these models through a server that allows the use and integration of an application used as a Web Browser for the manipulation and visualisation of the generated models, as well as the integration into a BIM software, which receives the information from the different components and data of the elaborated design, for its later development.

In this way, the dissertation takes as a case study the CREE prefabrication construction system implemented by CASAIS, developing a configurator to automate the generation of design using this system considering data based on their related feasibility.

The different objectives in which the dissertation focuses are the following:

1. Analysis of the literature on the use of BIM and Generative Design for prefabrication in construction.
2. Comparative analysis of digital tools, available on the market, in relation to BIM in the context of configurator development.
3. Proposal of a methodology using the selected tools that allow, the development of a configurator for the case study.
4. Development of a parametric computational model, for the case study to explore different configurations through Generative Design.
5. Validation of the computational model through its application in a sample project.

The dissertation starts with the analysis of the state of the art of the use of BIM in the context of prefabrication in construction. From there, it continues investigating the use of Generative Design tools and methodologies in the development of BIM configurators. The literature analysis of these, as well as a comparative analysis of different tools used for this purpose, is carried out, with the objective of selecting the most appropriate methodologies for the case study and the specific tools that could be used.

Based on this information, a methodology is proposed using the analysed tools that can, as a whole, form a configurator and that, in addition, could be delivered as a complete package to be used by the CASAIS company, in prefabrication systems. The use of Grasshopper is proposed as an initial methodology for the creation of the computational model, which could later be connected to the Rhino.Compute, used to process information remotely through a server. A web application could be developed and connected to the server in order to allow manipulation. Finally, the information generated could be imported into Revit through Speckle, a platform for interoperability and collaborative design processes.

The CREE construction system is analysed in order to define the existing parametric relationships, and then the computational model is developed through the visual programming language Grasshopper. Different approaches are carried out to achieve the objectives required by the company until a final model is achieved that meets the expected results in terms of model and data. To accomplish this, different tests are executed in sample projects that validate the configuration.

The framework for the development of the configurator was raised at a general level. This generic framework was then implemented in a specific context/problem (the case study). Therefore, regarding the possibility of having a user interface instead of implementing a web application, it was opted to use a plugin for Grashopper (due to time limitations and my programming knowledge). Thus, the focus of the dissertation took only the development of the computational model in Grasshopper, processed locally in Rhino, and the aforementioned User Interface implementation.

The other components of the general framework related to the use of Rhino Compute, the implementation of a web application and the connection with Revit through Speckle, were proposed for future development. With the part of the framework implemented was obtained, on the one hand, general information on the project and its various constituent elements of prefabrication, to continue being developed by professionals. Secondly, it was generated the information related to quantities of elements, different types and variations, among other KPIs, with which decision-making in the design phase is made possible.

1.3. Structure of the dissertation

The dissertation is composed by four main chapters. The first of them focuses on the use of BIM in relation to prefabrication in construction and the use of configurators. Then, in the next chapter, the the methodology to develop a configurator is discussed, and then in the next chapter, the analysis of the case study is carried out. The last chapter contains the implementation of the framework, focusing on the development of the parametric model to achieve the main goals related to the generation of models, data, and user interface.

The first chapter deals with the review of the existing literature on the use of BIM in prefabrication for construction. The gaps that are currently found in the implementation of this technology are evidenced, as well as the possibilities it offers for the prefabrication industry. Following this, reference is made to the use of automation in the design phases. Then, reference is made to the use of Generative Design strategies in the development of configurators for prefabrication systems, and a comparative analysis of some tools is made.

The second chapter contains the framework proposal, developed from the previous analysis of the literature and digital tools. With the definition of the existing gaps and the optimal tools to use, a framework for the implementation of a configurator for prefabrication in construction is explained. Then, the workflow of the methodology to be used and each of its different components are defined, showing their possibilities and limitations.

The third chapter presents the case study, which applies the CREE prefabrication construction system developed by CASAIS company. Reference is made to the different elements of this system, as well as the objectives and main parameters to be considered. For this, a parametric schema lining the previous information is developed through the methodology proposed for the configurator.

Finally, the fourth chapter contains the implementation of the methodology, focusing on the development of the Grasshopper program. It begins with an explanation of how the implementation of the general framework could be handled in future investigation, and continues with the different stages of development of the computational model.

Then the implementation of the User Interface made through the Human UI plugin for Grasshopper is explained, and the way in which the information generated by the computational model is organized to be finally exported.

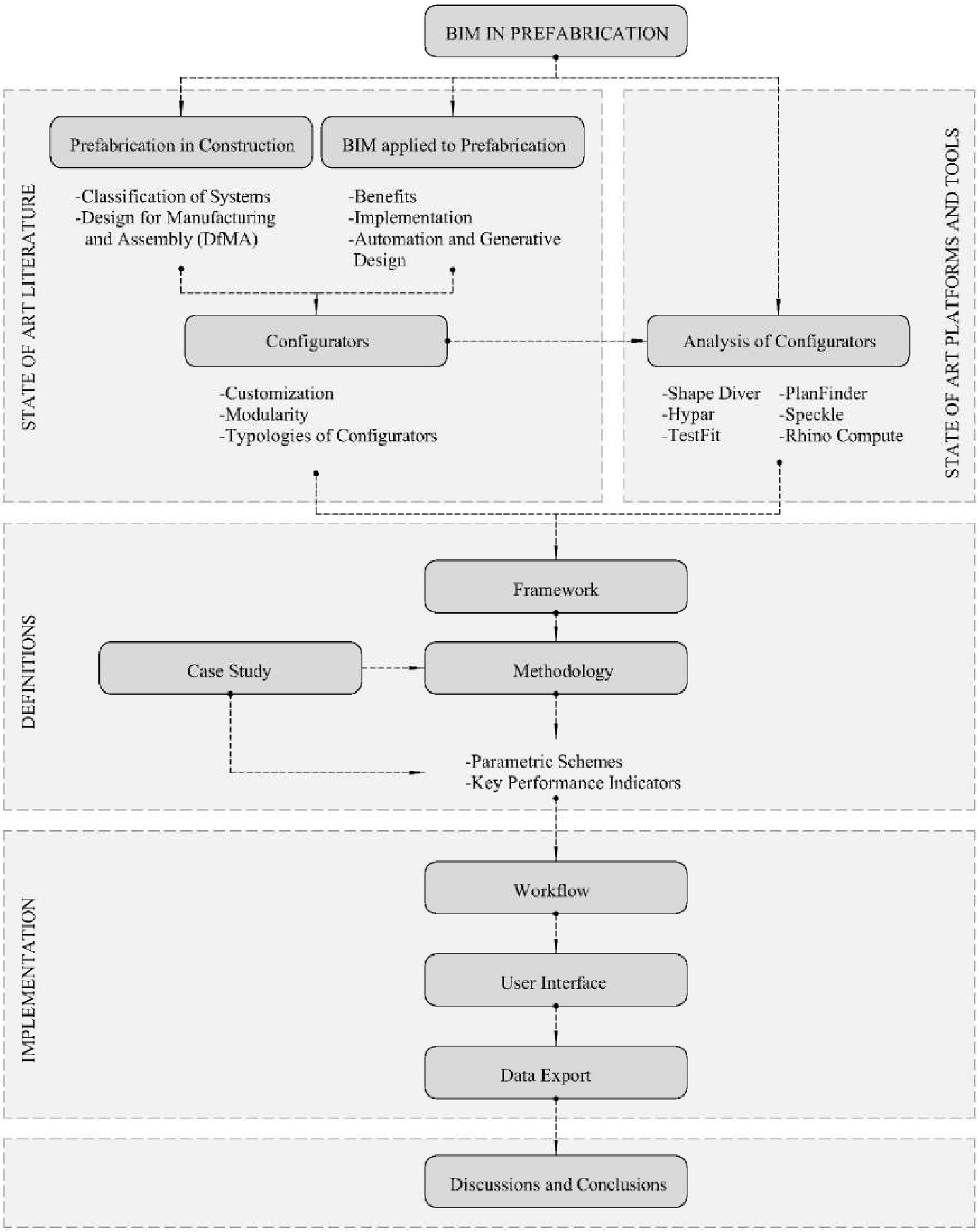

Figure 1 – Structure of the Dissertation

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2. BIM AND PREFABRICATION

The concept of prefabrication in buildings can be recognised since the second decade of the 20th century, when, after the First World War, developed countries in Europe, mainly Germany, shaped this system through industrialisation in construction. This approach offers many benefits and opportunities for the problems that the world faces related to the housing deficit or environmental crises, to name a few.

The topic to be dealt with in this section focuses on the use of prefabrication systems in the construction area, giving a background on what they are, their benefits and limitations, and their development in relation to BIM. The chapter is structured in a way that makes it evident how the adoption of this new processes in the Architecture, Engineering, and Construction (AEC) area has revolutionized the way of developing projects and how they enhance the search for productivity that prefabrication seeks.

After a review of the current literature on the use of BIM in the prefabrication of buildings, this section continues with a focus on the use of configurators tools that allow the automation of processes in design phases, as well as a better interaction between different stakeholders. The literature regarding configurators is explored and a comparative analysis is made between some of the tools currently used. The aim is to create a basis for the development of a methodology that contributes to the adoption of BIM in the prefabrication industry.

2.1. Prefabrication in Construction

Around 1920, just after the First World War, reference to prefabricated buildings began to be made. in a context in which developed countries in Europe, mainly Germany, through industrialised construction, gave rise to this concept. Prefabricated buildings refer to the “production and processing of a large number of on-site operations in the prefabricated components factory, and the installation is completed in the construction site”(Wang and Wang, 2021, pp. 03).

Prefabrication aims to create and accelerate construction methods, where the building is composed by parts that are built off-site in well-equipped manufacturing facilities and under a controlled environment (Auti and Patil, 2018). Subsequently the prefabricated components are transported from the factory to the construction site to be installed and assembled as finished parts of the building. The elements that can be prefabricated range from entire building spaces to small elements that, when assembled, make up larger components or units.

At present, due to the current problems around an affordable architecture with the growing world population or the environmental problems, prefabrication is increasingly accepted within the industry. This is because among its benefits are a “low-carbon economy, green environmental protection, energy saving, high efficiency, and high quality”. (Wang and Wang, 2021, pp. 03).

According to Auti and Patil (2018), there are four principles in off-site technology, which also make it a more attractive option compared to traditional construction methods. These are referred to as:

- Cost: Prefabrication technology is known for having greater consistency in costs compared to other construction methods.(Auti and Patil, 2018). It is also possible to have greater control over the amounts of materials required, allowing more efficient processes, in terms of subcontracting and material waste.(Bertram et al., 2019)

- Schedule: As these systems allow to manufacture the prefabricated components in factories, at the same time that the work is finished on site, there can be greater coordination of production of the elements, and various production techniques can be used. (Auti and Patil, 2018). The time efficiency in product delivery also increases.

- Efficiency: Prefabrication allows to transfer 80% of traditional work to factories (Bertram et al., 2019) and benefits from advance machinery and in digital technologies, which together allow greater worker efficiency. Tere is also a reduction of labor pressure, as it requires less effort to achieve greater results compared to traditional construction.

- Safety: Prefabrication provides the opportunity to have a work environment that allows better availability at a psychological level, which leads to greater productivity. (Auti and Patil, 2018). There is a reduction of unforeseen risks and predictable environmental conditions and services.

- Quality: The quality of the production is improved since the prefabrication technology allows an increase in the precision of the products and a greater control over each aspect related to the quality of their production. There is higher control over processes and less external variables affecting them compared to on-site construction, so the possibility of errors and unknowns is greatly limited.

- Sustainability: Greater sustainability by planning in advance the assembly and disassembly of construction elements, with the possibility of reuse. (Luther et al., 2007.)

Figure 2 shows a summary table develop in a research in the UK in 2017, on the benefits perceived by construction practitioners on prefabrication in the construction industry, rating them on a scale of 0 to 4.(Hashemi and Alonso-Zandari, 2017). In this it can be seen that the three most outstanding benefits were reduction in construction waste, time improvements and reduction of the potential for accidents on-site.

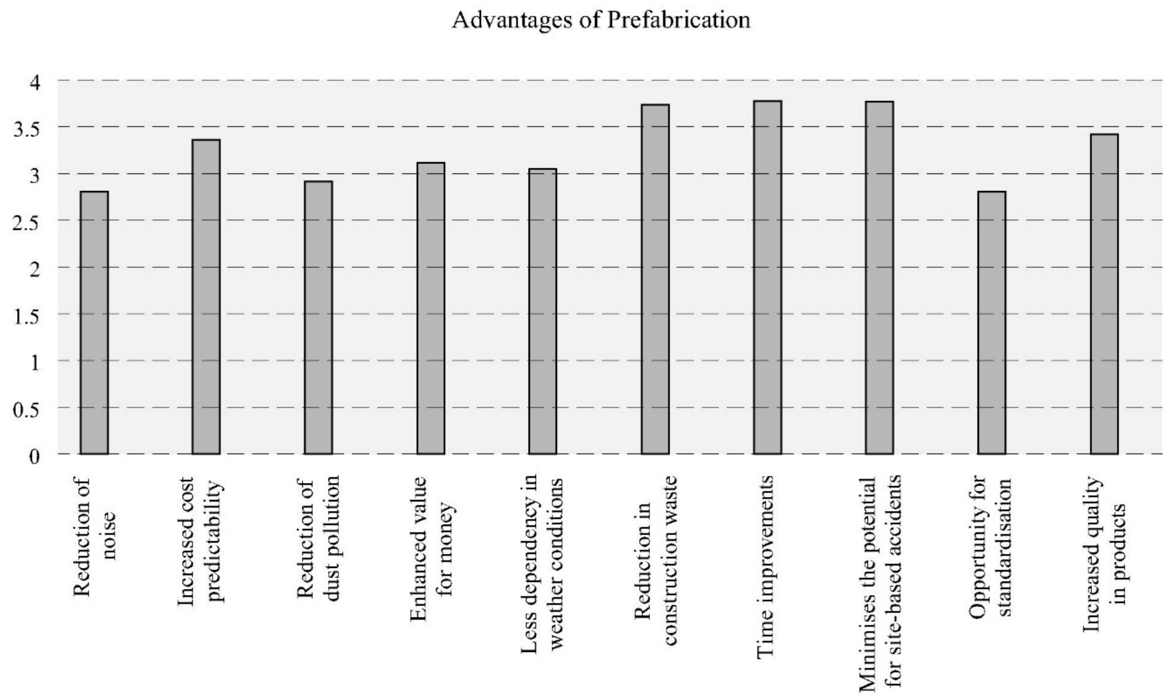

Figure 2 – Graphic analizing the advantage of prefabrication (Hashemi and Alonso-Zandari, 2017)

"Many pioneers considered modularity as a key component of prefabrication. Le Corbusier, Jean Prove, Konrand Washmann, all embraced various principles and interpretations of modular designs" (Luther et al., 2007. pp. 02). This modular design, which is an integral part of the principles of prefabrication, is based on the interfaces between materials, components and systems, where modules are defined and used as a unit for the conformation of the entire building.

Among the characteristics of a modular system:

- The use of separate components that can be connected or integrated together.
- The ease in adding or replacing components without compromising the performance of the system.
- The ability to create different spaces through the repetition of components.
- The simplicity of use and maintenance of the building. (Luther et al., 2007.)

There are different classifications regarding prefabrication systems. For example, Gunawardena and Mendis (2022) propose a classification based on element's level of functionality, identifying three main types of construction:

- Modular construction (Volumetric)
- Panelised construction (Flat panels)
- Hybrid prefab construction (semi-volumetric)

A modular system classification that focus on the classification on modular processes based on both prefabricated and non-prefabricated methods is proposed by Luther (2007). This classification, starts with three modular building categories (Panel/Skin, skeletal, cellular), and then it defines modular design based on how the modular building categories are designed implemented. Figure 3 shows such a classification.

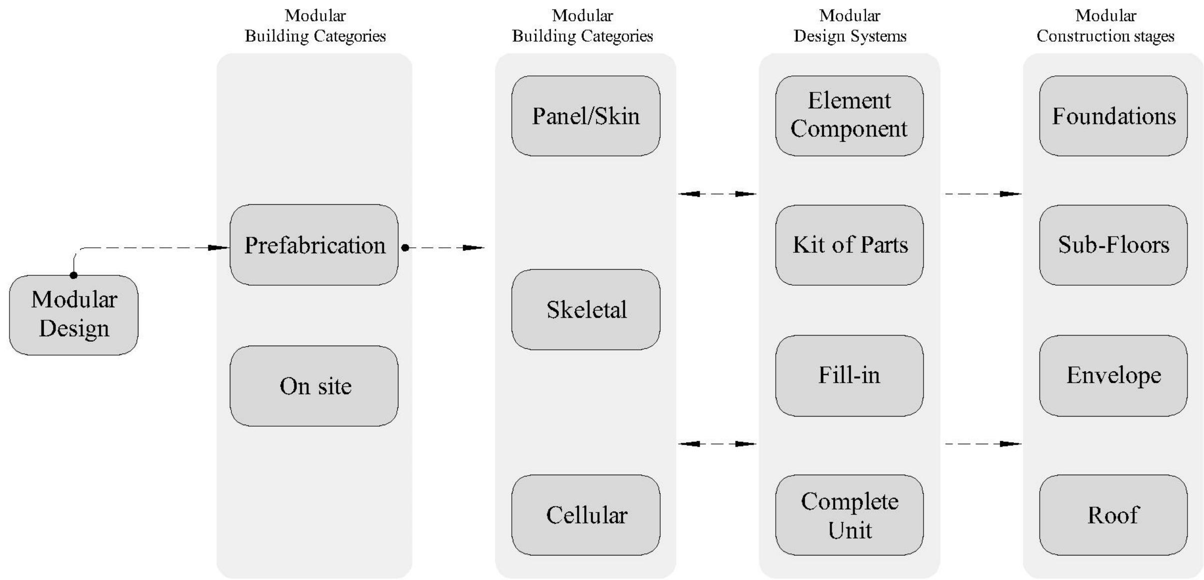

Figure 3 – A categorisation of modular prefabricated systems and construction methods (Luther et al., 2007.)

Design method for modular prefabricated elements is of great importance for these systems. “Early design decisions are important for projects, as they determine most of the economic and environmental impact of buildings” (Qi and Costin, 2023, pp. 01). Traditional design methods tend to only consider architectural, structural, or customer requirements, which causes problems in the life cycle of the building, since it does not consider the manufacturing, transportation, and assembly of the elements.

Through the integration of Design for Manufacture and Assembly (DfMA), designers can consider the requirements of the manufacturing and assembly stages of industrialised buildings, and in this way “make better decisions about materials, costs, manufacturability and assembly processes to determine the most efficient design” (Qi and Costin, 2023, pp. 02). This type of design approach is still in development within the prefabrication industry and its advantages are increasingly recognized over traditional systems.

Although DfMA still tends to take more time compared to traditional systems, since the industry is not shaped to work in this way, design firms are looking for options to develop libraries that potentially speed up and simplify design processes through automation (Bertram et al., 2019).

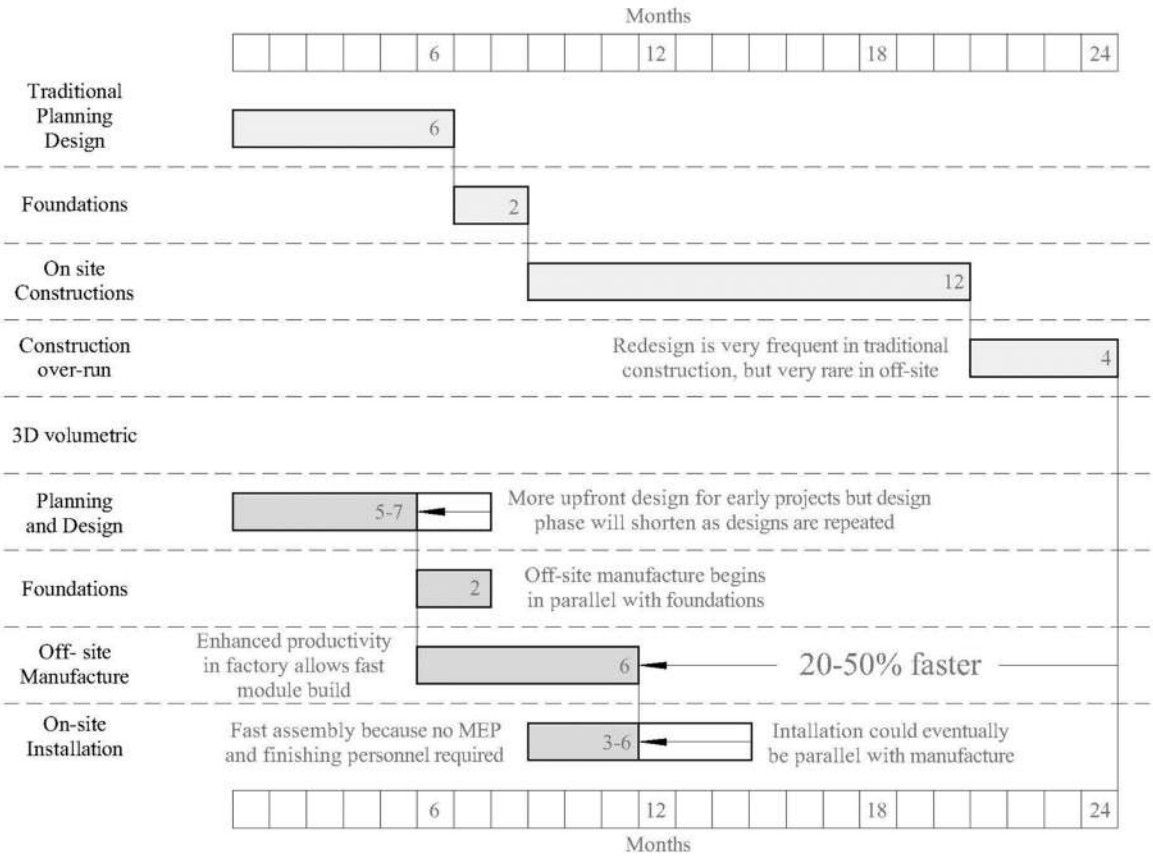

Figure 4 –Comparison of a project duration using traditional and modular construction techniques (Bertram et al., 2019)

Figure 4 shows a diagram (Bertram et al., 2019) that compares the times of using traditional on-site construction and prefabrication in the design and construction of an apartment. Although the time in prefabrication processes is reduced up to 50%, it should be noted that the stage that still needs to be improved is the conception and design phase.

2.2. BIM applied to prefabrication in construction

BIM has been presented as a very good alternative for productivity problems in the construction area. As an approach, BIM has raised interest throughout the construction industry around the world. “Some support this trend; others still have doubts about its real potential”. (Mahmoud et al., 2022, pp. 03). Different studies show that one of the biggest challenges that BIM faces is misinterpretation by the industry. But, as mentioned by several authors, in order to take advantage of novel processes, it is necessary to first understand them better.

In recent years, various definitions have been given, some of them based on BIM processes, others focused on the tools that are used, and others based on the objectives on which this technology focuses. Such perspectives lead some to view BIM as either a process, modeling software, project management tool, or a database for communication. “BIM could be defined as a set of technologies, processes and strategies, based on a 3D model that is shared among stakeholders, to better conduct a construction project and facilitate the sharing of information about a building, throughout its life cycle” (Mahmoud et al., 2022, pp. 03). When properly implemented, it can lead to many benefits such as better communication and coordination, time and cost savings, as well as improved productivity and quality

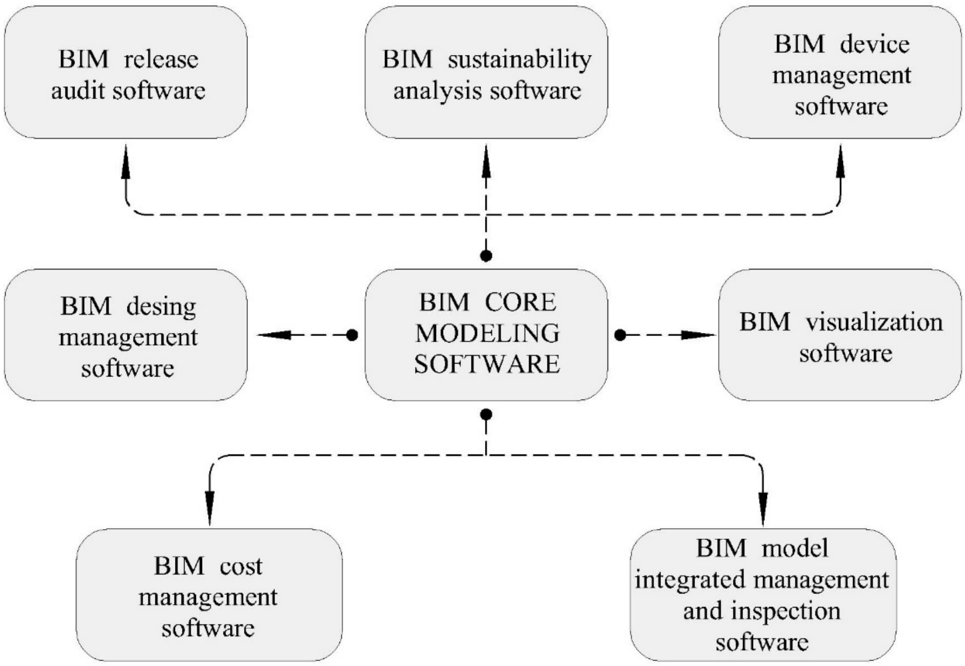

Figure 5 – BIM modelling software types (Jiang and Sun, 2020)

These three-dimensional models require the use of professional modeling tools, classified in Figure 5 within the most common modeling software.

Before the introduction of CAD technologies in the construction field, freehand drawings were the common means of representing projects. Through this, the drawing process could be improved, making it much more efficient than the traditional method, in terms of meeting schedules and allowing for greater complexity. The next great advance in relation to technologies in this line was developed around 1970's with the introduction of the BIM concept. By that moment, building prefabrication systems had already been in development and implementation for some time, and it was a great opportunity to make use of the processes and tools that BIM offered.(Wang and Wang, 2021)

As an approach, BIM integrates building data that can be shared and transmitted throughout the projects life cycle in planning, construction, operation, and maintenance. It allows design, engineering and technology professionals to access various construction information, providing a foundation for all those involved in the various processes to work together in a coordinated manner. Thus, BIM plays an important role in improving production efficiency, saving costs, reducing error, and reducing construction time (Hao et tal., 2021).

Compared to 3D CAD models, made of abstract geometric elements, in a BIM model all elements contain construction data, having a well-defined semantic and relationships with other elements. This allow all kinds of graphics, project reports, quantity charts or 2D representations of the projects, to be dynamically generated from the model. It also allows that each change made in this model, automatically produces the update in the rest of the information, thus ensuring much greater consistency of data.(Wang and Wang, 2021).

The use of BIM leads to improving the efficiency in the design of prefabricated buildings, their production and the management of construction processes, since it allows their simulation and the improvement of the flow of information. With the use of 3D modeling and the visualisation that these make possible, a better understanding of the entire project is ensured, greater precision and consistency of the information of each component and facilitates the exchange of information between the various work groups (Mahmoud et al., 2022).

In each of the phases of prefabrication projects, there are benefits that have been highlighted by the literature consulted. In the design phase BIM can increase the quality of the designs by displaying the degree of integration between the components, with the use of clash detection, and the checking of the construction processes. Generally, after being detected, a report can be produced that is sent to the respective professionals related to the systems to which the elements that are in collision belong, so that they can be evaluated and corrected, not only ahead of time but also with greater care and greater efficiency in communication between different professions.

In the production phase, it provides detailed information about the characteristics of the components, which allows greater coordination between the designer and the manufacturer. This leads to an efficient scheduling of the production process and reduces construction delays.

In the construction phase, BIM can help through the virtual reality model system to the careful management of the construction site for the assembly work of the components. Through this it is possible to have complete management of the work site, plan its layout and specifically indicate the areas for equipment, materials or facilities. In addition, each of the machinery, vehicles, road planning, operation routes and other management data of the workplace can be placed as an input of the BIM system to carry out simulations that allow to adequately see the operation problems, in order to optimize and adjust them on time. (Wang and Wang, 2021).

With the complete simulation of the construction of the buildings, it is possible to guide each phase of the prefabrication process. In addition, with the availability of tools that integrate schedules and costs into three-dimensional models, dynamic simulations for 4D (schedules) and 5D (costs) are possible. This allows detecting problems much more easily in the construction processes and schedules, in the feasibility of the projects and even allows a better management of safety in production and construction.

Currently, the application of BIM in prefabricated buildings is practiced almost entirely in the construction and production phases (Xiao and Bhola, 2022). BIM models, by providing rich geometry and semantic information related to resources, materials, and manufacturing information can be used to simulate different manufacturing strategies and identify the best prefabrication plan. In this context, research on the use of 3D printing technology suggests that this may be a solution to improve the flexibility and production of prefabrication (He et al., 2021).

In general, BIM offers many benefits in the construction phase, also related to the visualisation capacity that it provides through virtual animation. With the help of some softwares, it is possible to also get a good quality rendering effect, and the possibility of dynamic model display. With the material information associated with each component, images much closer to reality and animations can be produced. This method can help detect more efficiently and earlier technical problems, quality problems, or safety issues, and avoid them at the time of design and construction planning. (Wang and Wang, 2021).

During the maintenance phase, the BIM model updated with the information of the production stage can be used to coordinate the operation of the building teams, monitoring energy consumption, managing security and evacuation routes, etc. This makes it possible to locate elements or equipment that are not in good condition within the building in order to provide accurate and timely solutions, which in turn prevents accidents and improves efficiency in building maintenance.

Based on the researched literature on the benefits of integrating BIM in prefabrication, the following aspects could be highlighted:

- Prediction of completion time

- Schedule optimization

- Coordination of design and manufacturing models

- Reduction of manufacturing time

- Minimizing coordination errors

- Improving fabrication quality

-Supporting mass customisation

Figure 6 shows a framework for implementation of BIM in the prefabrication sector from a study carried out in Canada (Mahmoud et al., 2022). In this it is possible to see three main levels to be treated for its integration: Government, industry companies and team project. Referring the latter to the different phases in prefabrication projects and the main forms of implementation and advances that BIM could generate as a process. The government can have a role that promotes education in this type of processes, or generate standards and protocols for the BIM approach and also in the financial area, give support to companies that adopt this type of strategy or promoting BIM in public projects.

At present, the elaboration of the majority of prefabrication projects requires multidisciplinary collaboration for the design of the modules. In the traditional method, each of the professionals in charge of the design was expected to develop them independently, so constant consultation, modification, optimization and verification was necessary to minimize detail problems. Through the work environment provided by BIM, a large number of participants from different professions can collaborate in an integrated way on the design. "Each profession is responsible for the module editing of the profession, and multiple professions edit and modify the same 3D model, which can not only connect the design, production, construction, and decoration of prefabricated buildings in series"(Wang and Wang, 2021, pp. 06).

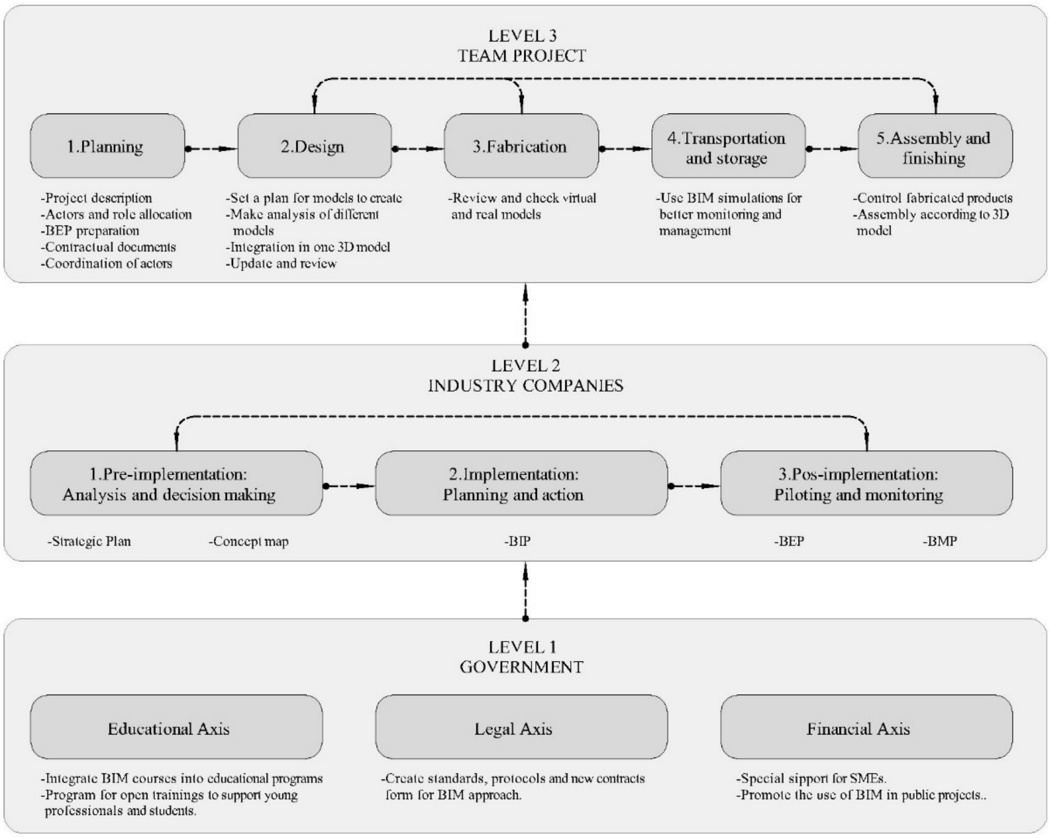

Figure 6 – Global BIM implementation framework for prefabrication industry. Adapted from (Mahmoud et al., 2022)

Figure 7 shows a methodology for the application of BIM in the design and manufacturing phases of modular elements, providing through its technology new approximations and possibilities for automation in design through Generative Design, or in manufacturing through 3D printing. It also allows to see the integration of different stakeholders that this technology makes possible from the initial design phases, an important factor for this industry. It becomes evident then that the BIM application can be in the design phases when the layout of the projects is planned, allowing that with the use of the standardized modules of a prefabrication system, optimization and Generative Design can be implemented. In the detailing process, it allows the geometric specification of the models and could also be used for a subsequent digital manufacturing of the elements.

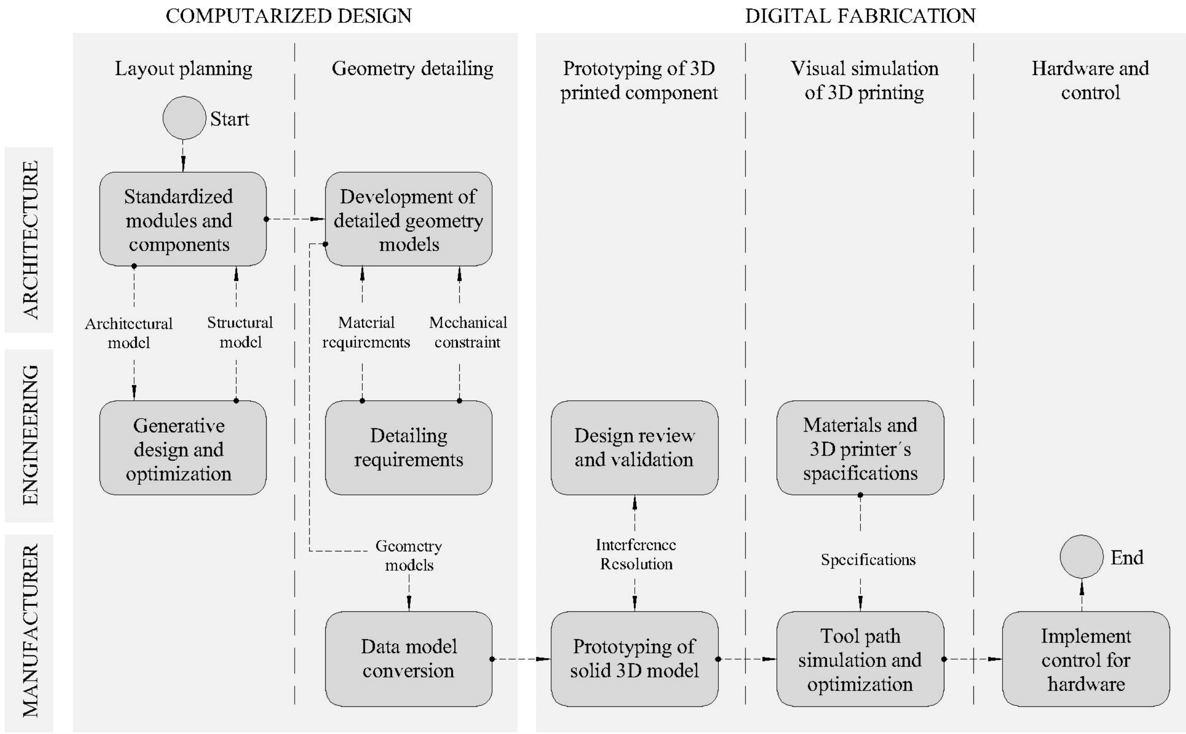

Figure 7 – Process map of BIM-enabled computerized design and fabrication of industrialised buildings.(He et al., 2021)

In this sense, BIM is a more suitable tool compared to traditional computer-aided design (CAD) when applied to industrial construction. One of the most important "features of BIM is the parametric design, where all the entities are present in component forms and each modification in the building design will be automatically reflected in other related parts".(Yuan et al., 2018, pp, 02). BIM environment provides the digital representation of the buildings with their geometry and semantic information, what allows the designers to identify the key parameters and the relationships between the different components of the systems (He et al., 2021). These predefined parametric relationships can be used to generate and optimize the building model in prefabrication systems.

As mentioned above DfMA is one of the mature principles of manufacturing in the industry and it is being introduced to the construction industry to improve current design processes in prefabricated buildings. The central objective of DfMA is to help designers to optimize the design of prefabricated buildings through the incorporation of professional knowledge and information from other phases within the design phase. This can be defined as "the design for easy of manufacture of the collection of the parts that will form the product and the design of the product for easy assembly" (Qi and Costin, 2023, pp. 02). In this way, one of the main approaches is the definition of the connections between the different components of the building, how to subdivide the whole building and how to assemble the parts.

In this regard, some research talks about DfMA oriented parametric design, which is the organic combination of DfMA and BIM (Yuan et al., 2018a). In this approach, one of the essential characteristics of BIM is taken, the use of parameters or variables to create or manipulate the design.

These parameters define aspects of the building and its components, such as size, shape, position and orientation, and are used in a parametric design, to establish relationships between the elements and their attributes through algorithms and rules.

With the help of the parametric methods used by BIM, a greater emphasis can be placed on including information from the manufacturing and assembly phases in the design stage. To this end, new approaches have been developed that also seek to take advantage of the characteristics of modular systems (they have more defined parameters and relationships than in traditional construction methods) with the aim of improving productivity through automation. This, in the design stage, gives opportunity for explorations in Generative Design.

Figure 8 shows an architectural design team oriented towards DfMA in which, compared to traditional design teams, it adds Split designer and assembly technicians. The architectural design firm takes information from the collaboration of the other two parties and develops the construction model. The Split Designer associated with the prefabricated-component party is in charge of subdividing the design of the building into components, so that they can be modular and prefabricated.

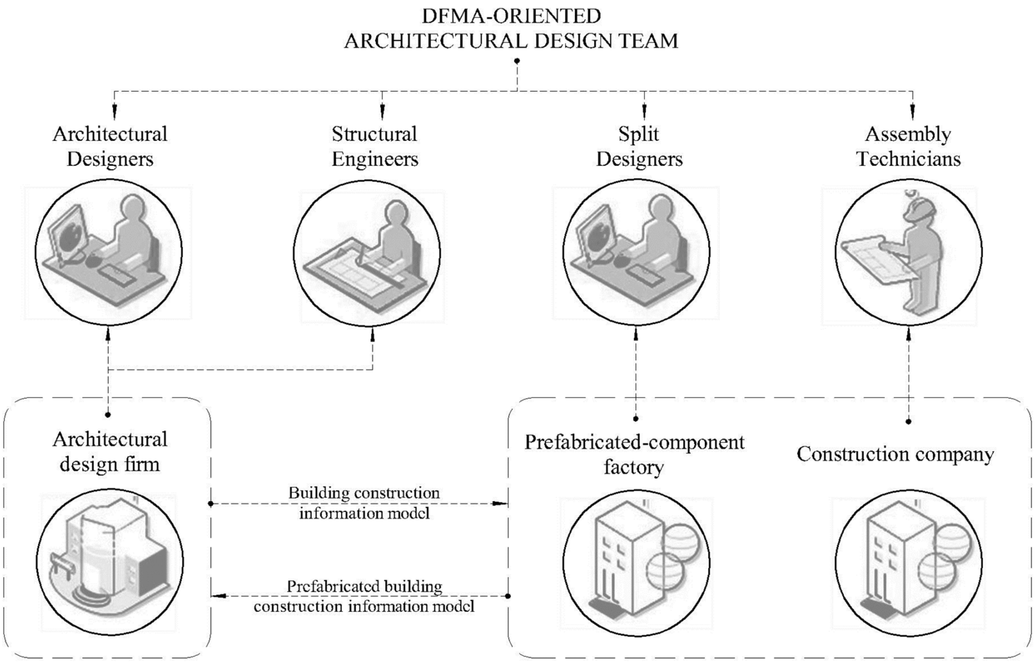

Figure 8– DFMA-oriented architectural design team (Yuan et al., 2018b)

2.3. Mass Customisation and Modularity

As has been commented with the reviewed literature, industrialised construction, for its development, has borrowed from the manufacturing industry an approach in the DfMA-based design process, in order to take into account, the manufacturing and assembly stages from the project conception stage. However, there is still a long way to learn for designers and planners, since "traditional architecture design has held stereotypical views of modular and volumetric buildings as dull, repetitive and unreliable" (Cao et al., 2021, pp. 02). This has caused that its adoption and implementation still have obstacles, especially in relation to design.

Taking this frame of reference, industrialised construction has opted for a strategy based on mass customisation. With the objective of providing customised products at the same price, with the same quality and in the same times as the mass production industry, this approach opts to try to combine design flexibility with the benefits that mass-made products make possible. For this reason, standardization is one of the prerequisites for mass customisation, where prefabricated construction can also serve as a support for this approach in the construction industry. (Bianconi et al., 2019).

Mass customisation then seeks to maintain the same objectives of mass production, such as economies of scales, but in addition to this, through modularization theories, product family architecture, and manufacturing systems that can be reconfigurable, it extends these benefits. towards greater flexibility.

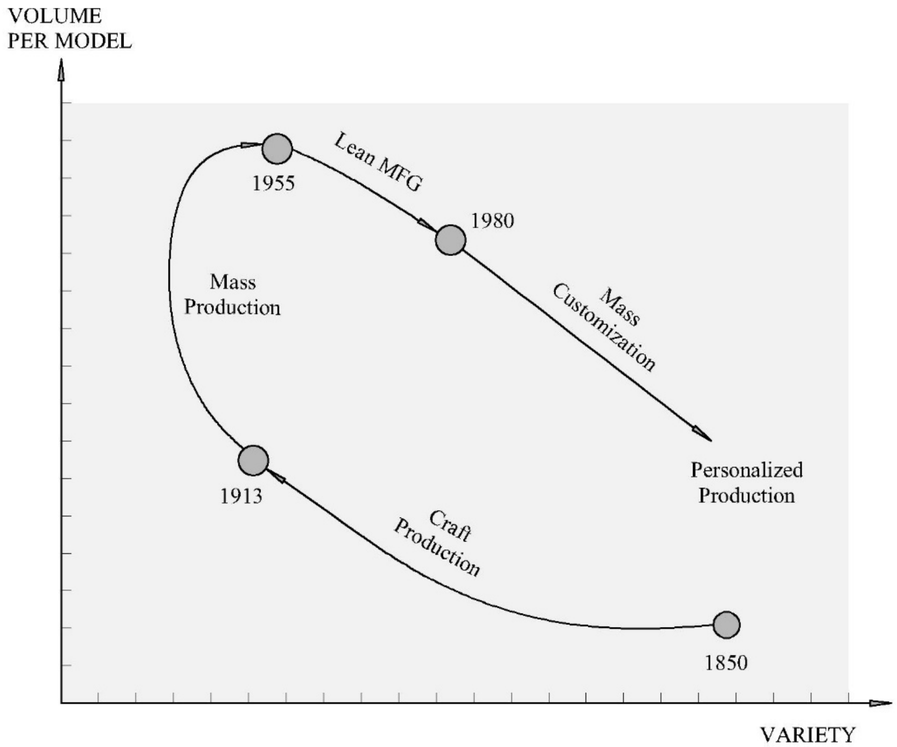

Figure 9– Volume-variety relationship in types of manufacturing systems (Hu, 2013a)

In this search for productivity and flexibility it can be dimensioned three large manufacturing paradigms that have evolved throughout history, as illustrated in Figure 9 comparing volume and variety of products, until ending with personalized production. Thus, the greater the customisation, the tendency is for a decrease in the volume of production, since modularization is not viable.

Departing from craft production, the mass production system reached its peak after the Second World War. It began with the introduction of the assembly line by Henry Ford and it was in this context that due to the high demand for products, this type of system characterised by interchangeability, moving assembly lines, and scientific management was generated(Hu, 2013b).

- Interchangeability: parts are made in bulk to a specific standard which allows swapping them.
- Moving assembly line: Instead of the workers moving from product to product for the fabrication, it is the products that move to groups of workers that make specific task repeatedly.

- Division of labor: Specialization of the task of the workers, into more granularity than before.
- Scientific management: Introduction of time studies, work training and separation of workers from management.

Although the main objective of mass production is to achieve greater productivity, in this system the manufacturers design the products, which are then brought to the consumers without them having a greater participation in the process. Over time, the demand for product variety grew and gave rise to mass customisation as a new manufacturing paradigm. “Through this, an "I designed myself" effect is achieved, where a personal attachment to the final product design makes the customer significantly willing to pay more for the product, for it to be customised”. (Larsen et al., 2019, pp. 02)

However, to give customers the opportunity for flexibility and individual customisation, one of the pillars that are considered as a base is modularization. Through the decomposition of complex systems into modules or small parts, designers are given the opportunity to have a higher level of variety in products, which in turn share certain characteristics (Jose and Tollenaere, 2005). In this way, although mass customisation allows the adjustment of the products in an individualized way, this process is limited to the predefined structure, which in comparison to mass production, still has great advantages in terms of flexibility.

Thus, modularization allows part of the product to be manufactured in volume as standard parts with the opportunity to have distinctiveness through modification of the modules themselves or combinations between them. The modules that are used can be made with mass production techniques, thus achieving cost reduction, greater productivity, and greater quality control, associated with this type of system.(Duray et al., 2000).

According to Mintzberg and Lampel (1996) a customised product must be designed according to the customer's specifications. So, identifying the initial point of customer involvement is critical in determining the degree of customisation. Taking as reference the production process in four stages: design, fabrication, assembly and use, if the customer's preferences are included in the first stage of design, the product can be highly customised. On the contrary, if its involvement is present only in the final stages of the process, the degree of customisation will not be very high.

Thus, it classifies the customisation process in three ways that it can occur, according to the stage of the product cycle in which it occurs and the degree of uniqueness of the product:

- Pure customisation: Products are designed and manufactured from scratch by each customer individually. This is included in the entire cycle, design, manufacturing, assembly and delivery, thus providing a product with high customisation.
- Tailored customisation: It is based on a basic initial design that is later modified to meet the requirements of a specific client. This is taken into account in the manufacturing phase, in which already established standard products are modified.
- Standardized customisation: In this, with the use of a predetermined set of standard elements, the final product is simply assembled. The customer becomes part of the process only in the assembly and delivery phase, and does so through the selection of certain standard options from a list.

The development of mass customisation is possible through concepts and technologies now characteristic of these systems. According to Hu (2013), they could be summarized in three main components:

- Product Family Architecture: Look for the manufacturer to develop a strategy in which certain functional modules are shared while others are provided with several variants, so that the assembly combination will have a high variety in the final products. The customer then chooses the variant module combination to be assembled.
- Reconfigurable Manufacturing System: Systems are designed in such a way that they can respond to changes in the market, in its structure and control, in order to adequately adjust its productivity and functionality.
- Delaying differentiation: It seeks to delay the point at which products take on unique characteristics, and thus manage the high variety in manufacturing systems. This reduces costs and improves the effectiveness of the system.

The customisation present in the manufacture products can have different levels that vary depending on the degree of flexibility in the design and the amount of manufacturing productivity of the elements. Thus, different strategies can be found among which, according to Thyesen and Hansen (2001), (Figure 10), Mass Customisation aims at having a good level of flexibility in the products and achieving a high quantity of product demand. This means that new products and processes must be implemented to achieve even greater productivity.

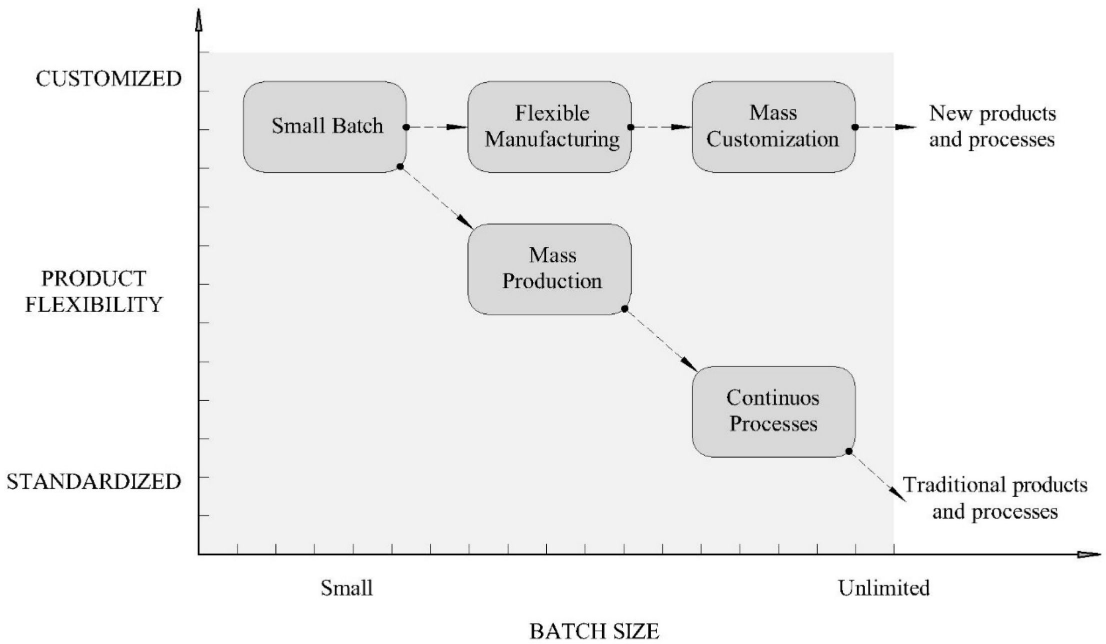

Figure 10– Strategies based on the quantity of product demand and level of customisation (Thysenn and Hansen, 2001)

To do this, as mentioned above, modularity can facilitate the increase in product features available and at the same time reduce costs. Therefore, for a good implementation of mass customisation, an effective use of modular product design is required. This concept can take several forms, and according to Urich and Tung (1991) it has been classified into several typologies:

- Component sharing modularity: Common components used in the design of a product. Products are designed around a basic unit of common components.
- Cut to fit modularity: The dimensions of a module are altered before combining it with others. Used when products have unique dimensions (length, width, height).
- Bus modularity: Possibility of adding a module to an existing series, when one or more modules are added to an existing base.
- Component swapping modularity: Ability to switch between options on a standard product. Modules are selected from a list of options and then added to a base product.
- Mix modularity: Similar to component swapping, only when modules are combined, they lose their unique identities.
- sectional modularity: Similar to component swapping, only it focuses on arranging the modules in a unique pattern.

Figure 11 illustrates the typologies of modularity in relation to the different levels of customisation and the degree of customer involvement in the production cycle. Thus, the more involved clients are from the design phases, the components tend to be original designs, and when they are only involved in final phases, the components tend to be standardized. This means that certain types of modularity are more or less suitable depending on the level of customisation and customer involvement.

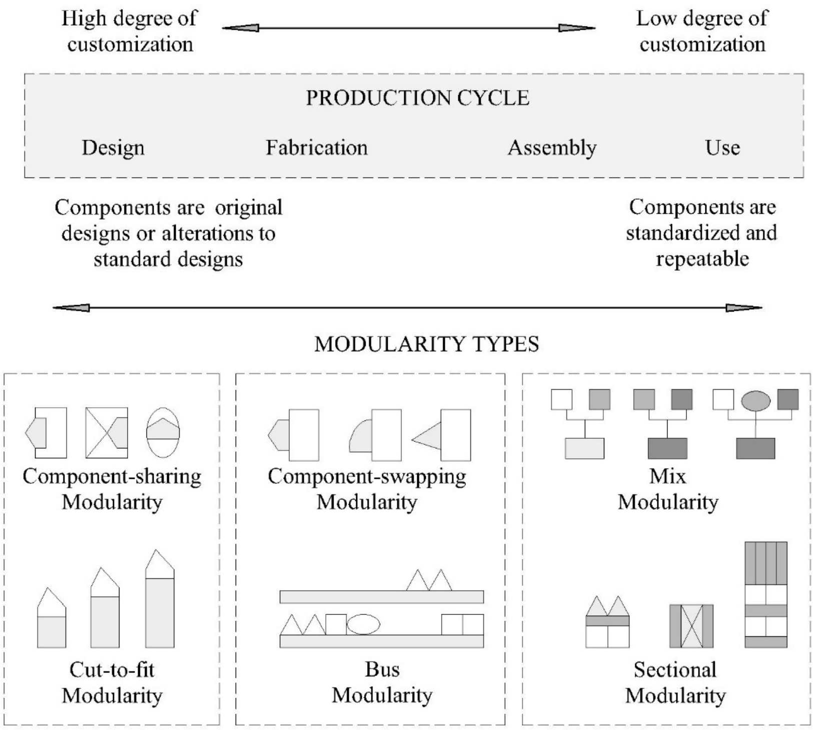

Figure 11– Customers involvement and modularity in the production cycle (Duray et al., 2000) **(Pine et al, 1993)**

2.4. Configurator´s overview

With the use of modularization in mass customisation, the variability of the products can be increased, however, “by increasing the customisation rate, the complexity of design and manufacturing grows exponentially, thus also increasing the complexity of the processes. To handle this complexity a configuration system is recommended” (Farr et al., 2014, pp 02), or a variety management strategy, at product and process levels. Among the strategies that can be managed at the product level according to Blecker and Abdelkafi (2006) are component commonality, product modularity and platforms.

In order to manage complexity and variety it is possible the use of platforms through module-based design or scale-based design. According to Simpson (2003), these can be defined as a collection of common elements, especially related to core technologies, which are implemented across a range of products, or a collection of assets (components, processes, knowledge, people and relationships), that are shared by a set of products.

It is in this sense that “the emergence of BIM as a virtual platform has been a major breakthrough with outstanding implications to facilitate customer-centric, object-oriented, just in time, made-to-order, build-to order, and lean approaches, in design and production in the prefabrication industry” (Farr et al., 2014, pp. 02). In order to achieve more customization, a firm must have the appropriate technology, the appropriate skilled people, or more likely the right mix of technology and specialized people. (Pine et al., 1993)

With the use of new technologies that have been developed, the implementation of mass customisation in the construction industry can be facilitated. Thus, BIM, according to Far (2014), can provide a great benefit mainly at three systemic levels:

- As a platform: It can offer families of components, where variations or alterations can be easily and quickly placed, which is one of the objectives of mass customisation.
- As a tool: It allows the fluid sharing of the families of components, between the different stages of construction, either from the design point to the assembly stage or the other way round. What also allows to adequately measure the implications of the alterations to a great level of detail.
- As an environment: Covers in a general way all the activities of the construction cycle and allows collaborative work processes between all the professionals related to them.

An example of product platforms, which first started in the manufacturing industry and is now being used in many more areas, are the so-called product configurators. This emerging technology seeks to support the objectives that are intended to be achieved with mass customisation, enabling flexibility in design that adjusts both to customer preferences and to the productivity and capabilities of manufacturers (Veenstra et al., 2006).

Product configurators have many definitions in the researched manufacturing literature:

- A platform containing a set of common modular components, or parts (Kit-of-parts) from which a stream of derived products can be efficiently developed and launched. (Meyer and Marc, 1997)
- An expert system that supports the user in the creation of product specifications, by restricting how many different components and various properties can be combined. (Haug et al, 2007)

- A decision support system, which automates the combination of kits-of-parts into efficient modules for production under certain rule sets, while allowing rapid generation of product variability to meet desired product characteristics for the client. (Cao et al., 2021)
- A software with logical capacity that allows the definition of all the possible options of a product and the variation in combinations, with a minimum of data as input. (Bourke et al, 2004)

According to Cao (2021, pp. 03), the main characteristics of product configurators could be defined as: "a kits-of-parts system that can be reused, intelligence driven by embedded expert knowledge, and high automatization capacity achieved through new technologies, such as APIs".

Creating and maintaining a product configurator can be described as consisting mainly of 6 processes (Figure 12). In the elicitation process, the knowledge engineer or designer gathers all the information related to the product for which the configurator is being developed. This information can be of various types, both verbal and written documentation, diagrams, formulas, sketches, etc.

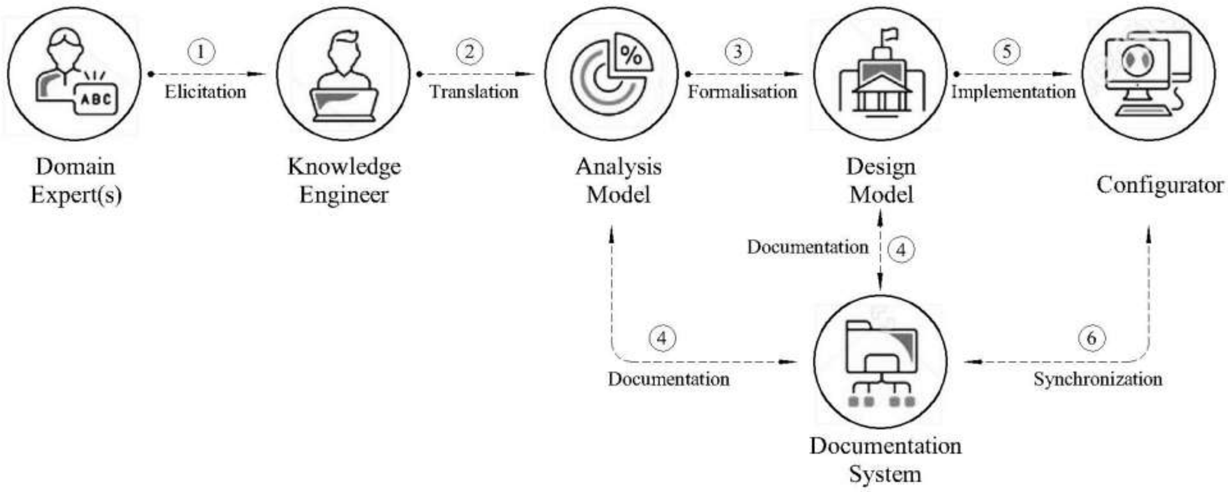

Figure 12– Process of creating a product configurator (Haug et al., 2012)

In the second process (translation) all the information collected is synthesized and recorded in analysis models in order to create a basis for discussing the information that will be included in the configurator and the one that will not. Depending on the type of information collected, the diagrams should also be appropriate for correct analysis and efficient communication with other experts. In addition, new information can be generated during this process, which was not taken into account at the beginning.

In the formalization process, the analysis models developed are adapted in such a way that their format is more in line with the implementation sought. These models may be in a rendering language system that is not compatible with the one used by the configurator's modeling environment, so they will need to be reconfigured. At this stage, aspects such as integration with other systems or the way to manage user interfaces must also be defined.

In the fourth process, referring to documentation, all the information that was collected and analysed during the analysis and design phases must be documented, in the event that other people, different from those who generated the information, must use or evaluate it. Since other people involved may not have the knowledge to understand the model environment of the configurator, it is necessary to create a documentation with a representation system that allows it.

In the next step, implementation, the models that have been designed are implemented in the chosen software, or in the programming language. Also, during this process new changes can arise in the model and new information can be generated.

Finally, in order to ensure the update of the generated model and the documentation, a synchronization process is necessary. So, when changes occur in the configurator and its development, the documentation must be updated to have the knowledge base implemented.

The implementation of a product platform, such as a configurator, is currently used as a technological tool to achieve mass customisation in the manufacturing industry. The products that are generated in this industry (buildings) not only handle information at the product level, but also at the project level. Thus, information at the product level could include design dimensions, precast modules, technical attributes, or production processes, while information at the project level would generally include site planning, site build elements, site properties, and on-site activities. (Ramaji and Memari, 2016)

For this reason, Cao and Hall (2019) suggest that a configurator suitable for the construction industry must have the ability to manage information at both product and project levels. With the use of configurator and BIM, there are benefits such as the presentation of different solutions for configurations, the possibility of multiple design and manufacturing options or various construction programming options. The use of the configurators in the construction industry can be summarized in aspects related to products, people or processes as shown in Table 1.

Table 1 – Benefits of configurators in construction industry (Cao and Hall, 2019)

	Benefits of configurators
Product	- Increases flexibility
	- Ensures feasibility.
People	- Minimizes the need for manual involvement
	- Smooths the learning curve on the use of BIM
Process	- Reduces time and costs both in design and production
	- Promotes efficiency in coordination
	- Increases efficiency in the development of construction documents
	- Preserves and reuses the knowledge of the options generated
	- More accurate planning

Within the researched literature, a couple of studies carried out by Cao and Hall (2019) and Cao and Bucher (2021) were taken as a reference, in which, after analyzing literature related to the application of configurators in the construction industry, specifically in the generation of mass-customised products, and from reviewing some web-based configurator tools applied to the construction house industry, they developed three approaches regarding the use of configurators:

1. An approach that addresses of the use of configurators into three strategic typologies.
2. Definition of the requirements that the stakeholders have of the configurators for each of the typologies.

Evaluation of the configurators from their technical approach, using a framework based on three tier architecture (presentation tier, application tier and data tier).

In the first place, with respect to the three strategic typologies developed, the following questions related to the use of configurators were raised:

- Who are the main users?
- When are these configurators used in the project process?
- How is the configurator used and what are the most important activities?
- What are the typical products that you want to achieve?
- What are the expected outputs that the configurator should generate?

Based on these questions, the three typologies were formulated. In the first typology they classified those configurators used in the planning phase of the projects. Real estate developers, landscape planners and architects are typically involved at this stage. The main objective of the configurators at this stage is to generate various development plans, including location plans and floor plans, assist investment decisions.

Typically, the type of representation is not very detailed in the form of plan graphics. However, according to Cao and Hall (2019), compared to traditional design methods, the use of configurators allows closer interaction with customers, who can interactively participate in the design by choosing from the given options and configurations, and also with the use of algorithms, the most optimal options can be identified using the rules embedded in the configuration. Finally, this information could be converted by the configurators into Building Information models to continue with the design process by professionals.

A second typology groups those configurators that are used in the design phase of the project and in which architects, engineers and fabricators mainly participate. In this section, the products that are sought to be obtained are related to the prefabrication modules, forms of assembly and definition of the parts. In this type of configurators, users define rules and constraints that can be saved for future projects. After these rules and limits are in the system the design parameters are added and building information models can be automatically generated, along with data and documentation, product specifications, drawings and bill of materials and quantities.

Finally, in the third typology those configurators that focus on supporting the production phase of construction projects are classified. According to Cao and Bucher (2021), this typology is less studied and achieved than the previous two, and it is less applied in commercial configurators. It is closely related to the adoption of DfMA principles, in which engineers and manufacturers put them into practice in the detailed design phase before the manufacturing process. generally, the configurator is used to optimize the components of prefabricated elements, grouping components with similar geometry and assigning standards with higher building performance to these modules, in order to increase the degree of standardization.

Expected outputs from this type of configurator include 3D building information models along with related manufacturing data and documentation, permit drawings, and quantity and material charts, where planimetry and drawing creation receives the most attention.

Table 2 – Typologies of configurators in the construction industry. (Cao et al., 2021)

	Typology 1	**Typology 2**	**Typology 3**
Who	Real State Developers Landscape Planners Architects	Architects Engineers Fabricators	Engineers Fabricators
When	Concept Design Stage Before Creating BIMs	Design Stage When Creating BIMs	Detailed Design Stage After Creating BIMs
How	1. Codify configuration logic. 2. Generate configuration by low-level representations. 3. Convert the representations to BIMs in CAD applications.	1. Codify configuration logic. 2. Enter configuration parameters into the UI of a plugin. 3. Generate BIMs as well as documents automatically in CAD applications.	1. Codify configuration logic. 2. Perform component optimization on the developed BIMs. 3. Cluster components with similar sizes and apply standard modules with higher performance.
Target	Site Plan Floor Plan	Prefabricated elements	Prefabricated elements
output	Sales models	3D Parametric models	Standard models

One of the problems that is found through the study of configurators is the lack of an example that tries to cover all the phases, since in general they focus on meeting specific needs, but there is still a marked fragmentation in terms of the flow of information and development throughout the entire project cycle.

After defining these three types of configurators according to the project phase in which they are focused, they analysed the main requirements of the users in relation to the main stakeholders, be they clients, designers, manufacturers or assemblers. Table 3 shows these requirements and the type of configurators that tend to meet them.

From this information, it can be deduced that the configurators classified within typology 2 tend to satisfy the majority of user requirements, since these are mainly focused on automating the work of specialists, which means a large number of activities in the construction industry.

Finally, they proposed the analysis of the configurators, based on three tier architecture, which is commonly implemented in the development of web applications. This framework includes the presentation tier, the application tier, and the data tier (Figure 13).

Table 3 – Users requirements for strategic typologies of configurators (Cao and Hall, 2019)

	USER REQUIREMENTS	TYPOLOGY 1	TYPOLOGY 2	TYPOLOGY 3
Clients	Visualise design options	X	X	X
	Select variant types of elements	X	X	
	output types and cost estimates	X		X
Designers	Perform parametric design	X	X	X
	Perform part´s connection		X	
	Perform structural analysis		X	X
	Perform clash detection		X	
	Perform component optimization			X
	Input building regulations	X	X	X
	Input product constraints	X	X	X
	output 3D parametric models	X	X	
	output engineering drawings		X	
Manufacturers	output production drawings		X	
	output bill of materials		X	
	output NC operational codes		X	
Assemblers	output schedules			
	output assembly instructions		X	
	output site layout			

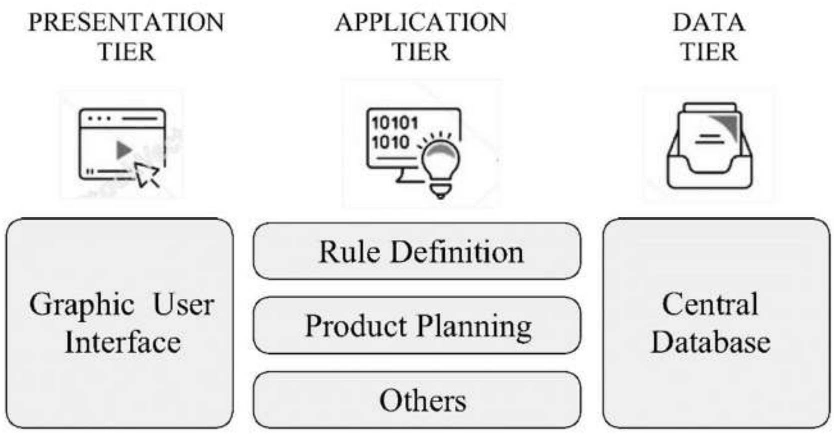

Figure 13– Three tier architecture of a configurator (Cao and Hall, 2019)

The presentation tier refers to the graphical user interface and allows users to participate in the design process. It receives the input from the user and shows the various views of the model and related information. Through API request the presentation tier communicates with the application tier to carry out the functionalities provided by the configurator. Through this, different ways are allowed for non-professionals and professionals to work collaboratively and the main product specification strategies are usually defined as:

- Select variant
- Configure to order
- Modify to order
- Engineering to order

And as for the design activities used in the configurators, four were defined that typically occur:

- Selecting standard elements
- Editing design parameters
- Arranging spatial layouts
- Defining configuration rules

The application tier is in charge of processing the main features of the configurator, where each of these features can be reused as a component. Each one of these components can be a programming code or an application, which are based on the multiple customisation combinations required by the users. For example, they cite the rule definition component, which transfers the knowledge of professionals in computer operable language, and the product planning component, which guides professionals in building the product architecture. These components can be built through API functions or programming languages.

The data tier stores information managed in the configurators and is connected to the application tier. Thus, components such as rule definition or product planning store and take information from it, which maintains a single source of truth of the information. However, few configurators separate their database from various applications, which means that at the time of updating in one place, it is not reflected in others, thus generating repetitive information exchange and information inconsistency. (Cao and Hall, 2019).

2.5. Comparative analysis of configurators and tools

After having investigated the current literature on BIM applied to the prefabrication industry, it was developed a study on important concepts in relation to its implementation, such as modularization, mass customisation and the use of configurators as tools that, allow flexibility, productivity and a greater flow of information throughout the different phases of the project life cycle. It was also found that these configurators allow the exchange of information between the various stakeholders in a more productive and simple way by seeking to be used even by non-professionals in the construction area.

Given then the importance of these tools associated with BIM, it was decided to carry out a study of some of the platforms used for this purpose. They were selected based on the functionalities they provide in terms of automation, information generation and interoperability, in addition to the level of use they present in the market and their availability to be used at least as a trial version. It began with some of those cited and studied by Brandão (2022) and others were introduced, which were proposed and discussed during the development of the dissertation. The purpose of this study was to understand the main functionalities and opportunities that the platforms and tools offer, as well as the gaps that still need to be solved, in order to create an appropriate methodology, using some of these tools applied to the case study proposed in the dissertation.

The platforms/tools selected were the following:

- ShapeDiver:
- Hypar
- TestFit
- PlanFinder
- Speckle
- Rhino Compute

For this study of configurators, it was taken as a reference the methodology used by Cao and Hall (2019) in their research on configurators used in the industrialised construction industry. They first define three types of configurators, mainly based on the project stage that they are implemented and were taken as a starting point to analyze the platforms. The configurator platforms were also compared with the two other topics covered in the reference methodology, these being: the main requirements of the different users of the configurators and the analysis of the technical approach that is implemented in each of the platforms (based on three-tier architecture).

In relation to the technical approach of the platforms and their characteristics of use, the comparison criteria used en la investigacion de Hall and Cao (2019) was taken and the comparison criteria by Brandão in his study of configurator platforms in mass customisation construction (2022). The latter taken as a reference due to the progress made specifically in those technical aspects of the configurators. These are:

- Development tools
- End-users
- Model
- Service capabilities
- Interoperability
- User interaction
- Wesite integration
- Input types
- data types
- output types
- File types outputs
- File types input

The first platform studied was ShapeDiver (Figure 14), a web-based tool that gives users the ability to create, customize, and share 3D parametric models. Through a web browser, it offers an infrastructure and tools to create interactive application models, allowing them to be manipulated in real time. This platform is designed to work with 3D modeling software such as Rhino 3D and Grasshopper, allowing users to create models using these tools and then upload them in Grasshopper format to the platform.

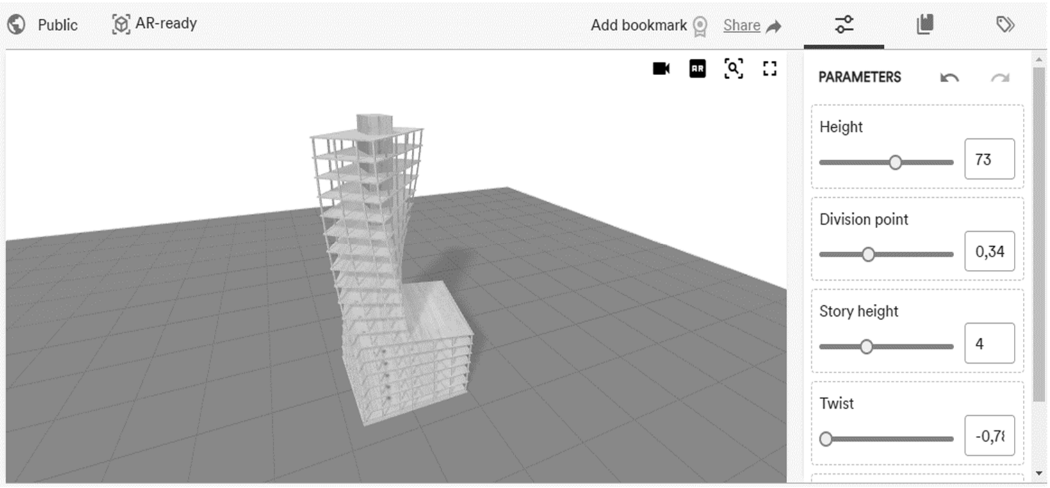

Figure 14- User Interface of ShapeDiver (model example of the platform)

When the models are uploaded, through the web interface offered, they can be configured and customised by users without the need for any other complementary software, which allows these models to be easily shared among different collaborators and clients, in addition to explore different design options, make changes in real time and visualise the final results, to be later shared or exported.

The parameters for the interactive modification of the models are previously established by the designer, through the use of the Grasshopper API. To develop parametric models for ShapeDiver, it is necessary to download and install a ShapeDiver plugin in this software, which contains the components related to the inputs and outputs to create the visual script, and that are then recognised by the platform once the file has been loaded. These parameters are read by the platform on uploading the Grasshopper model and displayed on the platform, together with the generated model. The generated model can be modified online. The configurator can be shared or encapsulated in another website. If the Grasshopper model author so chooses, the generated result may be downloaded or exported via URL or Grasshopper format.

The next platform investigated was Hypar (Figure 15). This is a cloud platform that provides an infrastructure with tools for three-dimensional modeling of buildings and through the use of algorithms allows Generative Design solutions based on parameters established in the various functionalities it offers. This platform is self-contained and does not require the use of other applications to be used.

It offers the visualisation of the models together with the related analytical data, in real time, allowing non-programming designer or users to explore design variations. The results of this process are not very detailed, so its greatest exploration is found in the design conception stage. In addition, this platform contains a repository where algorithms created with C# or Grasshopper can be uploaded and shared. This library is open-source.

The basic elements with which this platform works are called functions, which are basically algorithms with specific functionalities, such as the generative creation of facades, or columns based on parameters that the user can modify. These functions are contained in the platform library and can be used in different orders with the objective of creating workflows, however some depend on others to be able to generate their functionality.

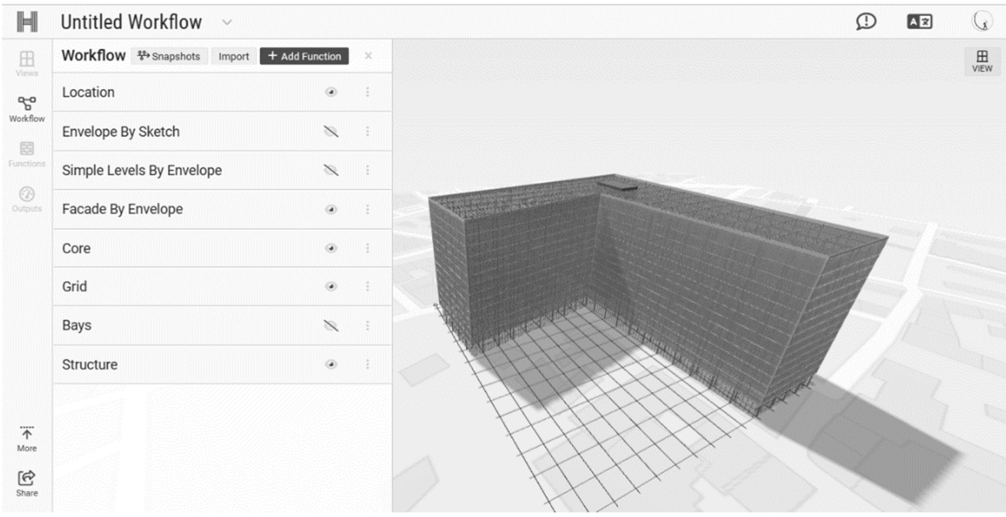

Figure 15- User Interface of Hypar (Functions and workflow)

Some workflows are already predefined in the platform, such as space planning, view analysis, or day light evaluation. However, it not only allows the creation of new workflows with the functions that it offers, but also gives the possibility of creating new functions with the use of C# or Grasshopper. These can also be related to those already existing on the platform, allowing greater dynamism in the exploration of functionalities. Finally, it should be noted that the platform gives the possibility of exporting the generated models in IFC or JSON formats, and also offers a plugin for Revit in order to allow interoperability with this software in a more dynamic way through JSON formats.

Testfit is other example of the platforms that can be found currently on the market (Figure 16), and is mainly focused on real state feasibility. This helps to do site planning for developers, architects and contractors, in order to maximize site potential, by offering a model generation infrastructure based on established options of building typologies.

For its use, it is necessary to download and install the application, which works through its connection to the platform's server via the Internet. This initially offers the selection of the project site and its perimeter. Then the user can select from six building typologies and continue developing the project with the different configurators grouped in each of these typologies. Thus, each of these has established a set of configurators associated with the elements that compose them, which give users the opportunity to have increasingly detailed selection parameters.

The model is generated in real time, as well as tabulations and development information, which allow control over aspects related to the feasibility of the project. Depending on the initial parameters set, it also generates different grouping or configuration options, which can be easily selected and evaluated. Although the final result is not a very detailed model, the information it provides on a general level about the buildings allows more objective decisions to be made in the design phases. It is worth mentioning that it also allows the possibility of exporting the models generated directly in the Revit API, through a plugin that gives the option of classifying the information that the user wants to import and the types of families that are assigned to the elements. Other export formats that it allows directly are SKP or DXF.

Figure 16- User Interface of Testfit (Building typologies and tabulations)

The fourth tool analysed was Plan Finder (Figure 17), which unlike the previous ones, is not a cloud platform but a plugin for CAD and BIM software. This allows the automatic creation of apartment models, using machine learning algorithms, with which it searches through a database of building plans and generates relevant options for the user according to the input that has been given.

For its use, it is then necessary to download the appropriate plugin from the platform, depending on the software in which it will be implemented, whether for Rhino, Revit or Grasshopper. Once installed, its use is not complex and displays an additional window with the options and parameters to choose from.

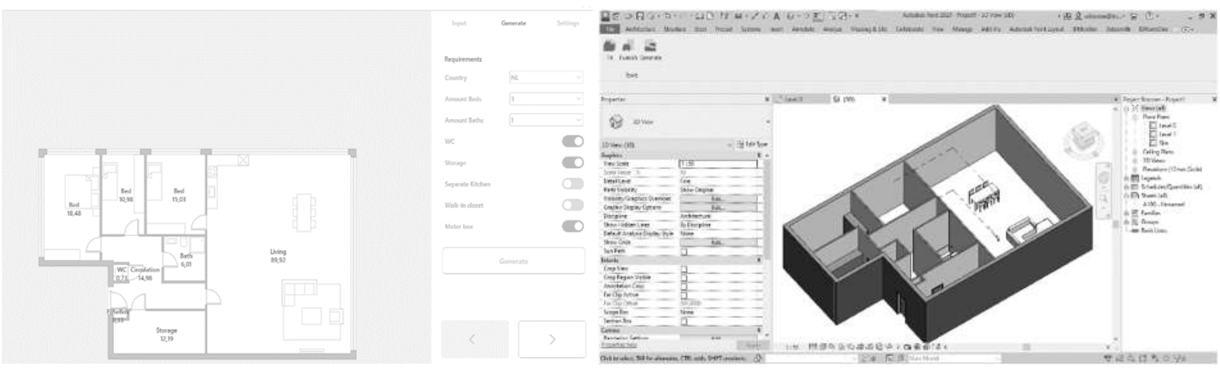

Figure 17-PlandFinder in Revit (User Interface and model)

It has three main functionalities: Generate, fit and furnish. The first functionality allows to generate floor plans simply by placing as input the outer boundary, the number of desired rooms and the location of the access to the apartment. The fit function also allows the generation of floor plans based on a perimeter set by the user, however the options that are given (based on a library of apartment floor plans) come close to but are not adjusted to the given perimeter. It is the user who decides whether to change the initial shape for the one recommended by the tool. Within this functionality it is also possible to create an individual library with previous projects, which makes the design process more agile. Finally, the function related to furnish, allows to automatically generate the furniture of the different spaces of the apartment, also giving different configuration options.

Another of the platforms currently used in the area of architecture, engineering and construction is Speckle (Figure 18), whose focus is on providing interoperability solutions between a large number of different software and applications. Its main objective is to address the challenge of data silos existing in the AEC industry, where information is generally fragmented and static within proprietary software formats. This platform then promotes the fluid transfer of data between various software tools, thus allowing interoperability and collaboration between the different stakeholders involved in the projects.

Speckle uses a client-server architecture, where the application used by the client can send and receive data to and from a central server, which has the functionality of storage and distribution of this data. In this way, it facilitates the real-time synchronization of changes in projects through the different interconnected applications, due to its ability to handle 3D models, BIM data and metadata, an aspect that is one of its key characteristics.

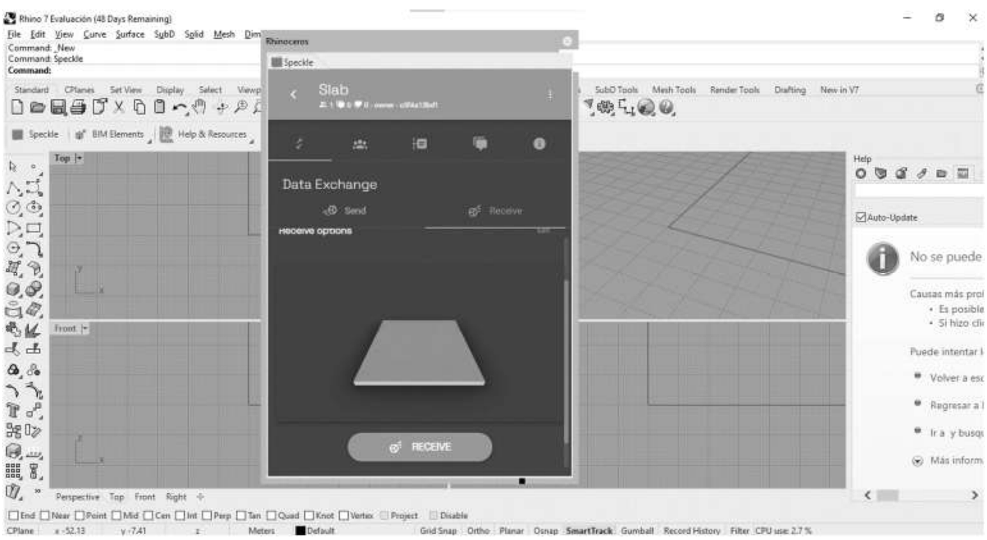

Figure 18-Speckle connector in Rhino (Receiving data from Revit)

For the exchange of information, the platform contains different plugins called connectors, which must be downloaded and installed in the software where the users want to implement it. When the information is ready to be shared, it is sent through the plugin in the software to the central server from where other clients can download the updates. This process can be easily automated through the platform, which allows the exchange of information in a fluid way, and also gives the possibility to keep track of changes and version of the files through a versioning system or even choose exactly the information to share and receive.

The last tool to be analysed was Rhino Compute (Figure 19), a cloud-based service that allows users to develop heavy computational tasks using cloud computing capabilities. This allows to run scripts made on Grasshopper and commands remotely on cloud servers, allowing the user to offload high-demanding computations to high-performant hardware on the cloud. In this way users can offload computationally intensive task such as complex geometry calculations, simulation or renderings, to the cloud.

Rhino Compute could be defined as a headless version of Rhino, where there is no user interface, but it is possible to do everything that Rhino does by using the cloud infrastructure. Users can access its computational capabilities through APIs, which allow developers to integrate Rhino Compute into their own applications, workflows or services. In this way, collaboration and distributed computing is facilitated, since multiple users can access the service simultaneously and share data and scripts.

To access the Rhino Compute server, the user must have a Rhino account and also have a compatible client application, such as Rhino, Grasshopper, or a custom application that can communicate with the Rhino Compute server using restful API. Once the connection with the server is established, the user can send the script or command created in the application via and API or web interface, so that the Rhino Compute server can then execute it on its own server hardware. The processed information is sent by the server to the user's computer where it can be viewed, analysed or further processed as needed.

Once the server is configured locally on the user's computer, it is possible to access the Rhino Compute functionalities through a plugin installed in the Rhino API, called Hops. Through the components offered by this plugin, it is possible to make clusters of Grasshopper scripts, which are automatically processed remotely by Rhino Compute.

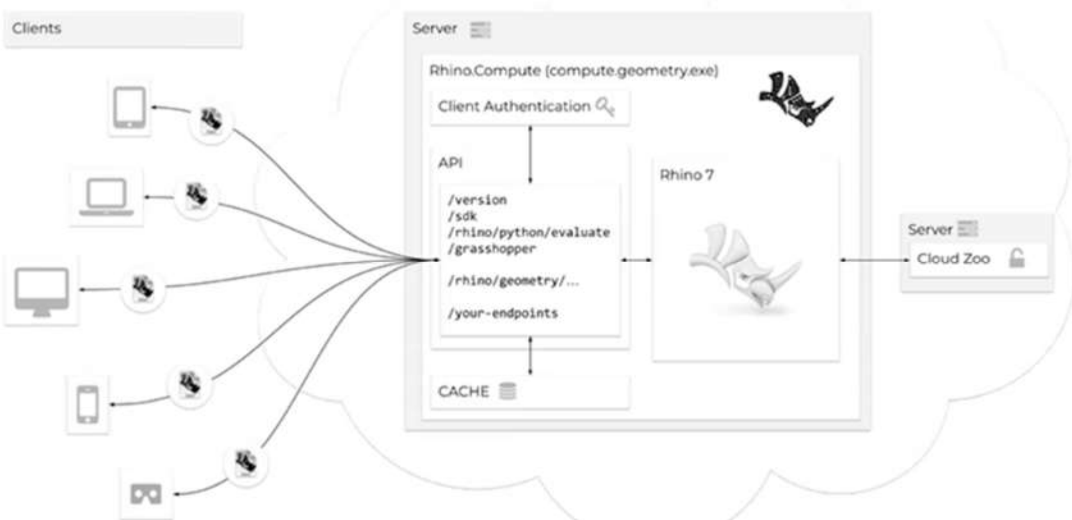

Figure 19-Rhino Compute workflow (Rhino developer guides)

Based on the study carried out on the previous 5 tools and/or platforms, the Table 4 was generated, firstly following the comparison criteria proposed by Cao and Hall (2019):

Table 4- Comparative analysis of tools according to typologies

Configurator /tool	Who	When	How	Target	output	Typology
SHAPEDIVER	Architects Clients	Planning And Design Stage	1. Prepare the Grasshopper file. 2. Upload the file to ShapeDiver. 3. Set up the model. 4. Share the model (Via URL)	(Generic platform)	Sales models	1
HYPAR	Architects Engineers	Planning and Design Stage	1. Define location. 2 Define the starting function to make the building. 3. Continue sketching with other functions, making a workflow 4. model is generated with default parameters.	Site plan Floor plan Prefab Elements	3D parametric models	2
SPECKLE	Architects Engineers	Planning and Design Stage	1. Configure connection between softwares (with plugins) 2. Automate workflows.	Site plan Floor plan Prefab Elements	3D parametric models	2
PLANFINDER	Architects Engineers	Planning and Design Stage	1. Install plugin in the software 2. Make the wall perimeter 3. Select point surrounded by walls. 4. Select facades and the entrance 5. Select among the generated options	Site plan Floor plan Prefab Elements	3D parametric models	2
TESTFIT	Architects Engineers	Planning and Design Stage	1. Download the application 2. Define location 3. Draw a site 4. Select a preset building. 5. Specify general parameters of the building	Site plan Floor plan	3D parametric models	2
RHINO COMPUTE	Architects Engineers	Planning, Design and production Stage	1. Connect to Rhino Compute 2. Send script in Grasshopper definition to Rhino Compute server via an API or web interface. 3. The Rhino Compute executes the script it on its own server hardware. 4. The server sends the results back to the user's computer.	(Generic Platform)	3D parametric models	3

The following comparative tables of the tools and/or platforms studied (Tables 5a and 5b), were developed taking as a reference the comparison criteria developed by Brandão (2022):

Table 5a- Comparative analysis of tools (technical approach)

Configurator /tool	Development tools	Use of programming language	End-users	model	Services / Capabilities	Interoperab.	UI interact.
SHAPEDIVER	Grasshopper	Grasshopper, Javascript, Python, C#, Java, Node.js	Designers and Non-Designers	SaaS	model hosting, compute, visualisation	Rhino GH support, 24 plugins and scripts (C#, VB and Python)	navigation, selection
HYPAR	Grasshopper / Visual Studio	C#, Python, Javascript, Typescript	Developers and Designers	SaaS	Design Development, model hosting, compute, visualisation	Rhino, Grasshopper, Revit (plugin), DXF	navigation, selection, drawing, delete
SPECKLE	Grasshopper / Dynamo / Visual Studio	Javascript (Node.js), Python, C#, Java, Ruby, Go, Rust	Developers and Designers	Open source	Design Development / Software Interoperability	Revit, Grasshopper, Dynamo, Rhino, Autocad, Sketchup, Excel, Archicad, Blender, Civil 3D, Tekla, Naviswork, (Other 14 software)	No
PLANFINDER	Grasshopper / Rhino / Revit	Javascript, Python, C++	Designers	SaaS	Design Development, compute, visualisation	No	navigation selection, drawing, delete
TESTFIT	Revit	Python, C#, Javascript, Typescript	Developers and Designers	SaaS	Design Development, compute, visualisation	Revit, Autocad (just one way)	navigation selection, drawing, delete
RHINO COMPUTE	Grasshopper / Rinho.Inside	C#, Python, Javascript, Typescript, Java	Developers and Designers	SaaS	Compute	Rhino, Grasshopper	No

Table 5b- Comparative analysis of tools (technical approach)

Configurator /tool	How to use	Website Integration	input types	data types	output types	file types output	file types input
SHAPEDIVER	Cloud application plugin for Grasshopper (set up file)	embedding / API	geometry, text, image, sliders, toggles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text, image	3Dm, stl, dxf, dwg, step, obj, txt, csv, gh, gcode, json, xml, ifc, jpeg, png, bmp, tiff, gif, pdf	txt, csv, json, xml, jpeg, gif, png, bmp, tiff, dxf, obj
HYPAR	Cloud platform plugin for Revit (converters are necessary)	embedding / API	geometry, text, image, sliders, toggles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text, image	png, pdf, dxf, 3Dm, json, gitf, ifc	dxf, 3Dm, json, jpg, jpeg, png, pdf, gh, xlsx, cs
SPECKLE	plugin for each software	embedding / API	geometry, text, image, dropdowns, toggles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text, image	Speckle neutral format	Speckle neutral format
PLANFINDER	plugin for Rhino, Revit and Grasshopper	No	geometry, text, sliders, toggles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text	3Dm, gh, rvt	3Dm, gh, rvt
TESTFIT	Application on pc plugin for Revit	embedding / API	geometry, text, sliders, toggles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text, image	Csv (tabular data), dxf(selected floot plan), gltf(3D modelview), pdf(foolr plans), skp	rsd (TestFit format)
RHINO COMPUTE	Cloud server	embedding / API	geometry, text, image, sliders, toggles, value lists, color	booleans, numbers, strings, points, surfaces, curves, BREPs and meshes	geometry, text, image	3Dm, obj, fbx, stl, dwg, dxf, pdf, png, jpg, csv, json, xyz, las	3Dm, gh, dwg, obj, skp, pdf, rvt(with plugin)

Among the tools and/or platforms analysed, it was found that ShapeDiver, compared to the others, is the one with the greatest accessibility by non-professional users, since its infrastructure allows the visualisation and modification of the parameters previously established by designers, simply and clearly. It also gives the possibility of sharing the modified models through URL, which makes it a fairly flexible option in terms of the flow of information between the different stakeholders.

The other tools require a higher level of knowledge on the part of the users, which is why they are aimed more at architects or engineers. For example, Hypar and Testfit, which could be classified within typology 2 of configurators (planning and design stage), allow a greater complexity of the user interface interaction, since they not only give the option of browsing, selecting and modifying parameters as in ShapeDiver, but they also allow you to draw and delete elements. The workflow of these two platforms is more elaborate and starts initially from the selection and definition of the site for the projects. However, from then on, Testfit, which focuses more on feasibility characteristics, tends to be more static in terms of the possibilities it offers, since it starts from certain pre-established typologies and the possibility of creating new ones is not very clear.

In this sense, Hypar, with the use of functions and workflows, allows greater dynamism in the configuration of the project design process, since it allows customizing the workflows and also creating new functions that can be added to those already existing in the platform. However, it does not have the display of tabulation and feasibility information present in Testfit.

Regarding interoperability with BIM software in these first three tools, ShapeDiver allows a great possibility of interaction with Rhino and Grasshopper as well as accepting a large number of plugins. In Hypar it is also possible to implement functions through Grasshopper and gives the possibility to interact bidirectionally with Revit through the plugin it offers, making it more versatile in its use compared to Testfit, which only allows export to Revit in one way and this through its own format that must be recognised with the use of a plug in.

Plan Finder is a great example of automation in the design phase, and can be classified within the second typology of configurators. It has the possibility of being used in various software (Rhino, Grasshopper or Revit), however its functionality is focused on apartment projects and their interior layout. This makes it a closed option for the exploration of the dissertation regarding the use of these tools in the area of prefabrication and the possibility of applying it to the case study. Tools like PlanFinder, which are plugins for a specific software, may be connected with other tools through platforms such as Speckle, which unlike all the previous ones is not focused on the automation of three-dimensional models but on the automation of workflows and interoperability, which gives great possibilities for the configuration of work methodologies.

Finally, Rhino Compute, which does not have its own user interface, and which offers the possibility of cloud-based processing of information, is in comparison to ShapeDiver, Hypar and Test fit, a much more flexible option in terms of creating a methodology, that can be applied to a specific case study. Since it has all the capabilities of Rhino in the calculation and creation of geometries and data, it allows customizing the configurator in a specific way for the requirements that are sought to be achieved. However, it depends on being properly integrated into a methodology that provides the possibility of viewing, creating scripts, modifying parameters and exporting information, as in the three aforementioned tools.

Table 6 contains the main characteristics and difficulties found in the tools and/or platforms studied, from the perspective of their integration in a methodology that can be applied in the creation of a configurator for the prefabrication industry in construction. The PlanFinder tool was excluded because it is a plugin with quite specific functionalities to be used in the dissertation methodology.

Table 6- Pro´s and con´s of the tools and/or platforms analysed

Configurator /tool	Pro´s	Con´s
SHAPEDIVER	Easy to use for non-professionals Possibility of creating own functions Open Source	Limited to its own navigation Limited to its own visualisation Not clear path for site inputs
HYPAR	Possibility of creating new Hypar functions in Grasshopper Make the own workflow plugin for Revit Open-source libraries Own computation	Not so easy to use for non-designers Limited to its way of visualisation
SPECKLE	High interoperability plugin for several softwares Automation of workflows Open source	It is not a configurator
TESTFIT	Final tabulations for feasibility Workflow: Draw the perimeter of the plot, typologies of buildings Connected with Revit to export	Not apparent possibility to add functions Limited to its way of visualisation Not open source
RHINO COMPUTE	High compute possibility Remote compute possibility Possibility of connection with web application	

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3. FRAMEWORK DEFINITION

In order to make a contribution to the present advance in the use of tools associated with BIM in the area of prefabrication in construction, which allows greater productivity and a better flow of information, a framework was developed that enables the implementation of these tools in a case study.

3.1. Identification of gaps

After having carried out the previous investigation on the use of BIM on prefabrication, as well as the comparative analysis of the configurator related tools selected, the framework was defined based on the possibilities that said study and analysis provided. The goal was to develop a configurator that gives the possibility of automation in the design stage (Generative Design) of the case study, and that allows obtaining relevant models and data related to the feasibility of the project options.

Some of the gaps found within the current use of these tools and/or platforms in the area of prefabrication in construction and that are sought to be implemented with the current framework proposal, are the following:

- Possibility of making a workflow of the configurator (process for the automatic generation of options made by a computational model), that adapts more precisely to the prefabrication elements of the case study.
- Obtaining data related to Key Performance Indicators (KPI), automatically, from different design options, taking into account those most relevant to the system.
- Supporitng/allowing for user-friendly interactions that does not required professional knowledge for it.
- Ability to process information from a server and to implement the workflow from a web browser, enabling greater ease of interaction between the different stakeholders and the flow of information.

3.2. Framework overview

Given these goals, the framework illustrated in the figure 20 was proposed. The tools that could be adapted to achieve the objectives sought were taken and some others were used as references in different aspects, related to visualisation, workflow, data extraction, graphic configuration, etc.

Among the tools analyzed, ShapeDiver had advantages for the implementation of the configurator, however some limitations were found in terms of the flexibility of visualization and navigation configurations, as well as the difficulty in adapting it to give as initial input the drawing of a perimeter of building . For this reason, it was decided to use Rhino Compute as a server for processing the configurator information, since it allows greater flexibility in the implementation of a configurator.

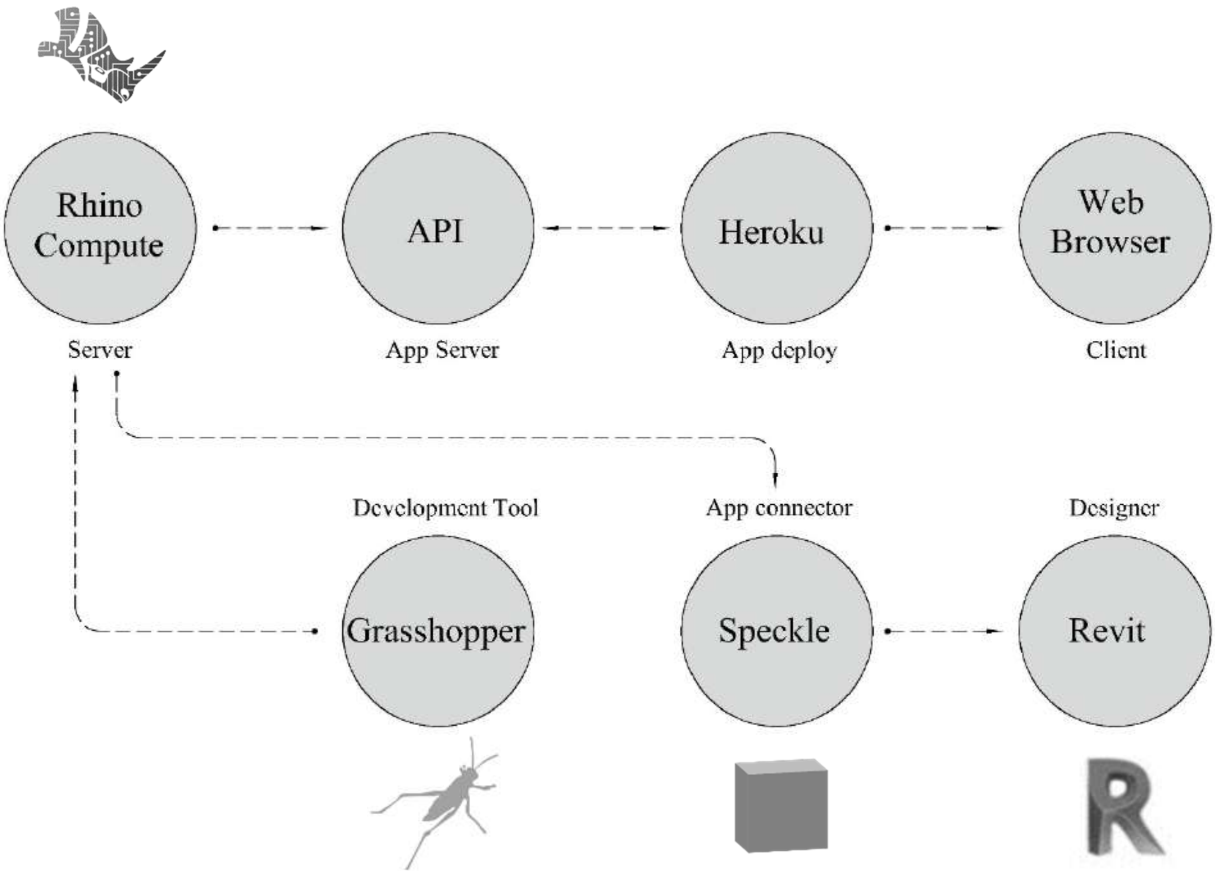

Figure 20- Framework diagram for configurator

De esta manera Rhino Compute es usado para procesar de manera remota el modelo computacional realizado a traves de Grasshopper, y se propone el desarrollo de una web browser, through which the user can interact with the computational model, allowing him to choose, within the established parameters, visualisation of the three-dimensional model as well as obtaining data and graphics. The use of Heroku is proposed for the app deployment, a tool currently available on the market that gives the possibility of creating an application with the help of programming codes. Within the investigation, other examples of tools of this type were found, and this one was mainly proposed, due to its flexibility of use and the possibility that it allows to connect to Rhino Compute through the API of this server.

Finally, to continue the design process in more detailed stages, a connection with Revit using Speckle is proposed. This allows interconnection with RhinoCompute and the automation workflows. This application would then serve as a connector, allowing the models created through the configurator to be used as input for subsequent phases of project development.

In summary, the configurator proposed makes use of a web browser, developed in the Heroku platform, which communicates with the Rhino Compute server using as the connector its API. The Rhino Compute server is in charge of processing the computational model developed through Grasshopper as well as receiving and returning the already processed information to the user. Once the configuration and selection of a model has been reached, it can be extracted and taken to the Revit software, through the Speckle interoperability platform.

3.3. Methodology

In the present dissertation, the previous framework was proposed at a general level, however the implementation focused on the section related to the development of the computational model, elaborated through the Grasshopper API. In this sense, some tests were made for its connection to the Rhino Compute server, for the processing of information remotely. For which it is necessary to use a plugin for Grasshopper called Hops.

As an alternative for the implementation of a web browser, it was decided to develop a user interface through the plugin HumanUI for Grasshopper. In addition, the Rhinoceros software, installed locally, was used as information processor. Figure 21 shows the diagram of the framework section implemented as an alternative for the creation of the configurator.

The creation of the configurator began with the analysis of the prefabrication construction system CREE used by CASAIS company (Figure 22), in order to determine the main components and modular elements and their relationships. As a result, parametric diagrams were generated that allowed the origin of a workflow, where a series of steps were established and implemented in the computational model elaborated through Grasshopper's visual programming.

The objective of the configurator was to allow exploring variations of the construction system based on the building dimensions and other user-defined parameters.

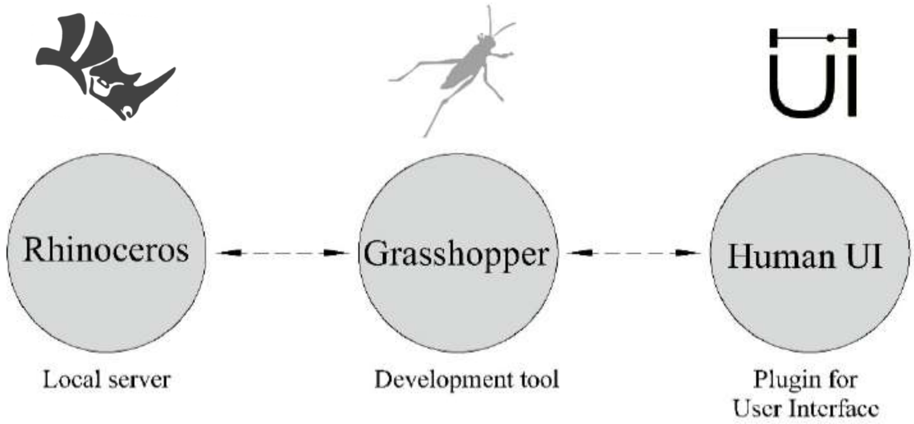

Figure 21- Section of the framework implemented

After developing the workflow in the computational model, the User Interface using the HumanUI plugin for Grasshopper was implemented, the design parameters to modify were defined, and the graphic components to allow proper visualisation throughout the project generation process were set. The KPIs were also established, which would be calculated automatically and displayed to the user through graphs and tables, in order to provide information on the feasibility of the project in relation to the decisions made for the configuration.

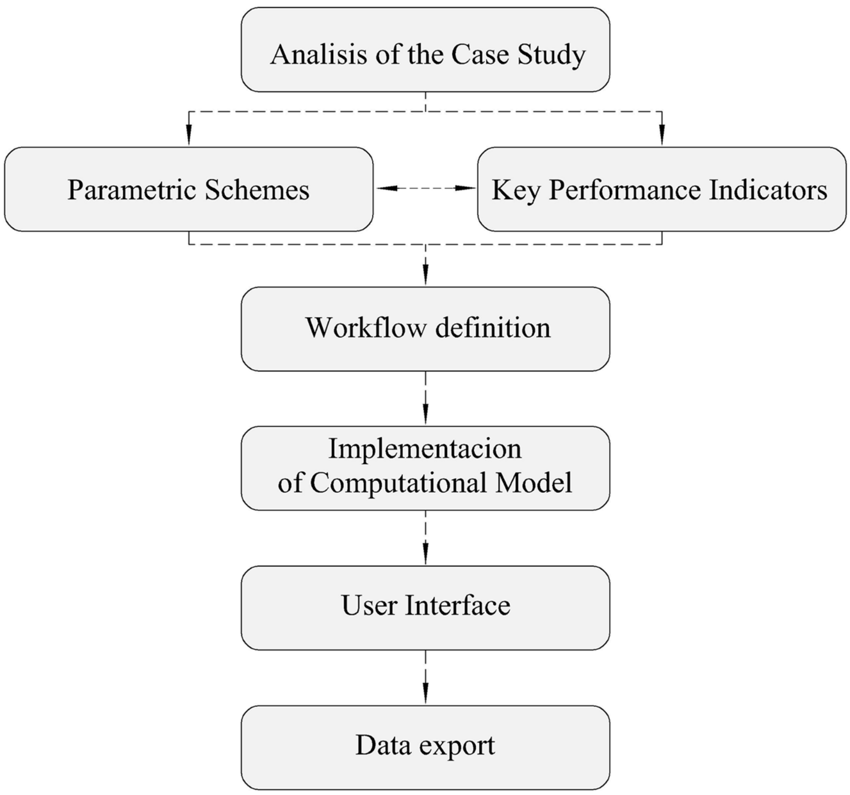

Figure 22- Diagram of the methodology

Finally, the model was configured to export the information generated in formats that could be used later. In this case, it was decided to extract the data related to inputs and outputs from the configurator in Excel format and the graphs, plan diagrams, 2D views and 3D views in JPG format.

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4. CREE SYSTEM

In order to deepen as well as to give a real context to the exploration of BIM applied to the construction prefabrication industry, with the use of automation and Generative Design tools, a case study was proposed by the company CASAIS. The company has recently adopted the system within its constructive repertoire and proposed it as a case study for the exploration of this dissertation, given its defined modular characteristics and the possibilities it offers for research into automation of the design phases.

4.1. DESCRIPTION OF THE SYSTEM

The CREE construction system is a hybrid prefabrication system of wood and concrete for high rise versatile building construction. This system is made up of modular elements that allow the off-site construction of basically the entire building, so that on-site work is reduced to the assembly of the individual prefabricated elements. Subsequent works using elements that have not been prefabricated try to be kept as few as possible.

This system has been especially used in projects for offices, hotels or apartments because it offers large spans at a structural level, allowing room layout flexibility. The system is designed primarily for buildings of at least 8 stories and has been tested to build up to 30 stories or 100 meters high.

The main elements that make up this system are (Figure 23):

- Foundation and vertical cores
- Slabs panels
- Glulam columns
- Steel or concrete middle girders
- Steel-concrete composite columns
- External walls

The foundation and vertical cores are built in reinforce concrete. Thus, the main elements that make up the vertical cores, such as walls, ceiling landings and stairs, are made of prefabricated elements that are later assembled on site. The slabs of the building system are made from hybrid modular panels of wood and concrete, supported by glulam columns along all the facades and inside by steel or concrete middle girders, which in turn rest on steel-concrete. composite columns.

All the columns are designed to have a structural behavior like hinged columns, both those along the façade, made of glulam, and those inside the building, made of steel-concrete composite. The exterior façade walls are built as timber frame elements, which are suspended from the building. These are prefabricated, directly attached to the façade columns and assembled on-site.

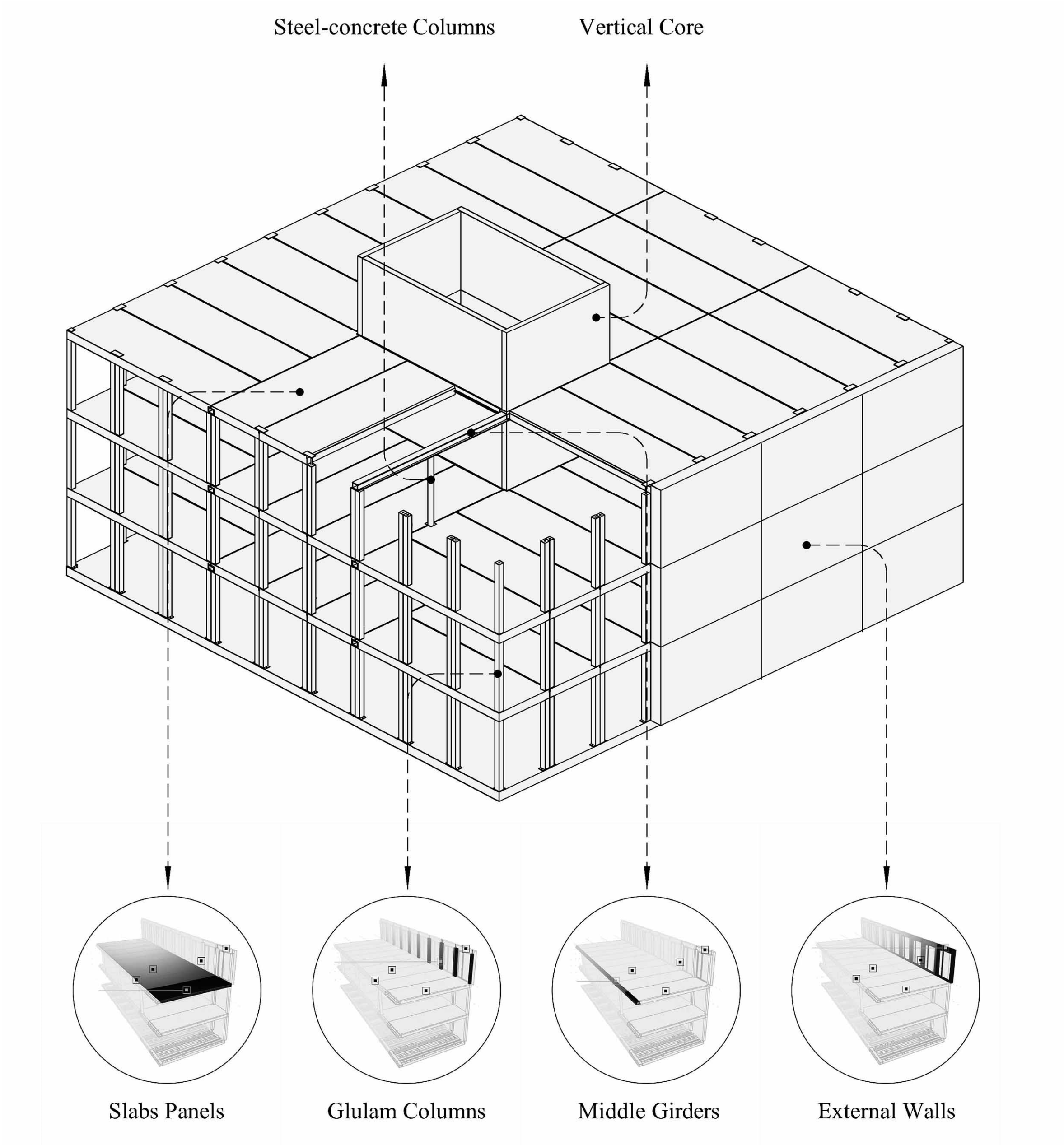


Figure 23- CREE system components (Modified from CREE Buildings)

Some other features of the system are:

- The stiffening of the building is achieved through the vertical cores of concrete, the slabs and wall panels.
- The standard height of the floors is 3.5 m. For heights greater than 3.85, new structural calculations must be made.
- It allows various materials and superstructures for the façade, since these are not structural.
- The axes grid of the system is based on the geometry of the slab modules. It is advisable to take as a starting point three possible spacings available, and keep these distances in both directions

of the project. These grids are based on the widths of the slab's panels and as for the lengths, multiples of the basic grid are used. The three recommended dimensions for the grids are: 2.5 m, 2.7 m and 3.0 m. (Figure 24).

- For the interior columns in steel-concrete composite, the maximum free span is 9.0 m.

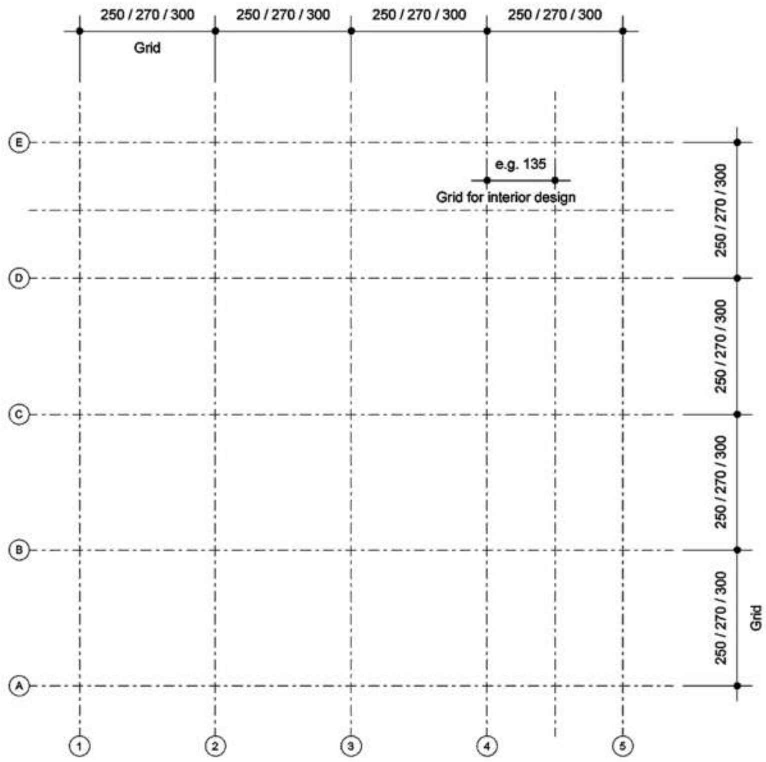


Figure 24- Recommended grids of the CREE system (Modified from CREE Buildings)

Regarding hybrid slab panels, the system offers two types: Flat slabs panels (Figure 25) and ribbed slabs panels (Figure 26), varying mainly in the configuration of glulam and concrete.

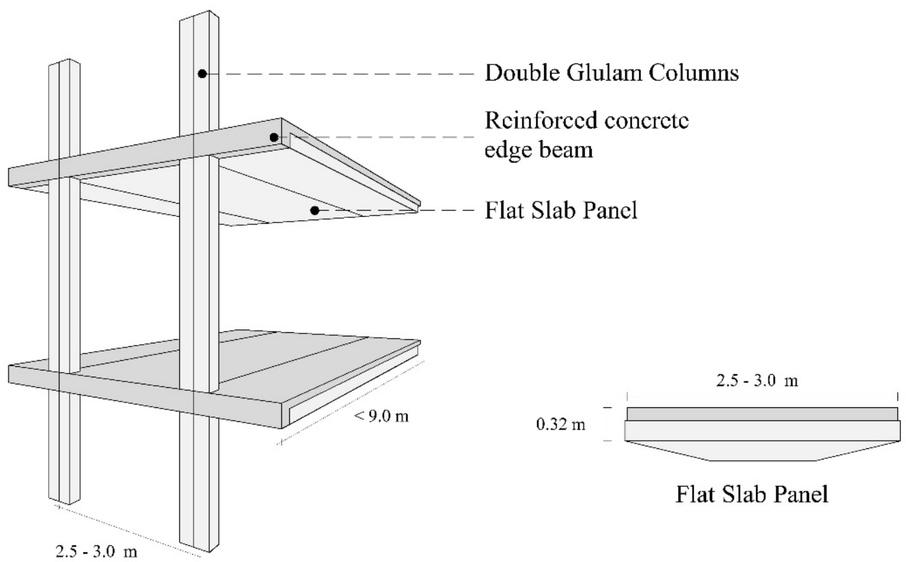


Figure 25- Flat slab Panel of CREE system (Modified from CREE Buildings)

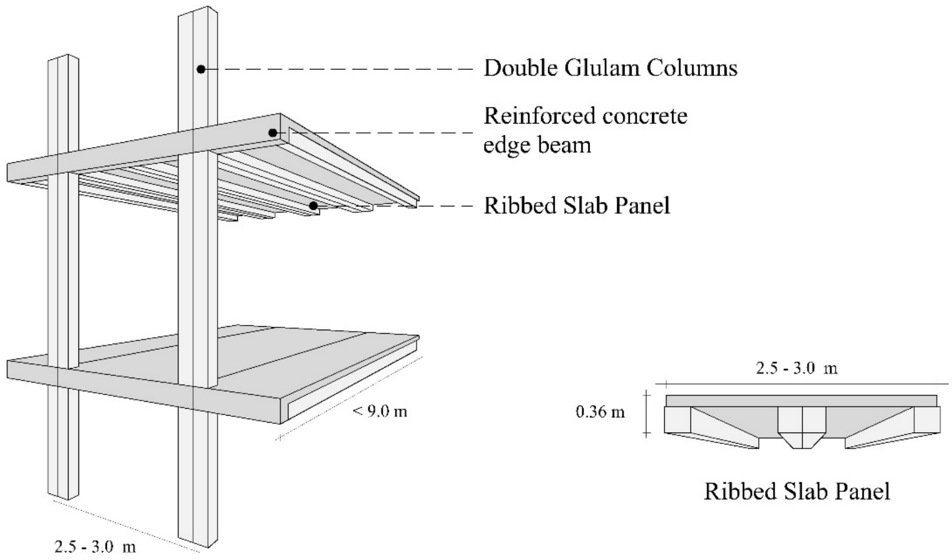


Figure 26- Ribbed slab Panel of CREE system (Modified from CREE Buildings)

The dimensions of these slabs vary between 2.5 m and 3.0 m in one direction and multiples of these measurements are used in the other direction, with the maximum length allowed being 9.0 m. The thickness of the slabs varies depending on the type, thus, the ribbed slabs have a total thickness of approximately 0.36 m (0.26 m of glulam beams and 0.10 m of concrete deck) and the flat slabs a total thickness of approximately 0.32 m (0.20 m of CLT Panel and 0.12 m of concrete deck), see Figures 25 and 26.

The glulam columns of the system are classified according to their form of grouping:

- Single: Used in the convex corners of the building
- Double: Used along the façade of the building
- Triple: Used in the concave corners or the building

On the ground floor the columns have a steel plate at the base, necessary for the connection with the foundation in concrete. The columns need a steel plate at the top that allows the connection of the adjacent slab panels to each other. The glulam columns have a square section of 0.24 m and are prefabricated and connected to the external wall panels. In cases where certain distances must be taken between the façade and the slab panels, the columns can increase in the direction of the façade (Figure 27).

The exterior walls of the façade are not included in the load-bearing structure of the building, they are mounted on the glulam columns. In this way, a fairly flexible façade design is allowed that could adjust to the requirements of the project. There is the possibility of assembling the structural glulam columns on-site with the facades previously connected to them, in this way waterproofing process is accelerated and work inside the building can begin more quickly.

To allow greater building depths than the maximum length of the hybrid slabs (9.0 m), central support girders are introduced, generally made of steel. The extremes of the slabs rest on these and thus allow longer distances between support columns. These elements are connected to the vertical cores and extend towards the façades. The system has two main types of girders: steel end girder, used if they are connected to the façades, and steel middle girder, used when it is located inside the building without connection to the façade. In order to support the slabs facing the vertical cores, steel L sections are used, connected to the concrete walls (Figure 28).

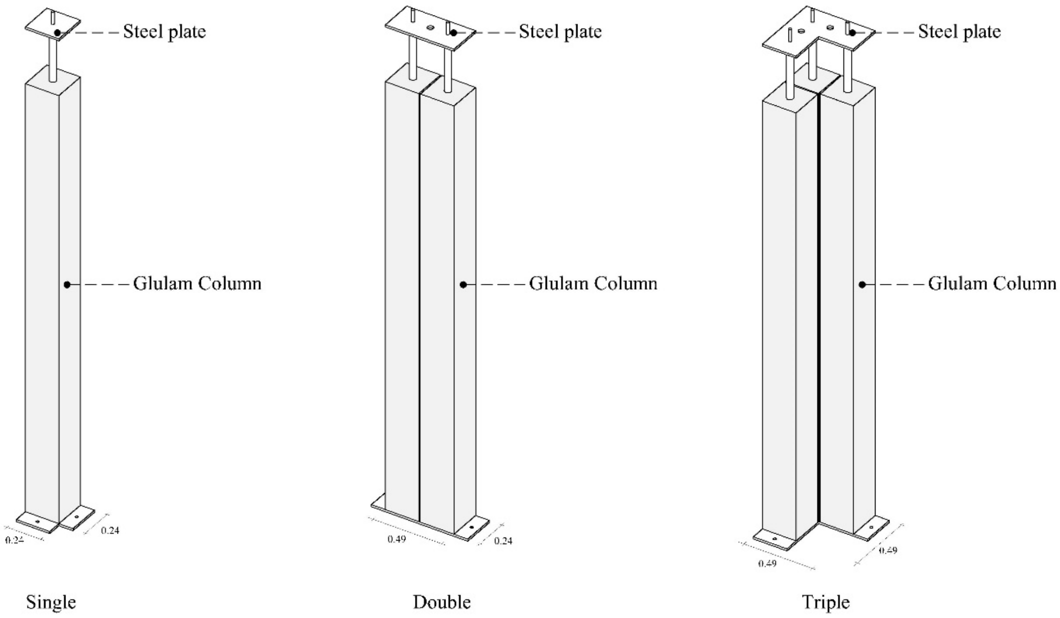


Figure 27- Glulam columns configuration of CREE system (Modified from CREE Buildings)

Finally, to give the possibility of longer spans in the interior area of the building, steel-concrete composite columns are used to support the girders. The maximum span allowed between these columns is 9.0 m. Figure 28 shows the girders, steel L sections and columns described.

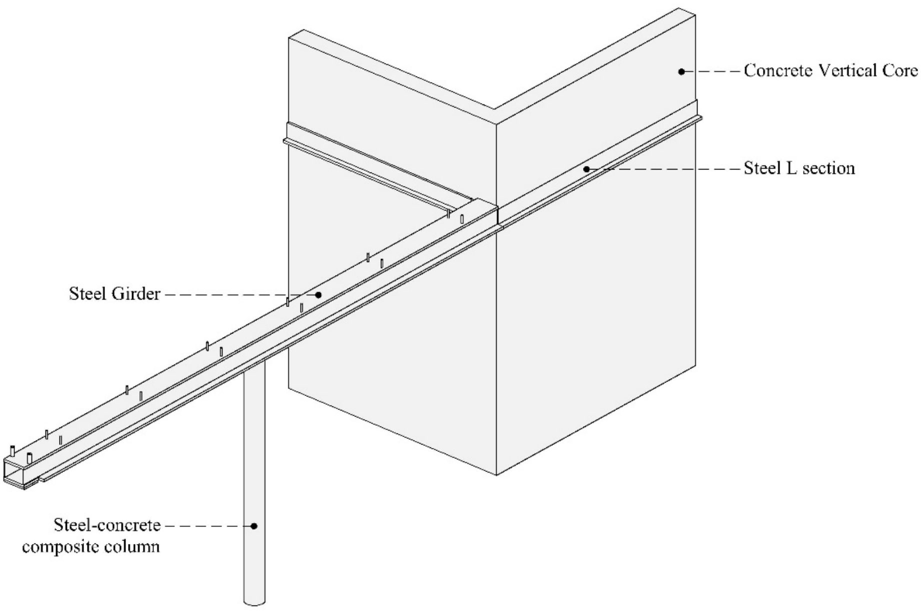


Figure 28- Steel girders, steel L sections and steel-concrete columns of CREE system (Modified from CREE Buildings)

Figure 29 describes the assembly sequence of the CREE System

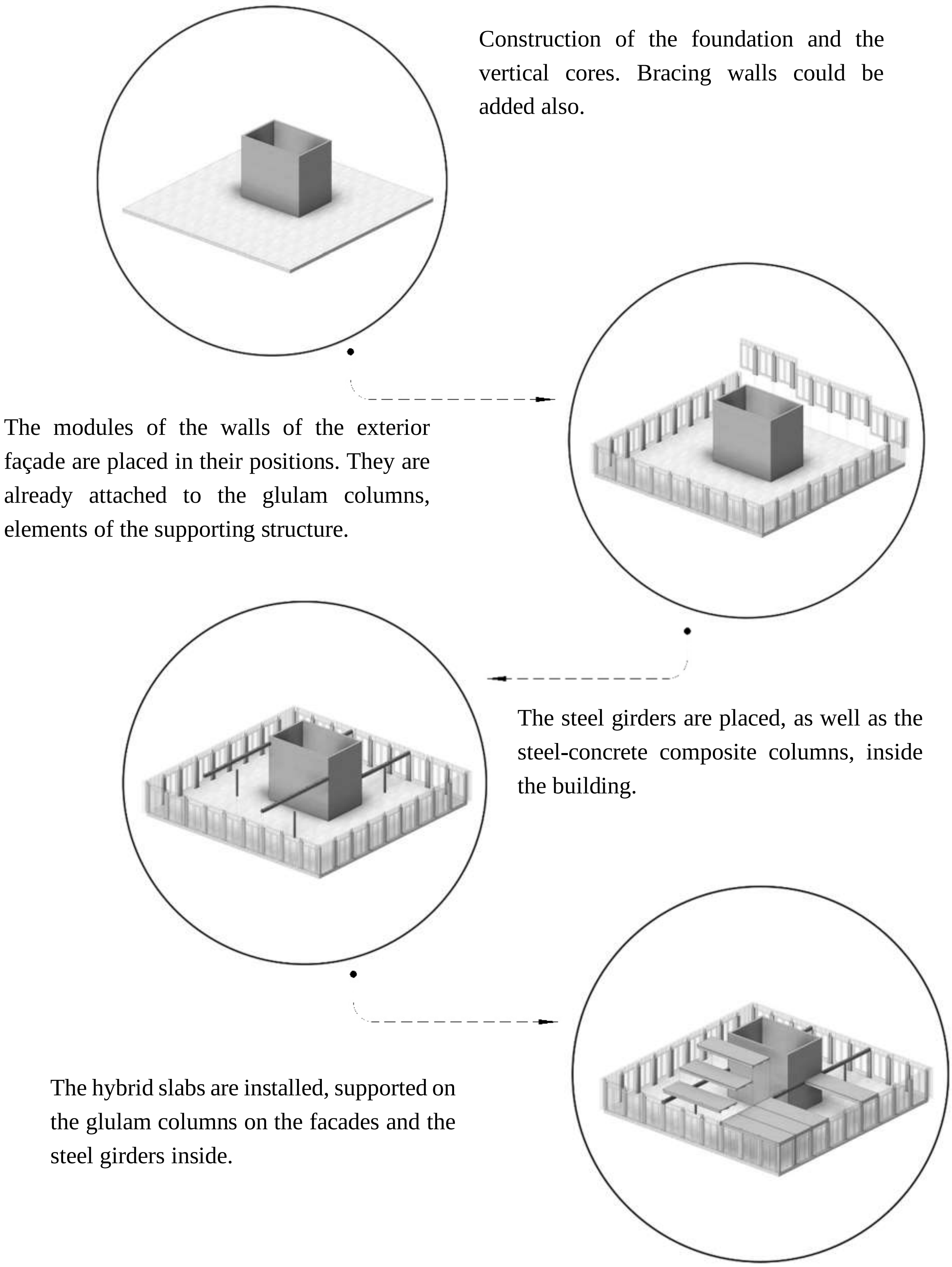


Figure 29- Assembly process of CREE system (Modified from CREE Buildings)

The CREE System allows for a wide variety of building layouts and is better suited for compact buildings that have plan dimensions in multiples of 2.5 m, 2.7 m or 3.0 m. (Figure 30). Since the slab modules are rectangular, in some buildings whose layout has oblique angles, the sections that deviate from 90 degrees should be positioned in some core areas, to avoid the need of special hybrid slabs.

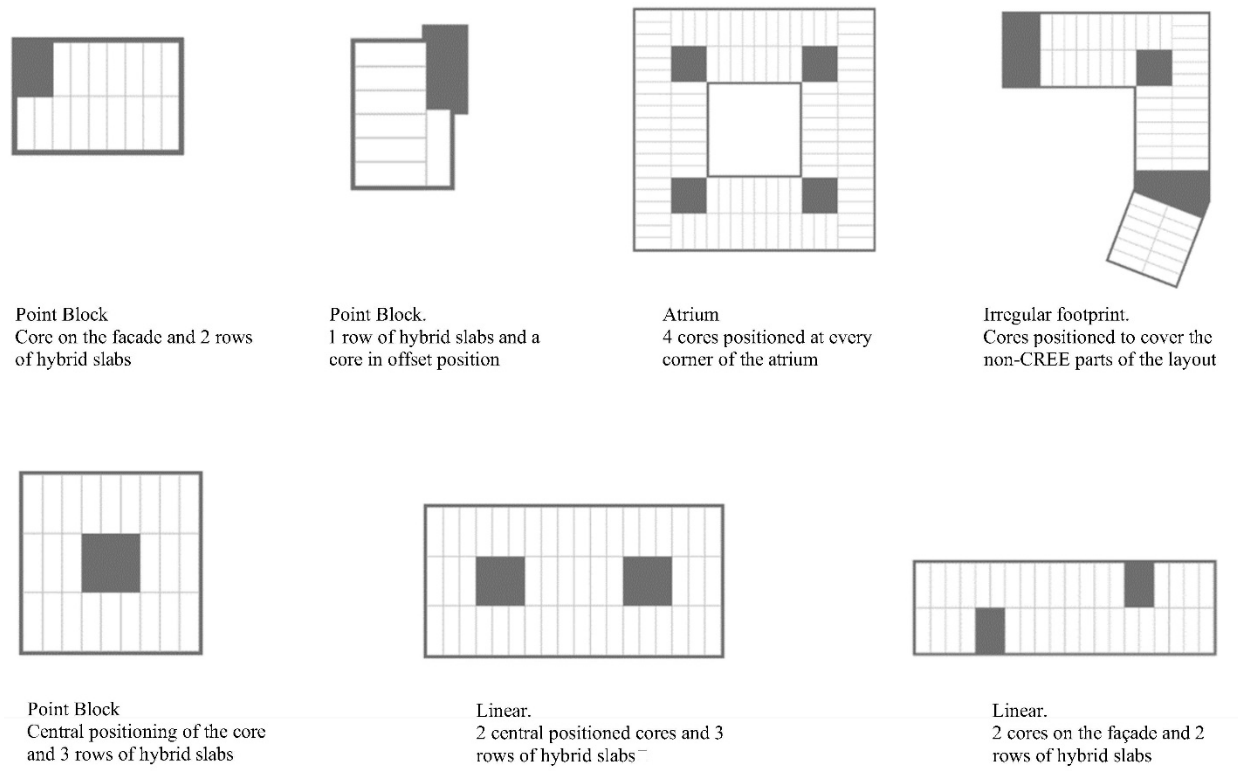


Figure 30- Layouts examples of CREE system (Modified from CREE Buildings)

4.2. PARAMETRIC SCHEMAS

In order to develop the computational model, schemas of the most relevant parameters of the system, related to the components and their relations, were developed. In addition, according to the analysis of the case study, it was decided to establish an order that was coherent with the development process of the projects that are intended to be generated through the computational model.

Since the initial input is the perimeter of the building, the first step is positioning the perimeter axes of the project (Figure 31). The next step is setting the interior axes, based on the dimensions of the slabs. Then, the necessary parameters for the positioning of the cores and the steel girders, elements that have interdependent relationships, were elaborated.

Table 7- List of main parameters implemented

Group	Parameter	Description
Perimeter axes	d	Spacing of the facade to perimeter axis
	f	Facade thickness
Interior axes	ns1	Number of subdivisions in first direction
	ns2	Number of subdivisions in second direction
	Int.L1	Interior length (between perimeter axes) in first direction
	Int.L2	Interior length (between perimeter axes) in second direction
	Dcg1	Maximum dimension of cell grid in first direction
	Dcg2	Maximum dimension of cell grid in second direction
Girders and cores	W.G.	Width of girder
	W1.G.	Width of the girder´s head
	SCpl	Spacing core-axis on the sides perpendicular to girders
Slabs dimensions	SSt	Typical spacing slab-axis
	SSg	Spacing slab-axis over girder
	SSl	Spacing slab-core on L sections
	Sub.L1	Final dimension of slab in first direction
	Sub.L2	Final dimension of slab in second direction
Perimeter columns	Cw	Column width
	D.axis 1	Column axis parallel to perimeter axis
	D.axis 2	Column axis perpendicular to perimeter axis
	D.axis 3	Column axis perpendicular to perimeter axis in cases of triple columns
Interior columns	Max Ssc	Maximum span on steel-concrete composite columns
Compound Shape	Min.Area.C	Minimum core Area
	A.slab	Area of grid cell based on slabs
	Max.L.C.	Maximum distance between cores
Facade sections	Cell	Distance between to axes perpendicular to the facade
General parameters		Height ground floor
		Height other floors
		Number of Floors
		Offset irregular cores
		Max. section length without cores
		Subdivision of larger spans on facade

It was continued with the parameters related to the final positioning of slabs and walls of cores, which take into account the necessary construction spacings. Then, the positioning parameters of the columns were discussed, beginning with the glulam columns, located along the entire façade, taking into account the different grouping typologies depending on their location, and ending with the interior steel columns, located along the steel girders.

The parameters for the initial subdivision were included in these schemas, in the cases in which the perimeter figure with which it begins was a compound shape. In addition, it was discussed the way in which the sections resulting from this subdivision could be grouped, and the general positioning of the cores within said sections.

4.2.1. Perimeter axes

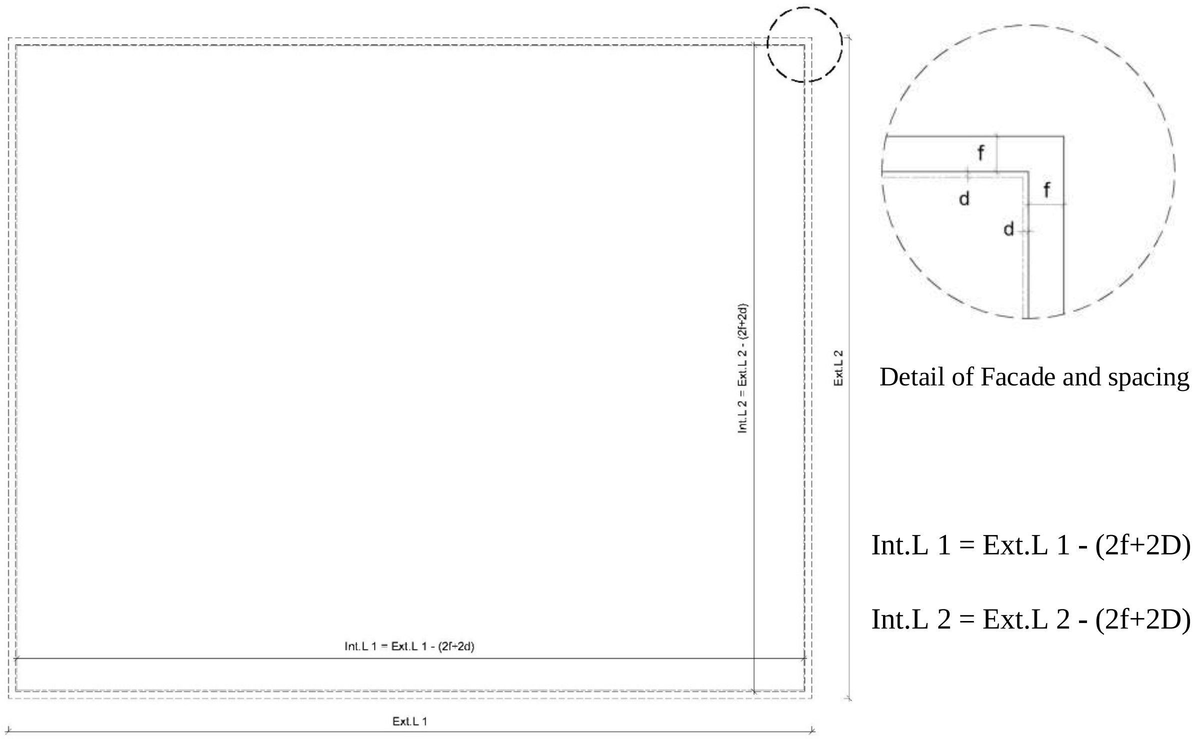


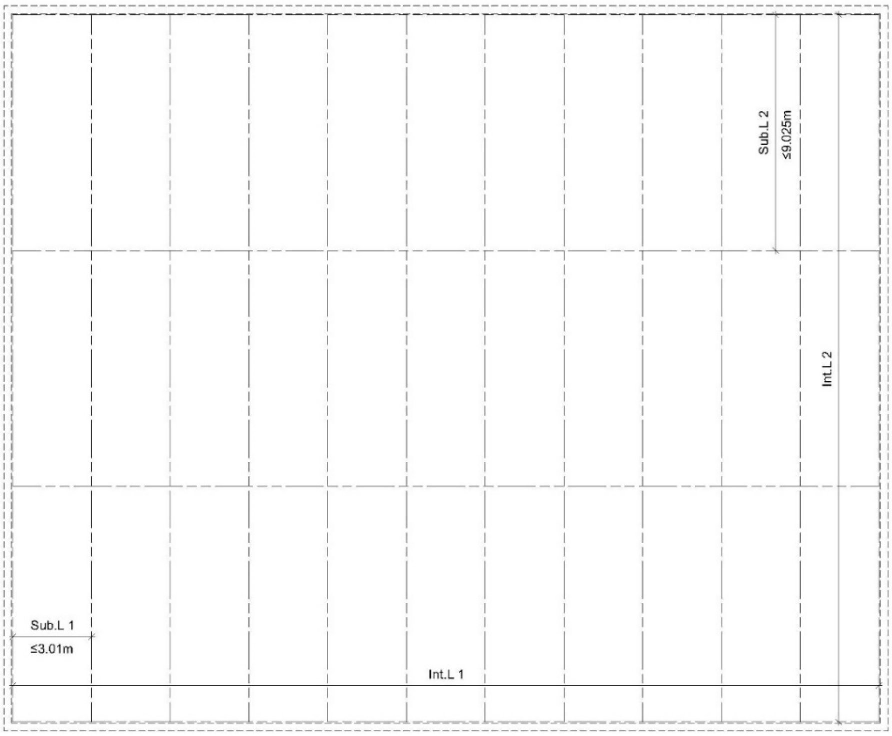
Figure 31- Parametric schema of perimeter axes

To generate the façade axes, the thickness of the façade *f* and the necessary distance from it to the axes *d* are taken into account. This last parameter can also vary depending on the technical requirements of the project. In this way, the sum of these two parameters corresponds to the offset distance at which the perimeter axes are placed. It could also be said that the internal length of a side, between perimeter axes, would be the external length of that side, less 2 times the sum of the parameters f and d (see this in Figure 31).

4.2.2. Interior axes

Regarding the distribution of the interior axes, these are based on the dimensions of the slabs, which, according to system requirements, cannot exceed 3.00 m in width and 9.00 m in length. Taking these requirements into account, the interior axes subdivision should never exceed these dimensions as well as includes the necessary distance between them.

Figure 32 shows the mathematical formulas used to calculate interior axes subdivision. For example, in one direction the number of subdivisions (ns1) is equal to the interior length (Int.L 1) divided by the maximum length of the slab in one direction plus the spacing. In the event that the result of such a division is not an integer number, a round ceiling is applied to this number and one more subdivision is added, in order to never exceed the maximum limit of slab dimensions.



Maximum dimensions of cell grid in two directions:
Dcg1 = 3.01
Dcg2 = 9.025

Number of Subdivisions 1:
Number of Subdivisions 1:
ns1 = Int.L 1 / Dcg1
if ns1 is not an integer:
$\lceil ns1 \rceil +1$

Number of Subdivisions 2:
ns2 = Int.L 2 /Dcg2
if ns2 is not an integer:
$\lceil ns2 \rceil +1$

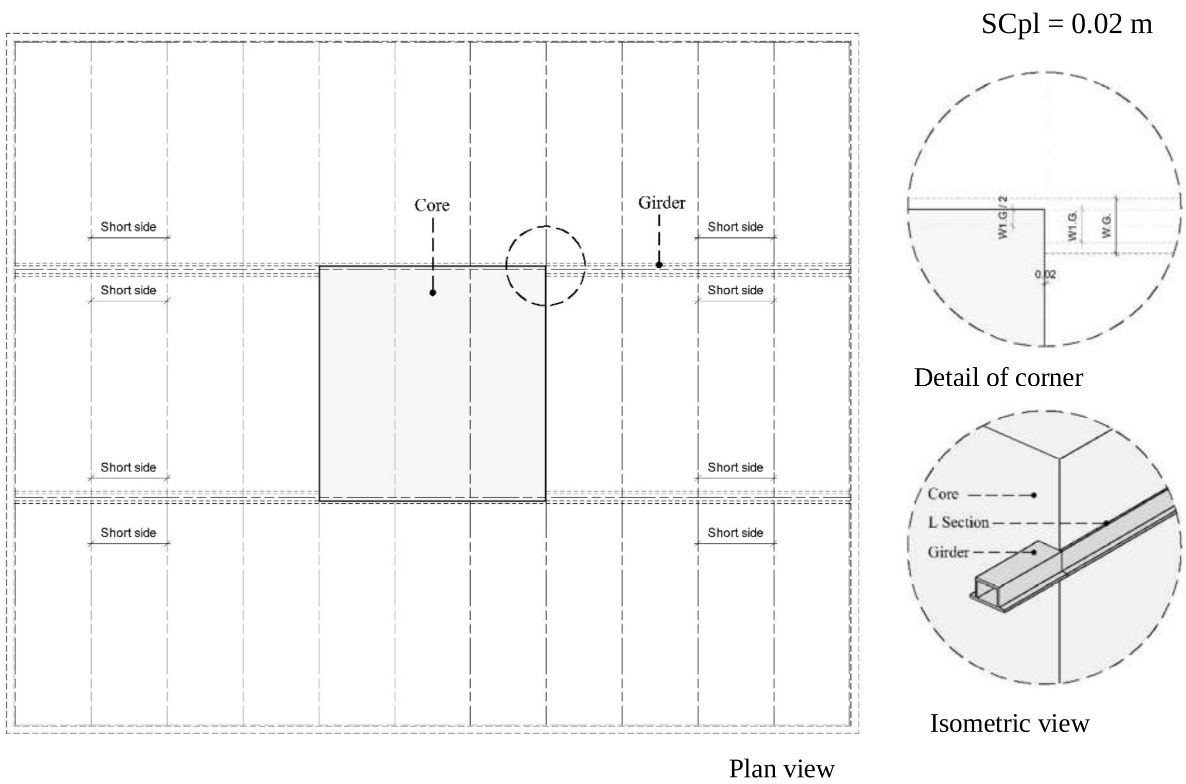
Plan view

Figure 32- Parametric schema of interior axes

4.2.3. Girders and cores

The steel girders of the system, which allow buildings with greater width to the building, are located mainly along the shorter sides of the slabs to make the most efficient use of their greater span. Additionally said girders must always be attached to some core areas and can be extended towards the facades, where they would rest on the glulam columns.

Regarding the cores, they are initially inserted within the axes grid, since in this way the slab prefabrication system becomes more efficient. So the grid of interior axes is used from which certain cells are taken to form the Cores. In order to give the appropriate dimensions for its union with the girders and the required constructive spacing with the slabs, the parameters shown in Figure 33 were introduced. The sides of the core, which are perpendicular to the girders, are distanced from the axes by 0.02 m towards the inside of the core, while the sides that are parallel to the directionality of the girders, advance towards the outside of the core by half the width of the girder head (W1.G / 2), in order to allow the adequate constructive union with the girders and the L sections.



Steel Girders:
Positioned along the short internal sides of the subdivisions.

Sides of the core:
- Perpendicular to the Girders: 0.02 m before the axis
- Aligned to the Girders: W1.G / 2 after the axis

Figure 33- Parametric schema of girders and core positioning

4.2.4. Slabs dimensions

Figure 34 develops the parametric diagram of the dimensions of the slabs, which is based on the grid of initial axes and on the different spacings required depending on the position. Detail A (Figure 34) shows the spacing between slabs and towards the façade, detail B (Figure 34) the spacing of a slab located in a corner of the project and detail C (Figure 34), the spacing required when the slabs are located in front of a core or on a girder.

The typical spacing between slabs towards the axes is 5 mm, but in cases where they are supported on a steel girder, the required distance to the axes is 20 mm. Shown in the figure are the formulas for the length and width dimensions of three types of slabs, depending on their relationship to cores or girders.

4.2.5. Perimeter columns

The next elements of the system to be parameterized were the glulam columns, which, as previously described, have three types of groupings depending on their location along the façade. Thus, in all the convex corners there are Single column typologies, in all the concave corners the Triple column typology and along the façades, at the intersections of the interior axes with the perimeter axes, the Double column typology.

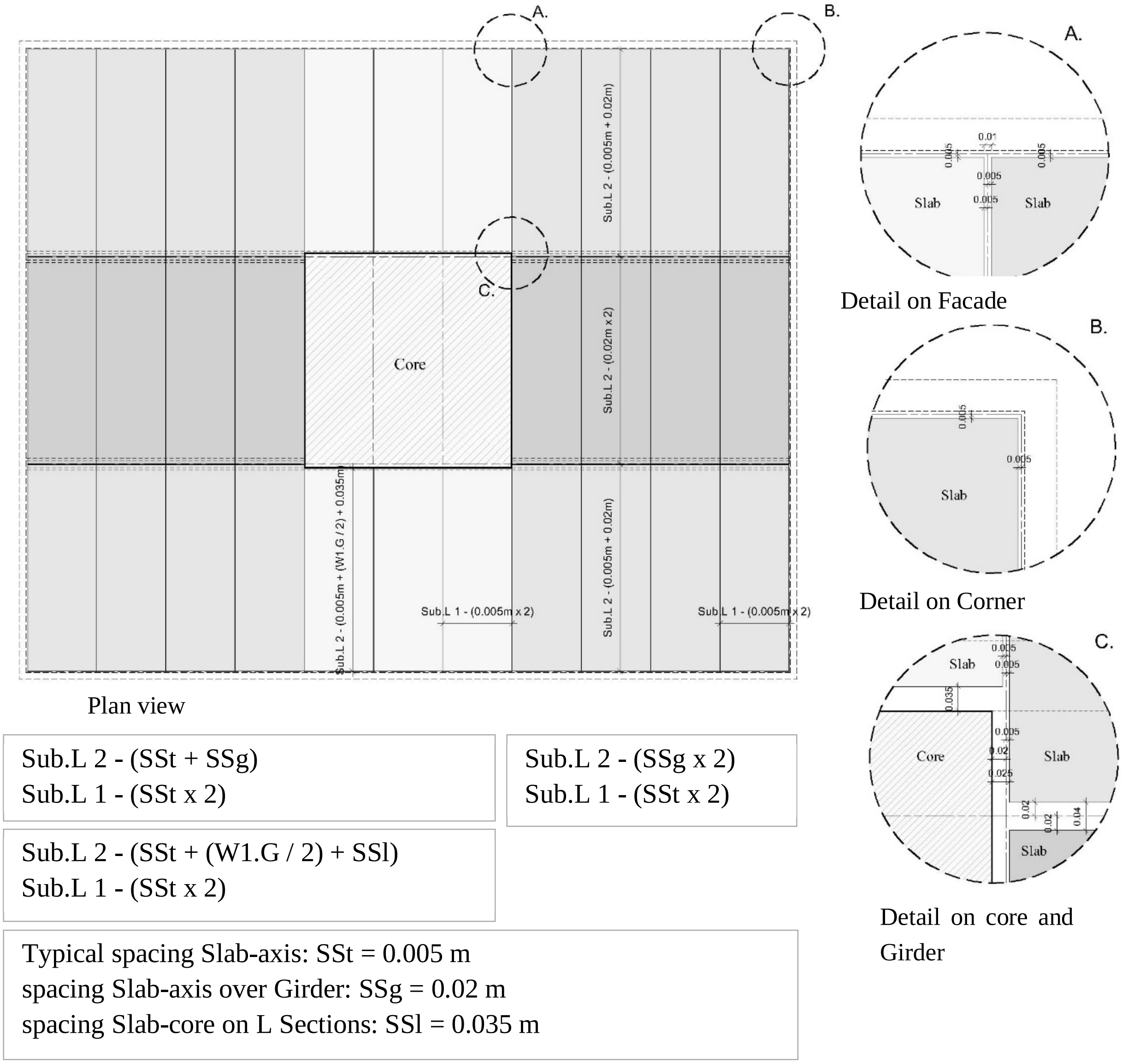


Figure 34- Parametric schema of slabs dimensions

Figure 35 shows the positioning of the column typologies and the parametric details of their specific location with respect to the interior and perimeter axes. It should be noted that one of the options of the case study system is distancing the façade with respect to the perimeter axes. Since the façade walls must be attached to the columns, the columns are allowed to extend towards the exterior, making their section rectangular.

The basic column section is 0.24 m by 0.24 m and can change depending on the distancing of the façade and the position of the column within the different typologies of grouping. Thus, as the Single column typology is typically located in corners, if the façade is distanced, its section must grow proportionally in length and width.

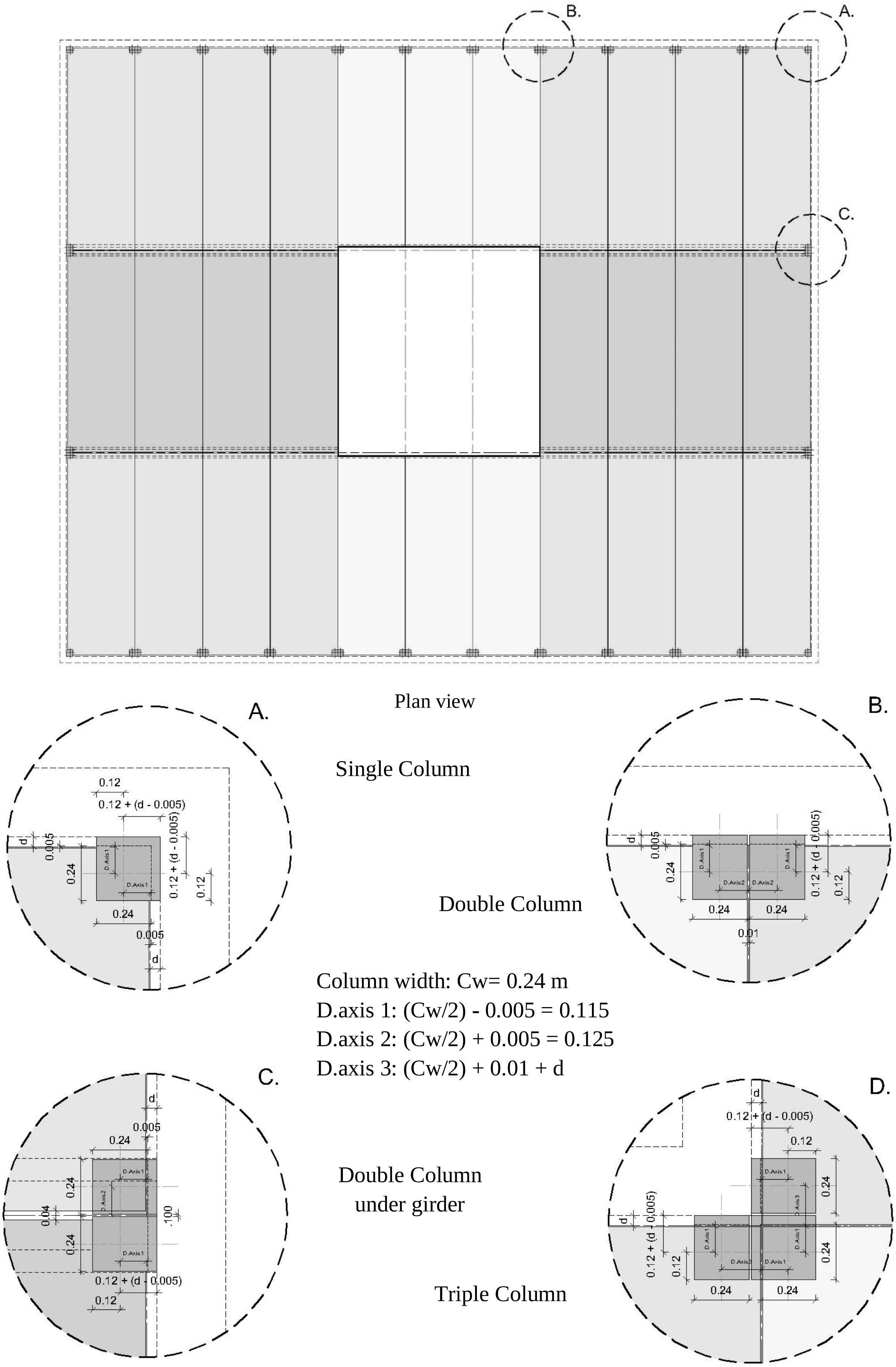


Figure 35- Parametric schema of perimeter columns

In the Double column typology, the columns only grow in the direction perpendicular to the façade in order to cover the façade distance and in the Triple column typology, the central column grows in length and width proportionally, but the two lateral columns only grow in the direction perpendicular to the façade. See details.

4.2.6. Interior columns

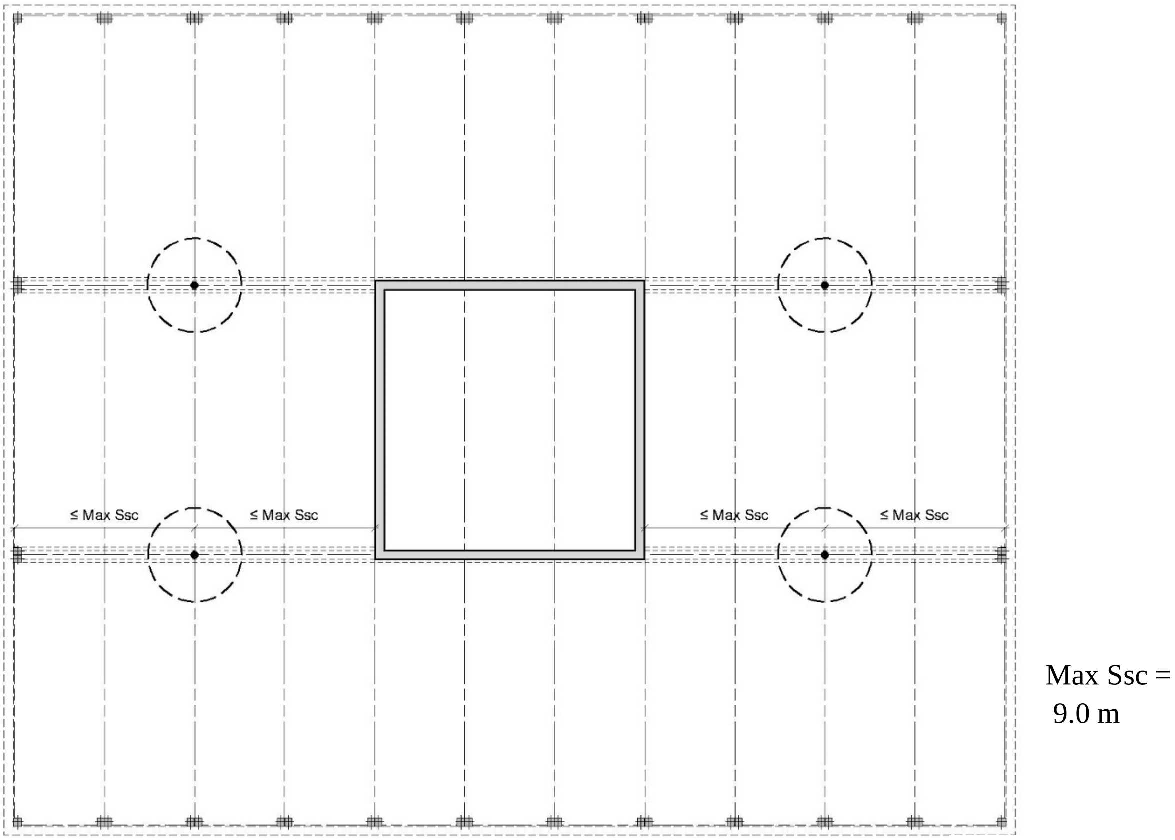


Figure 36- Parametric schema of interior columns

The steel-concrete composite columns are located inside the building, along the steel girders and must allow a span of no more than 9.0 m, which is the parameter Max Ssc (Maximum span steel columns) in Figure 36. In this way, for its distribution, the length of the girder is divided, which must be supported in sections that never exceed the allowed span. The steel columns are located, regardless of whether they are not aligned with the axes perpendicular to the axis of the girder.

4.2.7. Compound initial shape

In the event that the perimeter of the building is a composite shape, it must be subdivided into rectangles that in a later step can be grouped depending on the directionality of the slabs, as shown in Figure 37. In the example given, there are two possible grouping options for the composite shape subdivision.

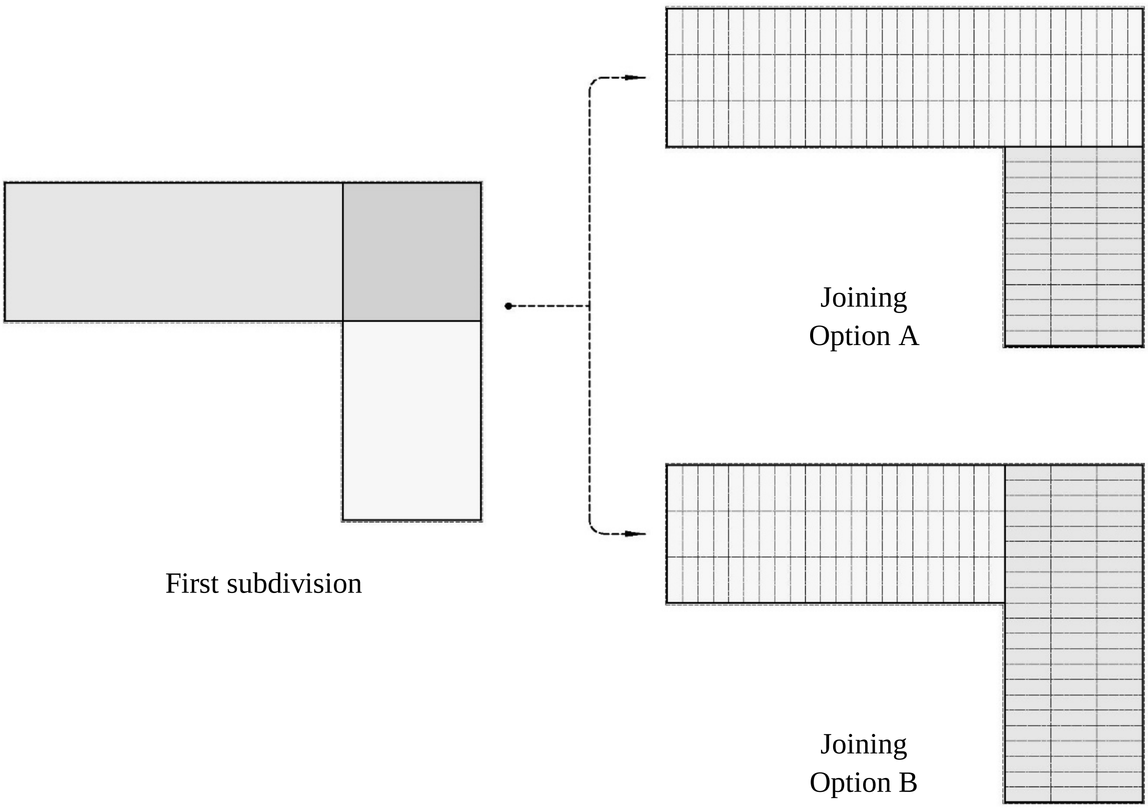


Figure 37- Parametric schema of compound shape

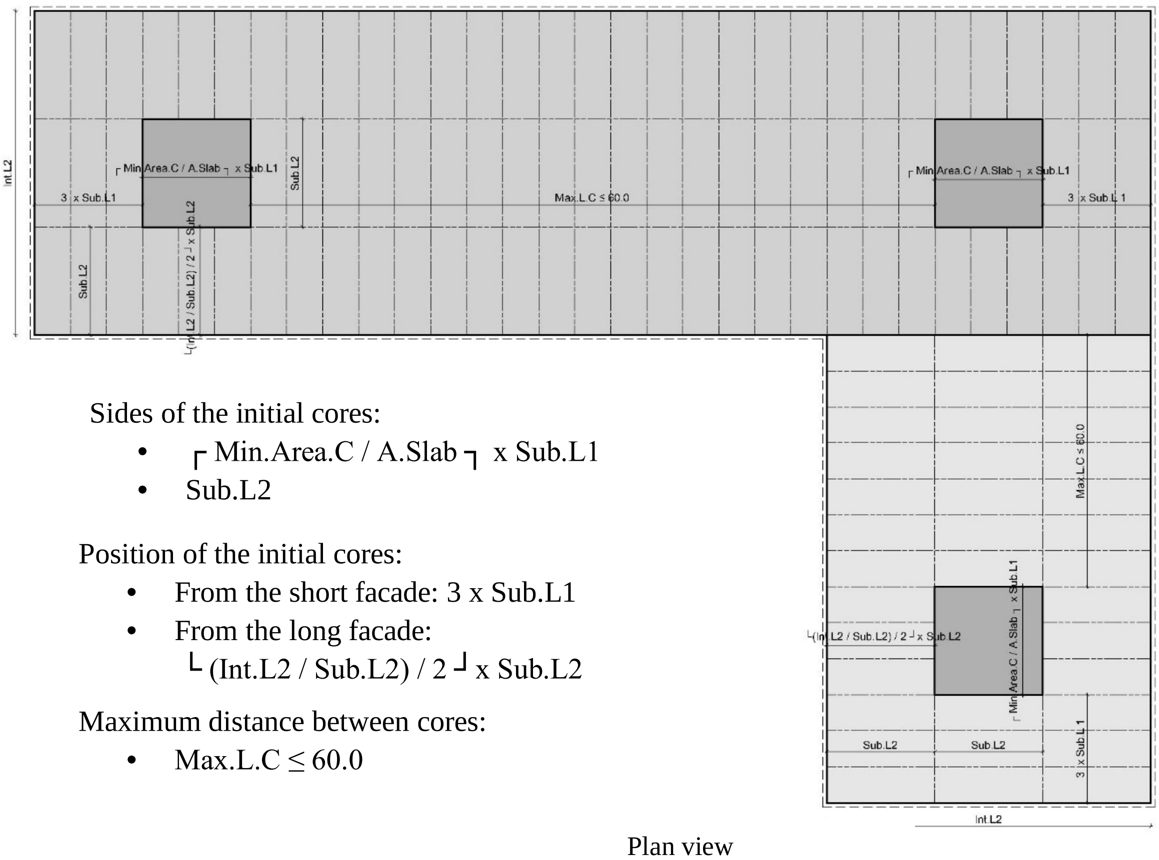
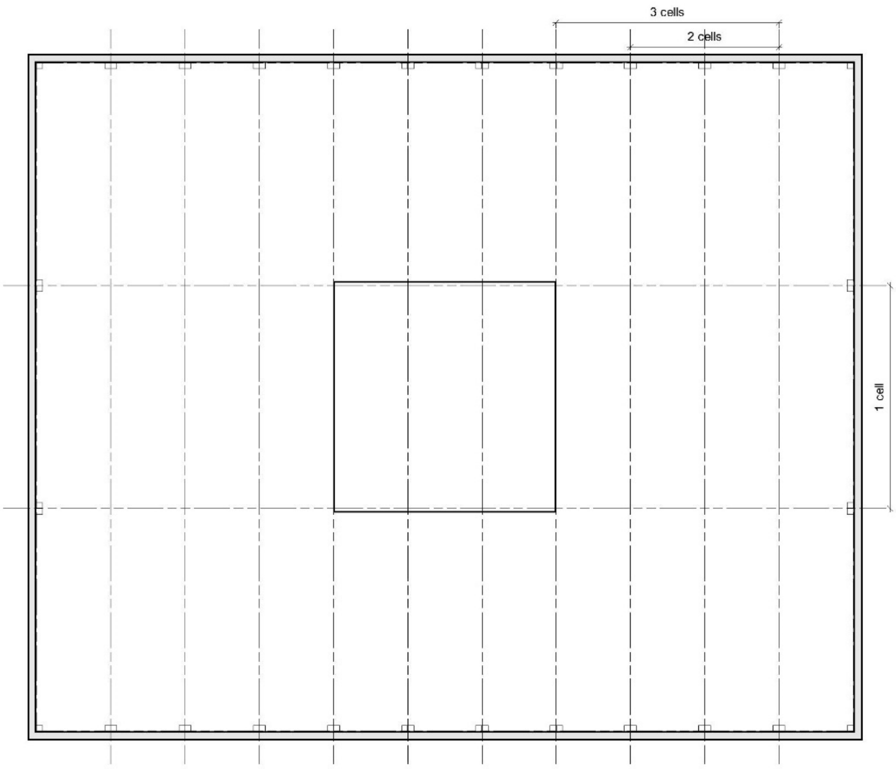


Figure 38- Parametric schema of distribution of cores

By having these new composite rectangles, it is possible to proceed to locate the cores according to the parameters shown in Figure 38. For an initial location, the grid of interior axes is used as a reference, based on the dimensions of slabs, since one of the objectives of the system is to maintain the largest number of modules of similar slabs. Thus, based on the area of the cells grid (A.slab) it is calculated the amount of slabs needed to reach the minimum area that the core must have (Min.Area.C). These cells are taken parallel to the longitudinal axis of the section in which the core will be located.

For the positioning of the cores within the sections, the row of cells closest to the longitudinal axis of the section is taken as the starting point and distances are taken from the smaller façades of the section, of approximately 3 cells. In addition, a maximum distance of 60 meters between the cores (Max.L.C) is placed as a parameter, which can be modified according to project requirements.

4.2.8. Façade sections



Plan view

Figure 39- Parametric schema of façade sections

For the distribution of the façade sections, the internal axes grid is taken as a parameter. The distance between the axes is taken as a unit, allowing to choose between 2 or 3 units for the facade sections whose distance is approximately 3.0 meters. In facades whose subdivisions are approximately 9.0 m, the length of the facade section would only be one unit (Figure 39). Regarding the height of the façade sections, according to system requirements, these have their base starting at the same level of the glulam columns attached to them, and their top matching the façade section of the next level.

4.3. KEY PERFORMANCE INDICATORS

Given that one of the main objectives of the configurator developed in this dissertation is to allow informed design decisions, a series of KPIs, were established to evaluate the various project options generated.

These KPIs are linked to the main objectives of the case study modular system in relation to modular amounts of elements, variability of these modules, general areas and ratios of areas between elements, maximum and minimum dimensions, among others, which allow better insights over the feasibility of the project. Table 8 shows the list of KPIs considered in the development of the configurator.

Table 8- Key Performance Indicators for Case Study

	Objective	Sorting	KPI
hybrid slabs	-Maximize the number of same-size elements.	-Classification based on size.	-Dimensions of types. -Quantities by types. -Total areas covered by types.
Cores	-Maximize orthogonality. -Maximize insertion in grid axes of slabs. -Fulfill minimum size required.	-Classification by element.	-Dimensions of elements. -Areas by element.
glulam columns	-Maximize the number of same-size elements.	-Classification by single, double or triple column grouping. -Classification by column section and height.	-Quantities by type of grouping. -Quantities by type of section and height.
steel girders	-Fulfill positioning requirements.	-Classification by length.	-Quantities by lengths. -Total length.
L sections	-Fulfill positioning requirements.	-Classification by length.	-Quantities by lengths. -Total length.
steel-Concrete columns	-Fulfill positioning required. -Minimize number of elements.	-Classification by height.	-Quantities by height.
Façade	-Maximize the number of same-size elements.	-Classification based on size.	-Dimensions of types. -Quantities by types. -Total areas covered
Ratio Areas	-Fulfill ratio areas slabs/cores required.		-Total areas of the componets of the system.

Regarding hybrid slabs, the objective is to maximize the use of elements of the same size, reducing costs and increasing construction efficiency. The information obtained from the project proposals is classified according to the dimensions of the elements, so those with the same widths and lengths are grouped into a typology. The resulting information would be the dimensions and quantities of each type of slabs and the total area of these elements used in the project.

For the vertical cores in particular, it is convenient that these are orthogonal, since in this way, pieces of slabs with irregular shapes are avoided. Therefore, maximizing the insertion of the cores within the grid of slabs axes is the most convenient for the system. This also allows efficient positioning and connection with the girders, elements that must be supported on the walls of the cores. Another requirement cores must meet is a minimum area and dimensions, related with the stairs, circulations and elevators they contain, which are dependent on the requirements of each project. The information generated is classified by element and the KPI's results are the dimensions and areas of each one.

It also seeks to maximize the same-size section and height of the perimeter glulam columns, so in principle it is proposed that the levels of the building all have the same height, except perhaps for the ground floor. Since, as previously mentioned, the façade columns can be extended outwards, there can be more than one type of column in a project. Thus, depending on the project, the information generated is classified first into grouping typologies of glulam columns and secondly into types of column sections. The res would contain the counts by column grouping types and the column counts by section type and height.

The steel girders and L sections are classified according to their lengths, and a quantity for each length type is provided. The total length for both the steel girders and the L sections is also provided. The KPI obtained are the quantities of these elements by type of length. The distribution of steel-concrete interior columns aims to minimize their number, thus increasing the flexibility of the interior layout. The information obtained is classified by element heights, since the section is generally the same and the only change that could arise would be the variation in height of the ground floor. The KPI obtained are the amounts of these elements by type of height.

The last components of the system to be treated are the facades, divided into sections of lengths based on the grid of interior axes of the project. The algorithm seeks to minimize the size variation. The information obtained is also classified into typologies defined by the dimensions of lengths and widths. Finally, the KPIs obtained from these elements are the dimensions of the typologies, the quantities per typology and the total façade areas in the project.

The last KPI is the ratio of areas between cores and slabs, it informs us of the proportion of usable space, a factor which is sought to be maximized.

5. IMPLEMENTATION OF THE METHODOLOGY

After having analysed the CREE prefabrication construction system, its constituent elements and the relationships between them, it was proceeded to elaborate, based on the information collected, a set of parametric schemas, related to the main parameters of the system to be taken into account. With this synthesized information, the KPIs were also defined, which would be set as objectives of the information to be supplied by the computational model, and in this way have a data set of the different design options explored. This would allow to measure quantities, ratios of areas, and efficiency, and thus objectively compare the feasibility of each of the explorations.

The next step to develop, having the input of the schemas, and the objective of the information of KPIs, was the implementation of the methodology, exposed in chapter of Framework Definition. As mentioned, this would focus on the elaboration of the computational model developed through the Grasshopper API, and processed locally with the Rhinoceros 7 software. Starting with the definition of the workflow, three main steps were defined for the development of the computational model, being these: the general structure of the model, the development of the User Interface, and the processing of the information to be exported.

5.1. WORKFLOW DEFINITION

Three main sections were then defined for the development of the computational model. It began by establishing the general structure of information processing, for which seventeen steps were implemented that, beginning with the input from the perimeter of the project to be designed, allows the automatic definition of the CREE system components. Based on the inputs of the different parameters that were also being defined, it is proposed that the configurator has a part of the design elaboration automatically, thus opting for a Generative Design, and on the other hand gives the possibility of interaction with the user, by allowing him to define parameters as he goes through the configuration (Figure 40)

After having this first computational structure that begins with the perimeter of the building and ends with the extrusion of the system components to generate a three-dimensional model, it was continued with the second section, dedicated to the development and implementation of the User Interface. For this, the HumanUI plugin was used, which allowed the generation of a User Interface and setting its relevant parameters for the elaboration of the project, in addition to generating graphs, tables and 2D and 3D visualisations, automatically showing the results of the decisions made along the design process. Said information displayed in the User Interface shows those KPIs that were sought to be defined.

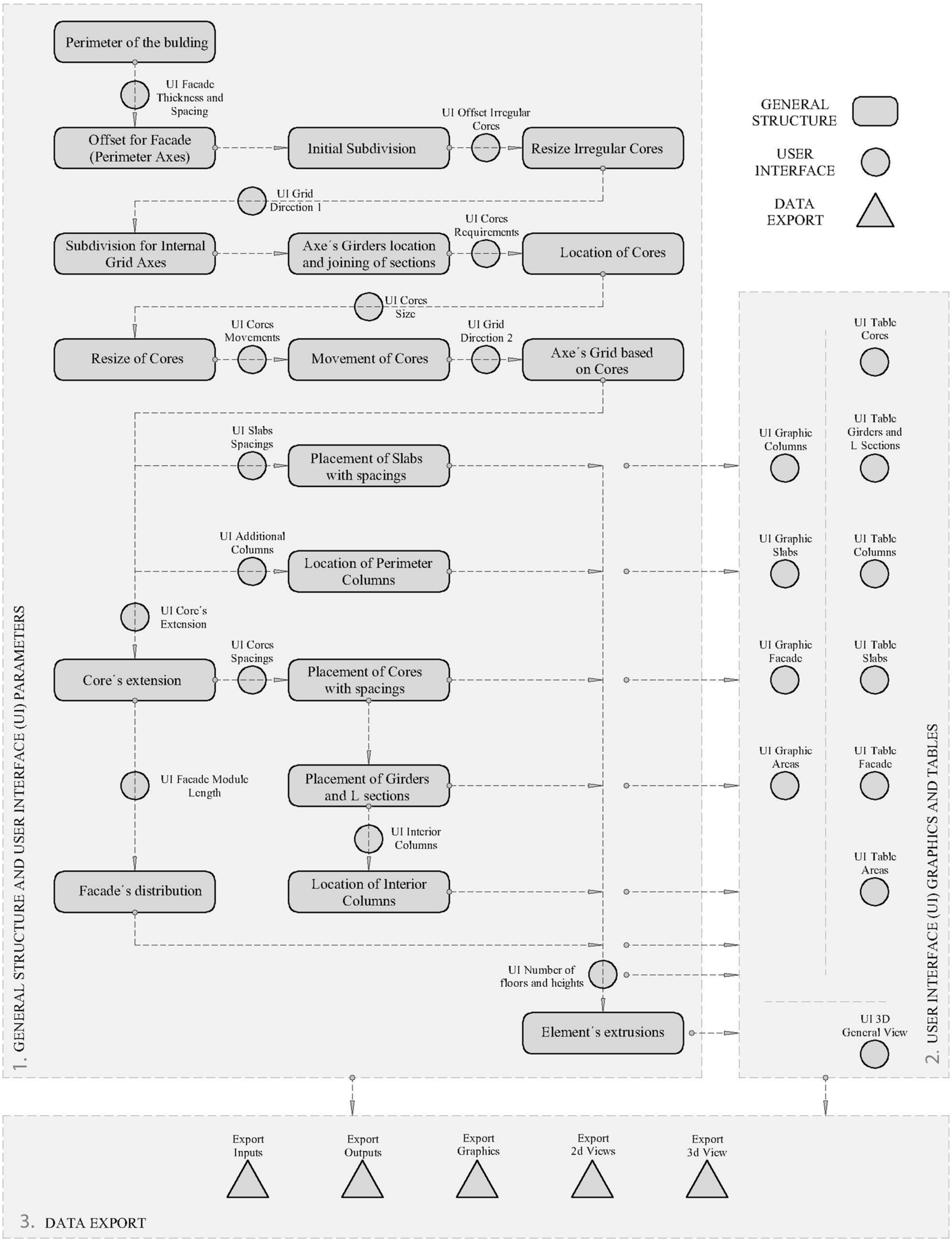


Figure 40- Workflow schema of the computational model

Finally, in the third section, the part of the computational model related to the organisation of the information was developed, in order to be exported in formats that would allow its subsequent use. This with the aim of giving the possibility of continuing with the development of the design proposals or to have the chosen project configuration options as a database. For this, export parameter options were included within the User Interface, in which files in .xls or .jpg format could be saved, that contain the inputs of the given parameters, the outputs of the information generated, 2D views 3D views and graphics.

Figure 40 shows the workflow of the computational model with the previously described sections and the elements that compose them. In this, it can also be seen that in the general structure of the computational model section, elements of the User Interface configuration are included, these elements being those related to the parameters that are given to the user, throughout the configuration of the project. When it reaches the point of having the information of the system components already defined, these data are transferred to the second section (UI graphics and tables), in which they are developed in the User Interface, either as graphics of different formats or tables with organised and detailed information. It is the data obtained from the first and second sections, which are organised and defined to be exported in the third section (data export).

The following subchapters area focused in the three sections of the computational model previously described, and the steps and/or components of the visual script that were implemented will be addressed. Thus, for the general structure section, the 17 steps that shape the Generative Design process will be explained. For the User Interface section, three groups of components will be developed: those inserted in the first section, which give the possibility of changing parameters by the user, those related to the creation of graphs and those that allow the creation of tables. For the export data section, the specific information components that are planned to be exported from both the general structure section (inputs and outputs) and the User interface section (graphics and 2D and 3D images) are developed.

5.2. IMPLEMENTATION OF COMPUTATIONAL MODEL

The first of the three sections of the computational model covers all the information processing, starting from the initial input of the building perimeter, until obtaining the three-dimensional model with all the elements of the CREE system, automatically. This first section was defined as general structure and it involves a computational process based on seventeen steps, shown in Figure 41. The order of these steps and their dependencies attend to the relational hierarchies between elements and their parameters, concluded through the implementation of the parametric schemas, previously exposed.

The computational model starts with the location of the perimeter axes of the building, and then, based on this geometry, it looks for an organised way to subdivide the interior area using the dimensions of the hybrid slabs, and then defines the inner grid of axes. To get there, it subdivides the initial shape into basic rectangular shapes, leaving aside the irregular parts, to be taken as cores (to avoid slabs of non-orthogonal shapes). Once these shapes are obtained, they are subdivided once more based on the dimensions of the slabs, to then be joined with the attached sections depending on the continuity of the direction of the axes grid.

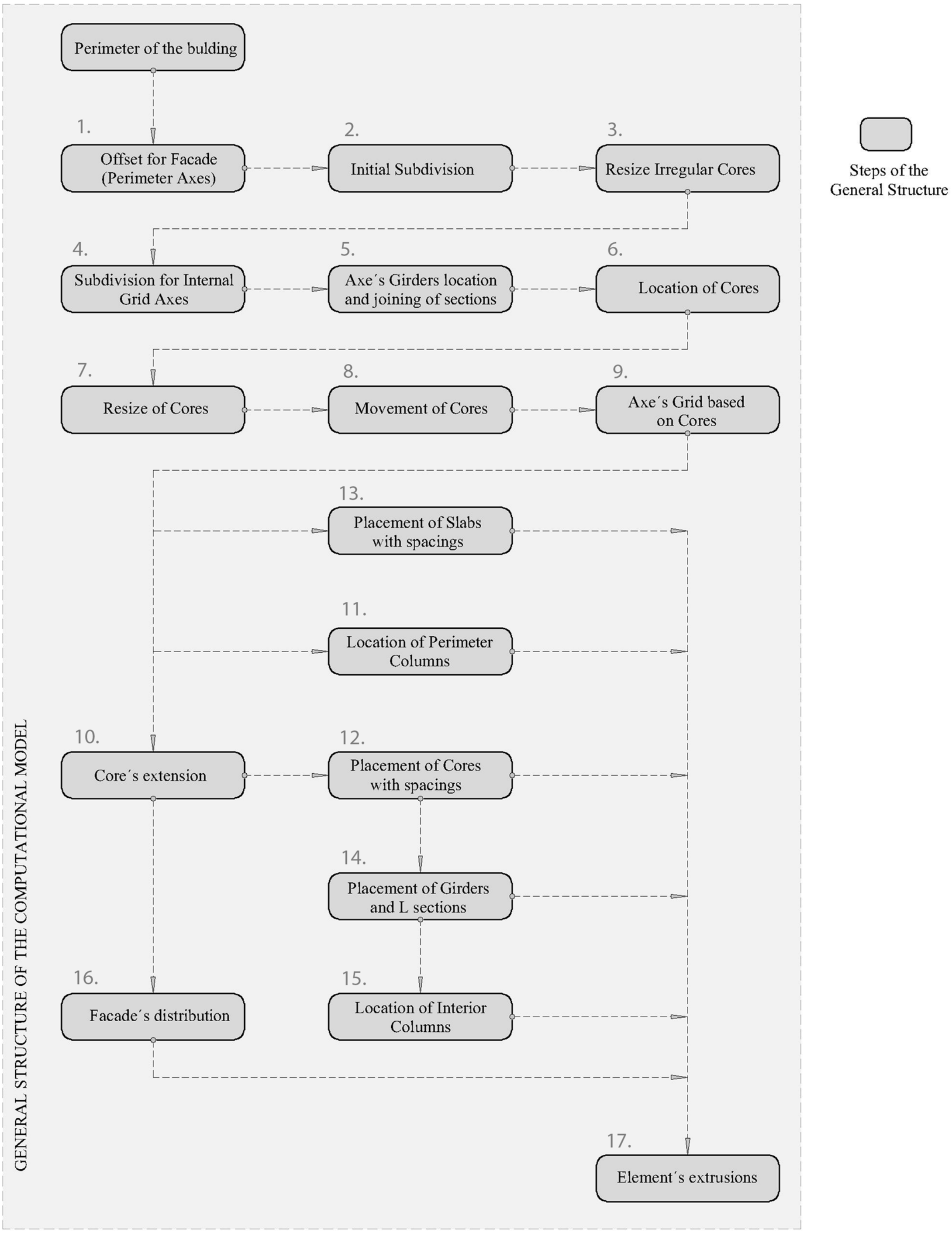


Figure 41- Schema of the first section of the computational model (general structure)

With the sections formed, the cores are located automatically. Then the other elements are positioned by having the interior defined with the cores and the grid of axes. Thus, the slabs are positioned with the recommended spacings of the system, the perimeter glulam columns, the steel girders, L sections, and the steel-concrete columns inside. Once the perimeter columns are defined, it is also possible to locate the facade panels. Finally, when the configuration of all the components is obtained in plan, it was proceeded to extrude them and apply the respective elevations, depending on the parameters placed as input for levels heights and number of levels.

5.2.1. Offset for Façade (perimeter axes)

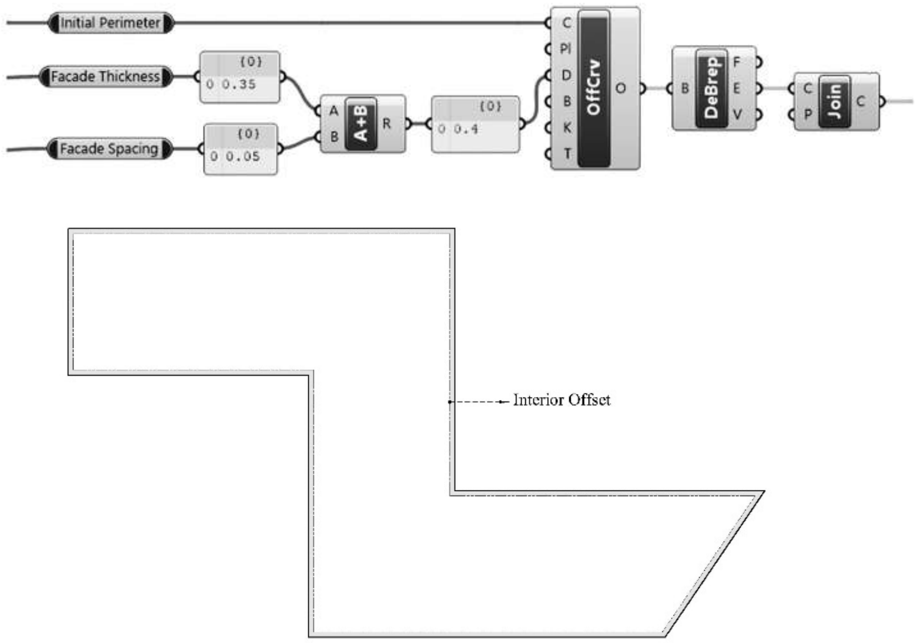


Figure 42- Offset for Façade (perimeter axes). Visual script and design solution (plan view)

The first step of the computational model takes as input the initial perimeter of the building to be developed, and an offset is made towards the interior with the added distance of the facade thickness and the facade spacing. This spacing refers to the distance that the façade could have with respect to the perimeter axis, a parameter that can be modified depending on the project requirements. The result of this first step is then the set of perimeter axes, with which the interior of the building begins to be developed (Figure 42)

5.2.2. Initial subdivision

The initial subdivision is performed when the initial perimeter of the building is a composite shape, subdividing into simpler shapes, such as rectangles, triangles or in some cases rhombuses. The rectangular sections are then used for the positioning of the slabs, whereas the others are used for the location of cores.

Figure 43 shows the visual script of the subdivision, in which the shape from the previous step (perimeter axes) is taken and the concave corners are found. From them, the lines that are related to each of these points are rotated in such a way that they allow the interior subdivision of the shape. For this, the sense of organisation of the corners of the shape had to be organised and thus specify the directions of rotation of the lines. For the cases in which there are shapes with non-orthogonal endings, the convex corners that do not have 90° angles are sought.

After having the shape subdivided, the resulting shapes are classified in terms of shape.

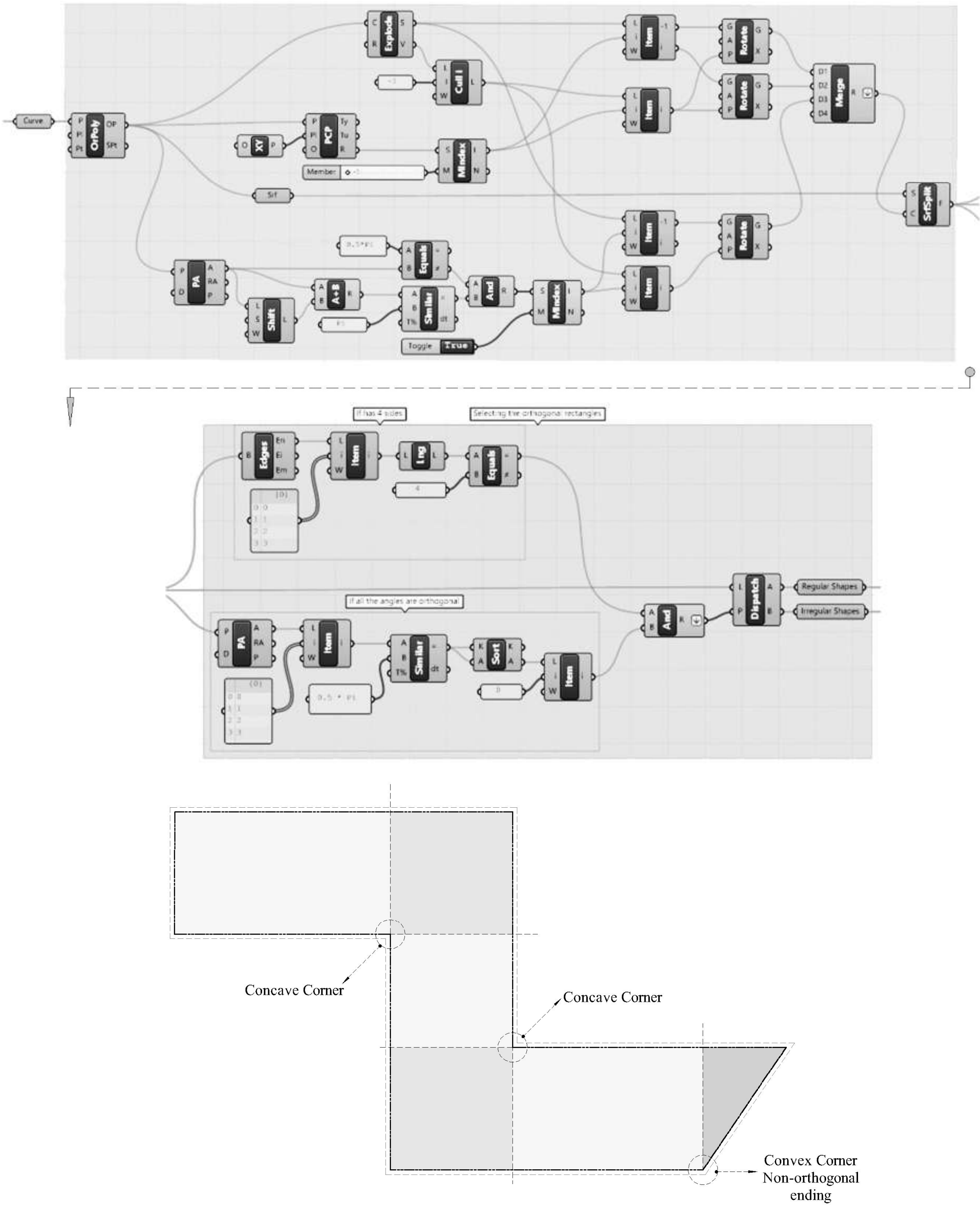


Figure 43- Initial subdivision Visual script and design solution (plan view)

5.2.3. Resize irregular cores

In design solutions in which non-rectangular shapes are generated after the initial subdivision, it has been previously mentioned that these would be taken as cores, in order to use only the rectangular sections for the positioning of the slabs, this being the most optimal way of use the prefabrication system.

These irregular cores present in their geometry, on many occasions, angles that are too acute for their use to be functional, so that the possibility exists, within the computational model, of resizing the side adjacent to these angles, which is related to some another section of the initial shape. For this, the sides of the irregular sections involved in the sharp corners and that are attached to the sides of some other regular sections are located, and then an offset is made to give more functional space to the irregular cores (Figure 44).

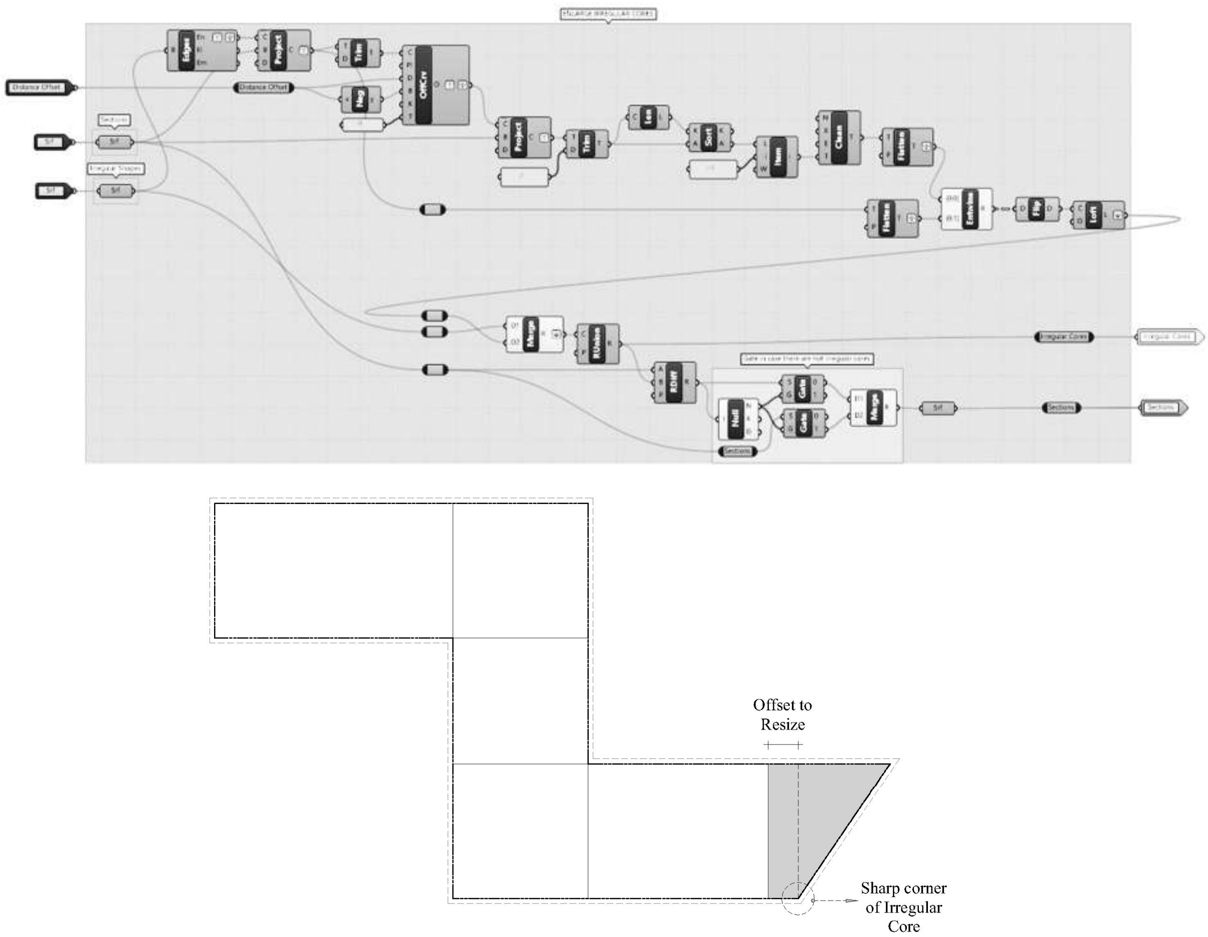


Figure 44- Resize irregular cores. Visual script and design solution (plan view)

In the visual script a filter was developed for the flow of information from the sections of the previous step, in the case that irregular cores are not present. The outputs of this step are the resize of irregular sections and the resize regular sections if they are attached to an irregular section.

5.2.4. Subdivision for internal grid axes

Once the sections are defined, the next procedure is to subdivide them again to generate the interior grid of axes. This grid is based on the dimensions of the slabs, and in order to include the spacing between them, the maximum subdivision dimensions considered are 3.01 m in one direction and 9.01 m in the other direction. It is given to the user the option to change the directionality of the subdivisions.

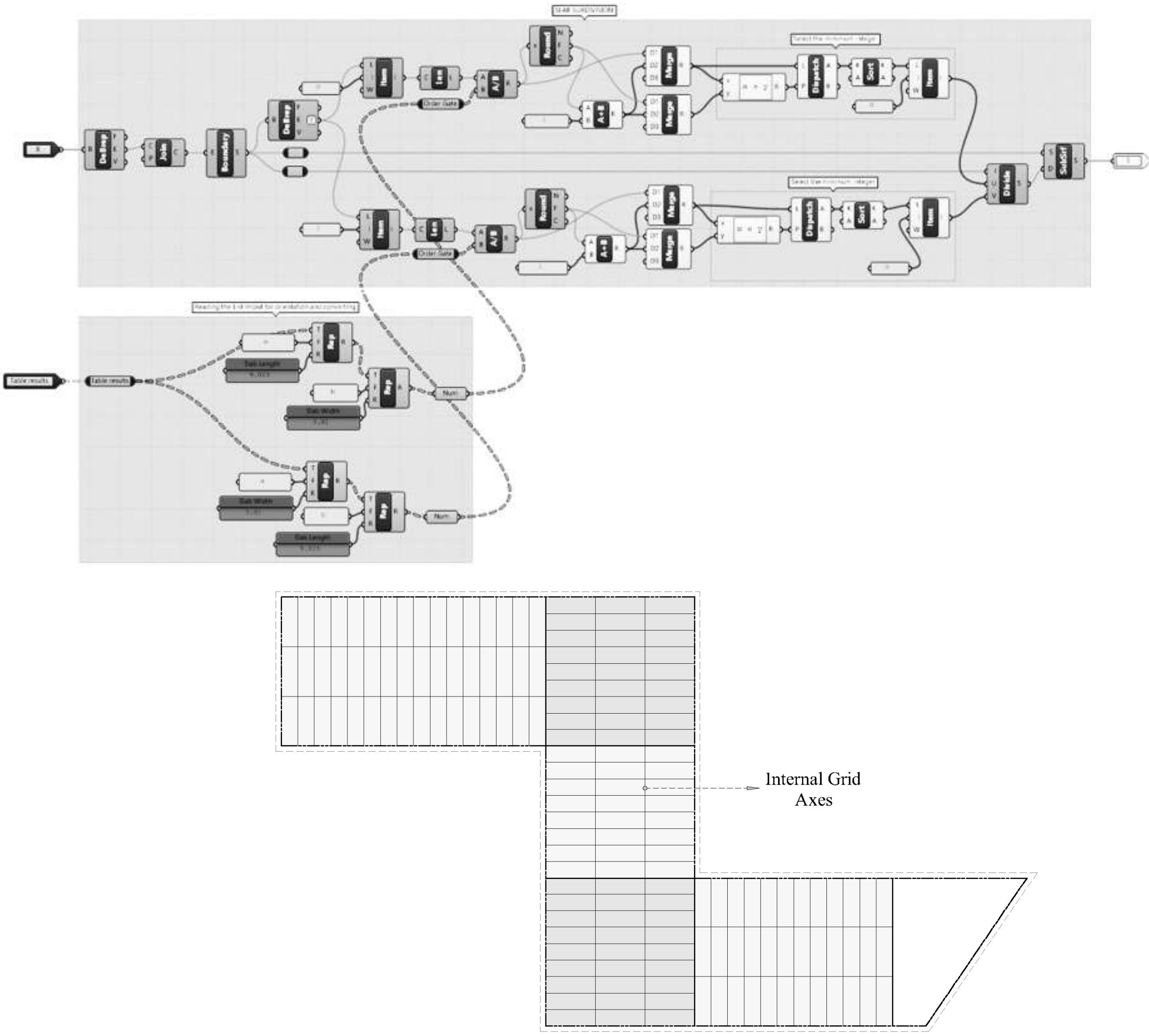


Figure 45- Subdivision for internal grid axes. Visual script and design solution (plan view)

Given these requirements, one of the longest sides of each of the sections is then taken, and their lengths are subdivided by 3.01, to then take one of the smaller sides of each of the sections and subdivide it into 9.01. If the result of these divisions is not an integer, a floor round of the number is made and a unit is added. The objective is to reach a number of subdivisions in each direction, which never exceeds the established maximum dimension. Finally, after defining the number of subdivisions in both directions, of each of the sections, this input is used to create a grid and subdivide each section into cells.

The option is given to change the directionality of the subdivisions of each section (being these 3.01 or 9.01), then the directions can be determined with the letters a or b (inputs stablshed by the user), which are then changed by the mentioned subdivision dimensions. The information obtained in this step is the set of cells of each section, which are taken as the interior grid of axes. See figure 45.

5.2.5. Girders axes location and joining of sections

The objective of this step is to join the sections obtained from the first subdivision, based on the continuity of the axes of the girders. These are always located on the shorter sides of the cells achieved in the previous step, since, as previously mentioned, the slabs rest in this way on the girders to achieve greater depth in the project. Being so, it starts from the location of all the shorter sides of the cells, to later be joined and form continuous lines, which form the axes of the girders. The lines that are aligned to the perimeter axes are excluded, since the girders are only located inside the project and never on the facades.

By having these axes of the girders, one of each group of parallel axes of the same dimensions is taken, in order to serve as a reference to join the sections. Thus, by intersecting the sections with the mentioned guide lines, groups of sections are obtained, which can be joined. The union of these sections is then obtained, based on the directionality and continuity of the axes of the girders (Figure 46). The final output of this step are the initial axes of the girders and the cells or grid of interior axes, classified in the new sections that have been joined.

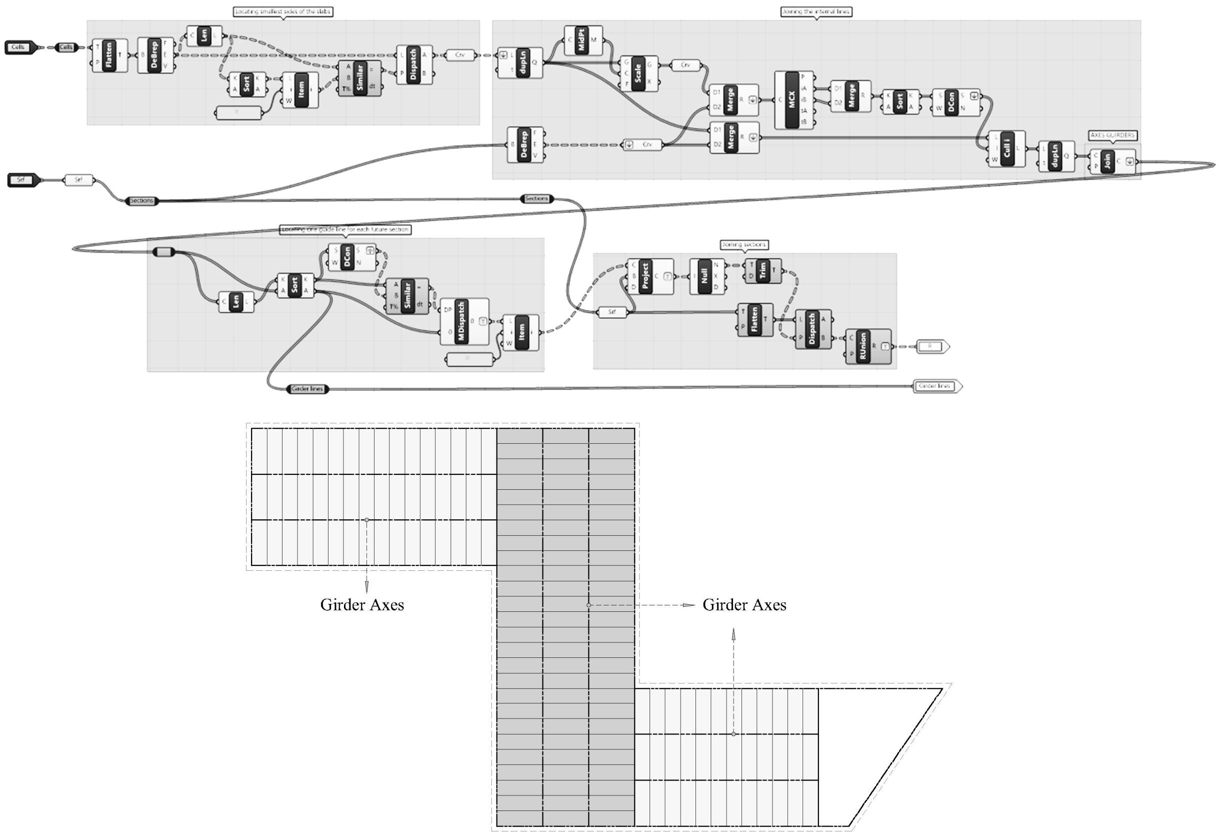


Figure 46- Girders axes location and joining of sections. Visual script and design solution (plan view)

5.2.6. Location of cores

After having the slabs grid, divided into the previously described sections, the next step was to locate the cores, in each of the sections. To do this, it was started with some initial parameters in the computational model, referring to the minimum size of the cores, their minimum area, the maximum ratio in area between cores and area of the section in which they are located, and the maximum distance between cores. Within the proposed methodology, it was defined that, the cores would be initially adjusted to the slabs grid in order to have a more efficient location, that maintains the largest number of slabs of the same dimensions. Thus, an attempt was made to select the appropriate cells within these grids and take them as a reference to form the cores.

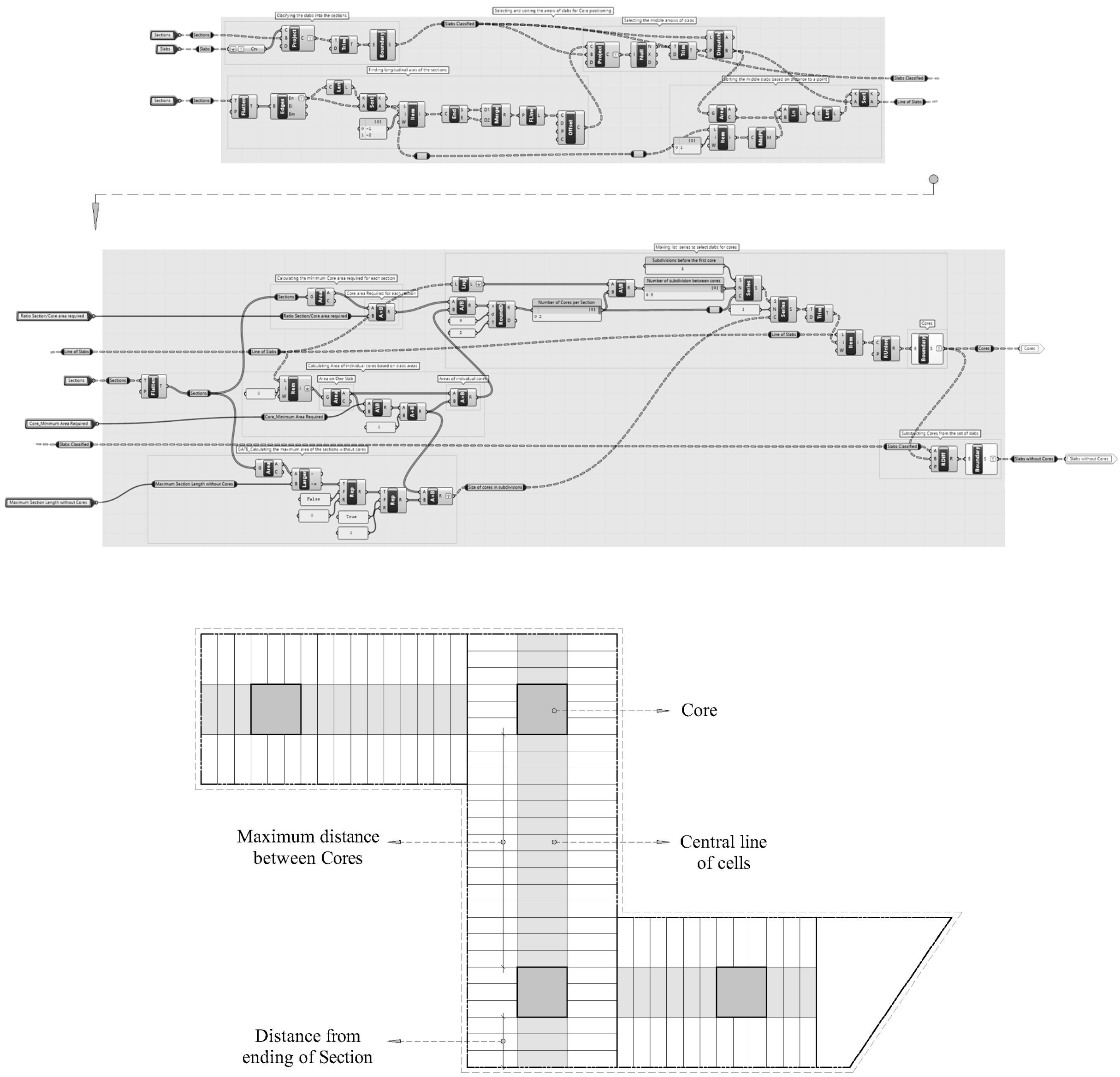


Figure 47- Location of cores. Visual script and design solution (plan view)

The implemented parametric workflow startedby locating the longitudinal axes of each of the sections, and then based on these, selected the most central line of slabs cells, where the cores would be located. After selecting these groups of slab cells in each section, they were organised with respect to a base point, so that their organised selection would be possible. Immediately afterwards, it was taken as as reference the parameters of minimum core areas, core/section area ratio, maximum distances between cores, and the approximate distance between the ends of the sections and the cores, in order to create a list of the specific cells to select and group, allow the conformation of the cores.

Figure 47 shows the script implemented for this step, which takes the grids of slabs and sections as main inputs, as well as the parameters described above, and generates as a result the cores of each section and the grid of cells of slabs, to which in addition, those that have been taken to conform the core have been subtracted. The plan shows the selections of the central lines of the slabs cells, as well as the positioning of the cores mentioned.

5.2.7. Resize of cores

Once the cores have been defined, positioned automatically according to the parameters defined in the previous step, there is the possibility of adjusting their size. this can be done by scaling cores in one or two directions based on tehir centroid. The new dimensions inserted for lengths and widths are taken, and they are used as divisors of the corresponding initial lengths, in this way scale factors are obtained with which the cores are resized.

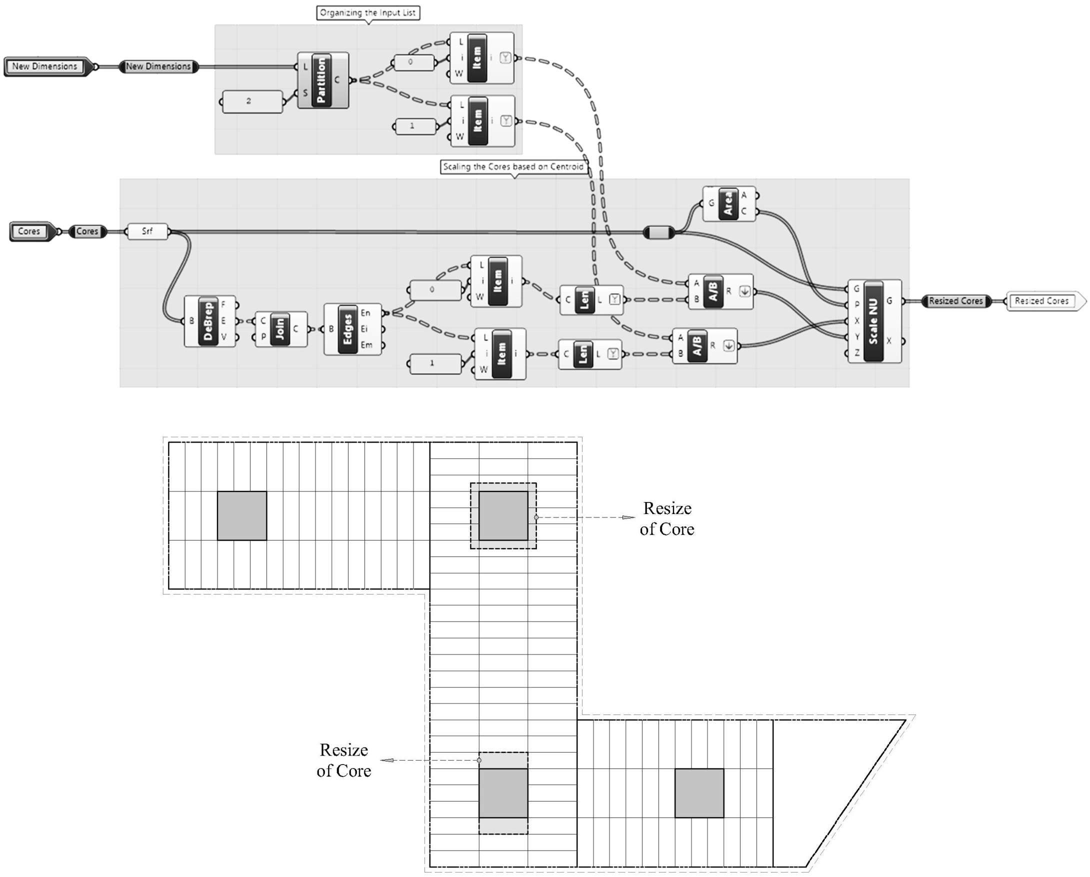


Figure 48- Resize of cores. Visual script and design solution (plan view)

Figure 48 shows the corresponding visual script, with which the list of cores with the new assigned dimensions is obtained as output. In the graph it can be seen that the objective of this step is to be able to change lengths and widths of each of the cores, independently.

5.2.8. Movement of cores

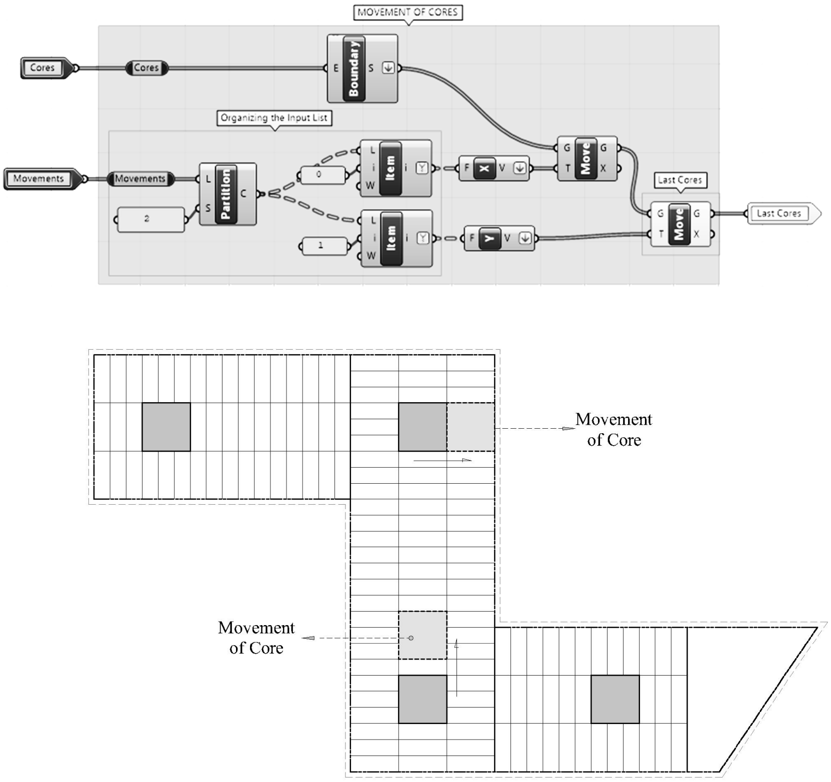


Figure 49- Movement of cores. Visual script and design solution (plan view)

Similar to the previous step, there is the possibility of moving cores in two directions, adjusting them to align with the main axes of the sections. The list of both positive and negative displacements in X or Y is taken and applied in an ordered manner, first in one direction and then in the other. Figure 49 shows the script and the explanatory graph of the movements of the cores. The output resulting from this step is the list of cores with the new positions.

5.2.9. Axes grid based on cores

With the modified sizes and positions of the cores, it is necessary to redefine the internal grid of axes to avoid overlaps between slabs and cores. For this, two main subdivision steps were implemented: Firstly, the sections in which the cores are found are subdivided, based on the extended sides of each one, which generates cells associated with the lengths of the sides of the cores. Figure 50 shows the graph with the mentioned cells (result of this first subdivision) and the visual script generating the list of cells from which the core cells have been subtracted.

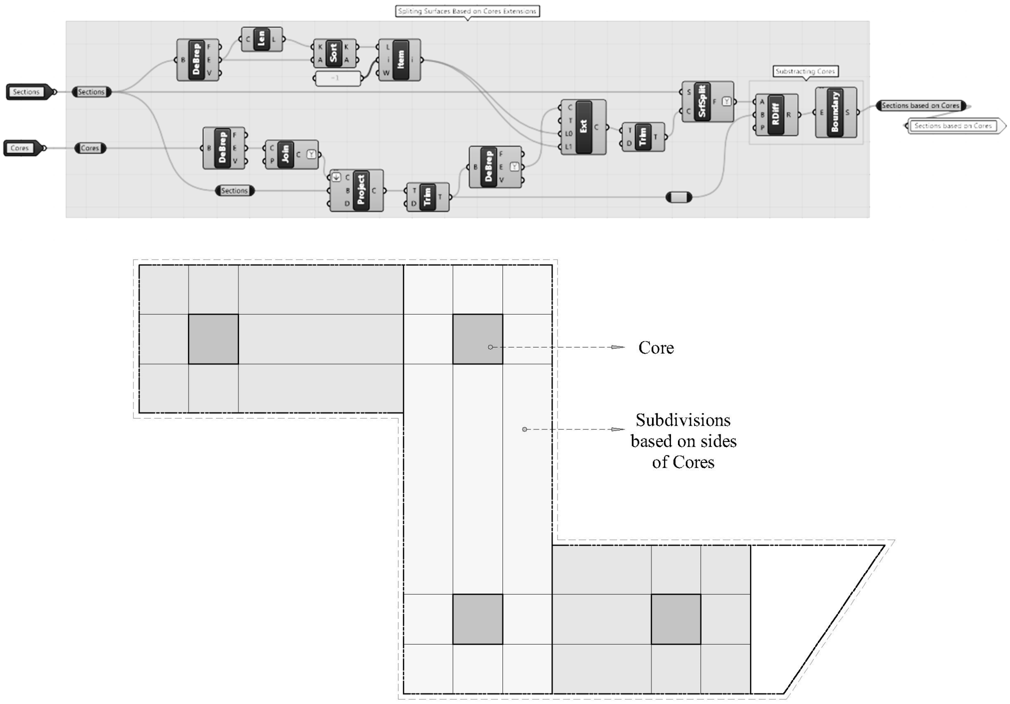


Figure 50- Axes grid based on cores (subdivision 1). Visual script and design solution (plan view)

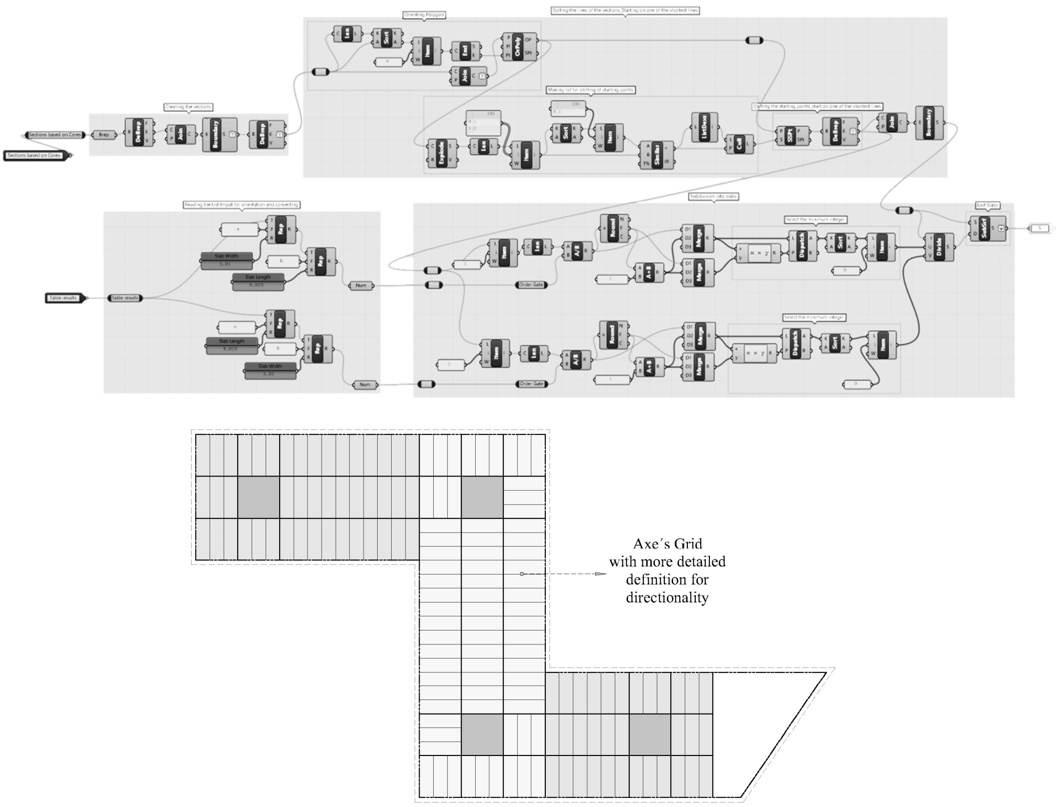


Figure 51- Axes grid based on cores (subdivision 2). Visual script and design solution (plan view)

Secondly, these last cells are taken and subdivided again, this time based on the maximum width and length dimensions of the hybrid slabs, as was done in step 4. To do this subdivision, the orientation of each cell had to be rearranged first to be as close as possible to the directionality established by the user in step 4.

Immediately afterwards, each one of the cells is subdivided according to the selected directionality, which can be alternated (See Figure 51). Finally, in this step, the grid of axes based on the cores is obtained, which has allowed a greater definition in the directions of the cells of the slabs.

5.2.10. Cores extension

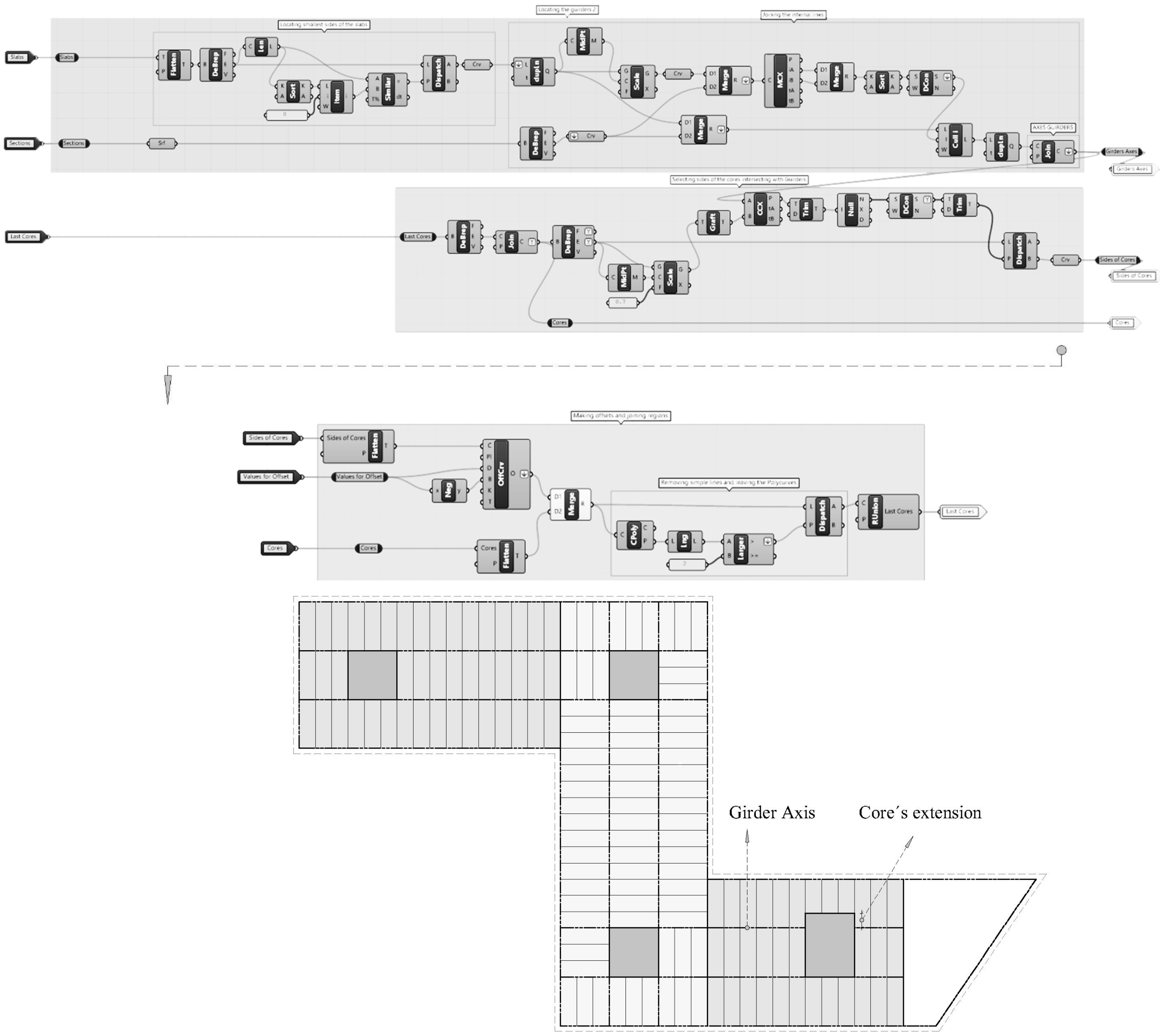


Figure 52- Cores extension. Visual script and design solution (plan view)

Until now, the inner axes grid (based on the dimensions of the slabs) and the positioning of the cores are closely linked to allow the axes of the girders (elements where the slabs rest) to end at the corners of the cores. In this step, the option is given to increase the size of the cores, on the sides parallel to the axes of the girders, without altering the axes grid.

This extension of the cores is divided into two steps in the computational model. In the first one, the axes of the girders are located again, based on the last grid of interior axes, these being located along the shorter sides of the grid cells. After obtaining these lines from all the cells, those that are aligned are joined and those that are on the perimeter axes are extracted (as mentioned above, the girders are only located inside the building). Once the axes of the girders are available, they are used to locate the sides of the cores that are on them, so that these are the ones that can be modified to increase the size of the cores.

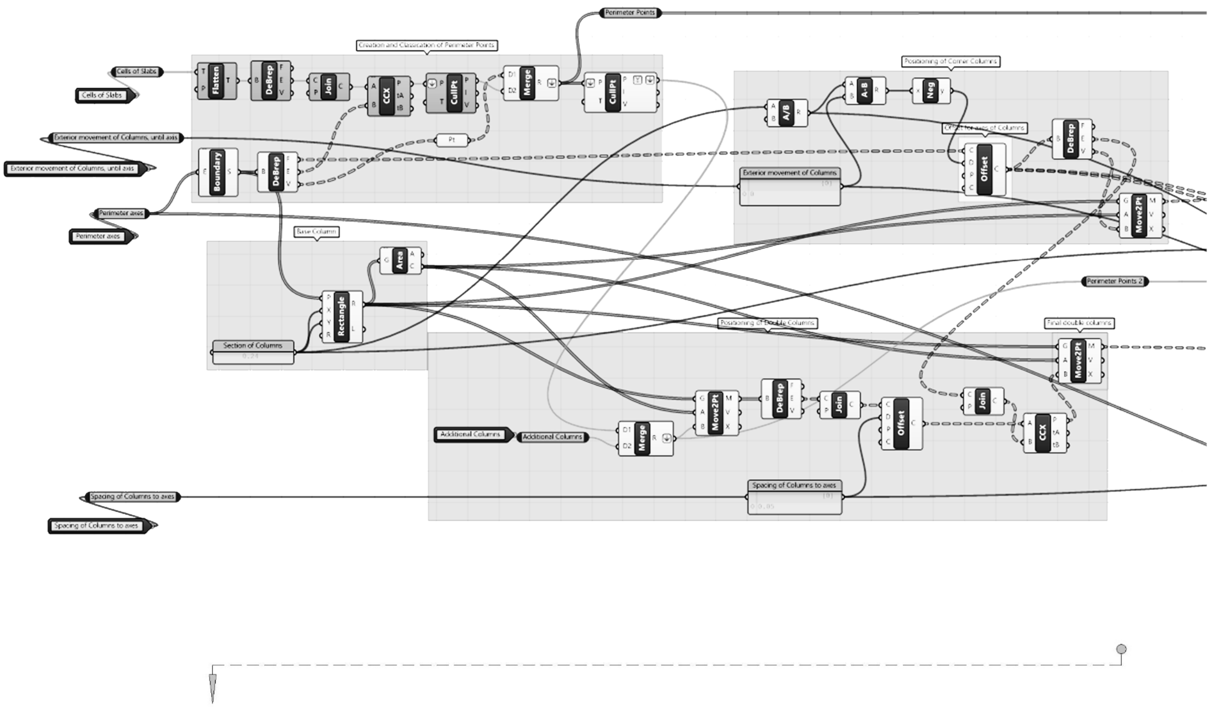
Secondly, once the sides of the cores that can be modified have been selected, the option is given so that an offset can be applied to each of them with the dimension to extend the core. The region formed from the offset, joins the region of the core to obtain the final shape, however, as can be seen in Figure 52, it was necessary to implement in the visual script, a classification of lines and polylines, to subtract the simple lines in cases where extensions are not generated in the cores.

5.2.11. Location of perimeter columns

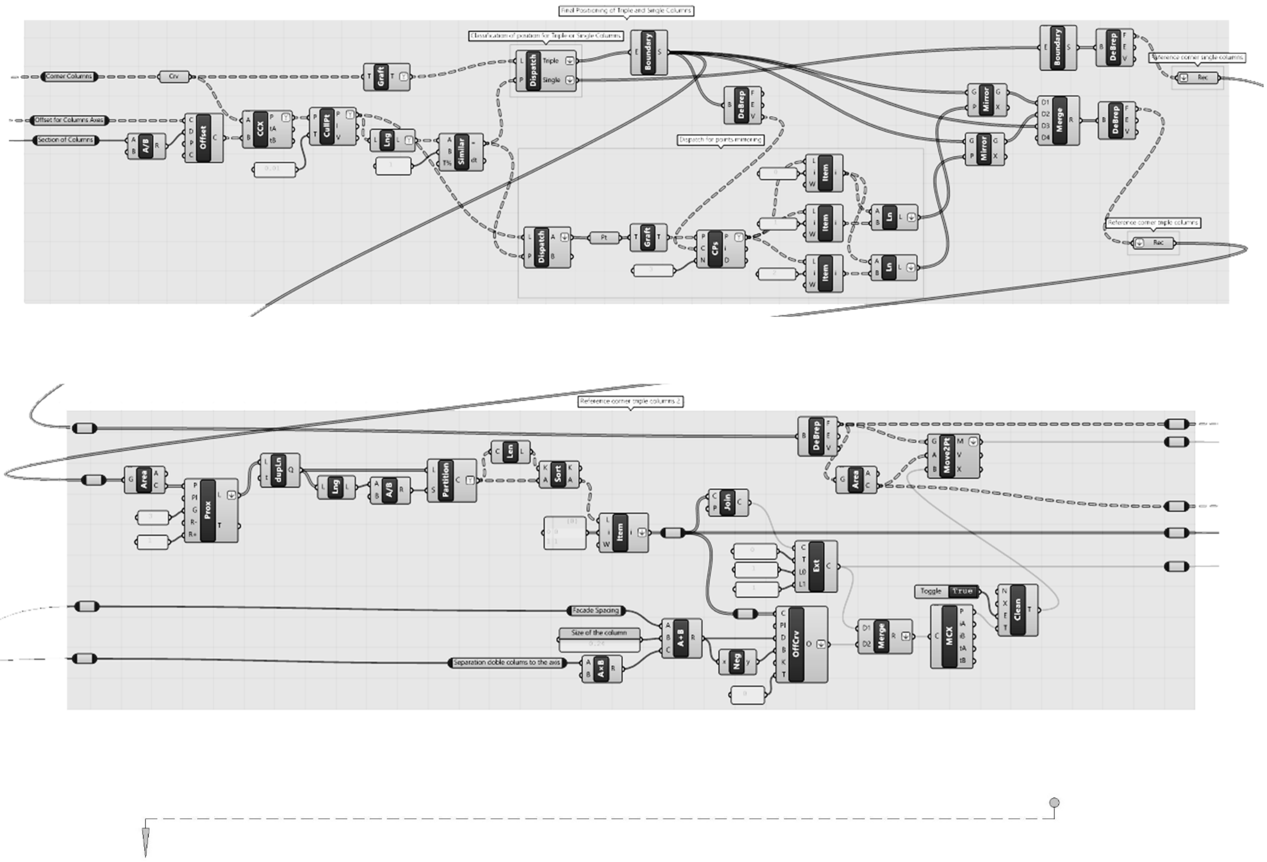
Once the interior grid of axes and the perimeter axes have been defined, it is possible, based on these, to locate the glulam columns along the facades of the project. As mentioned in the description of the CREE system, there are three types of grouping of these columns depending on the location. Thus, in the concave corner there is only one column, in the convex corners there are groups of three columns and along the façades there are groups of two columns, centered on the axes of the interior grid.

This column location step was divided into four parts. First, the axes of the columns were generated, parallel to the perimeter axes of the project, and all the central points where the columns would be located were positioned, with reference to the interior grid of axes. For this, it was necessary to locate or move the insertion points, depending on the set of columns, which in principle were classified between columns located in corners or along the facades. (Figure 53A). It is also given the option of being able to insert additional locations of double columns in the spans that are close to 9.0 m (They are located at the center of the span).

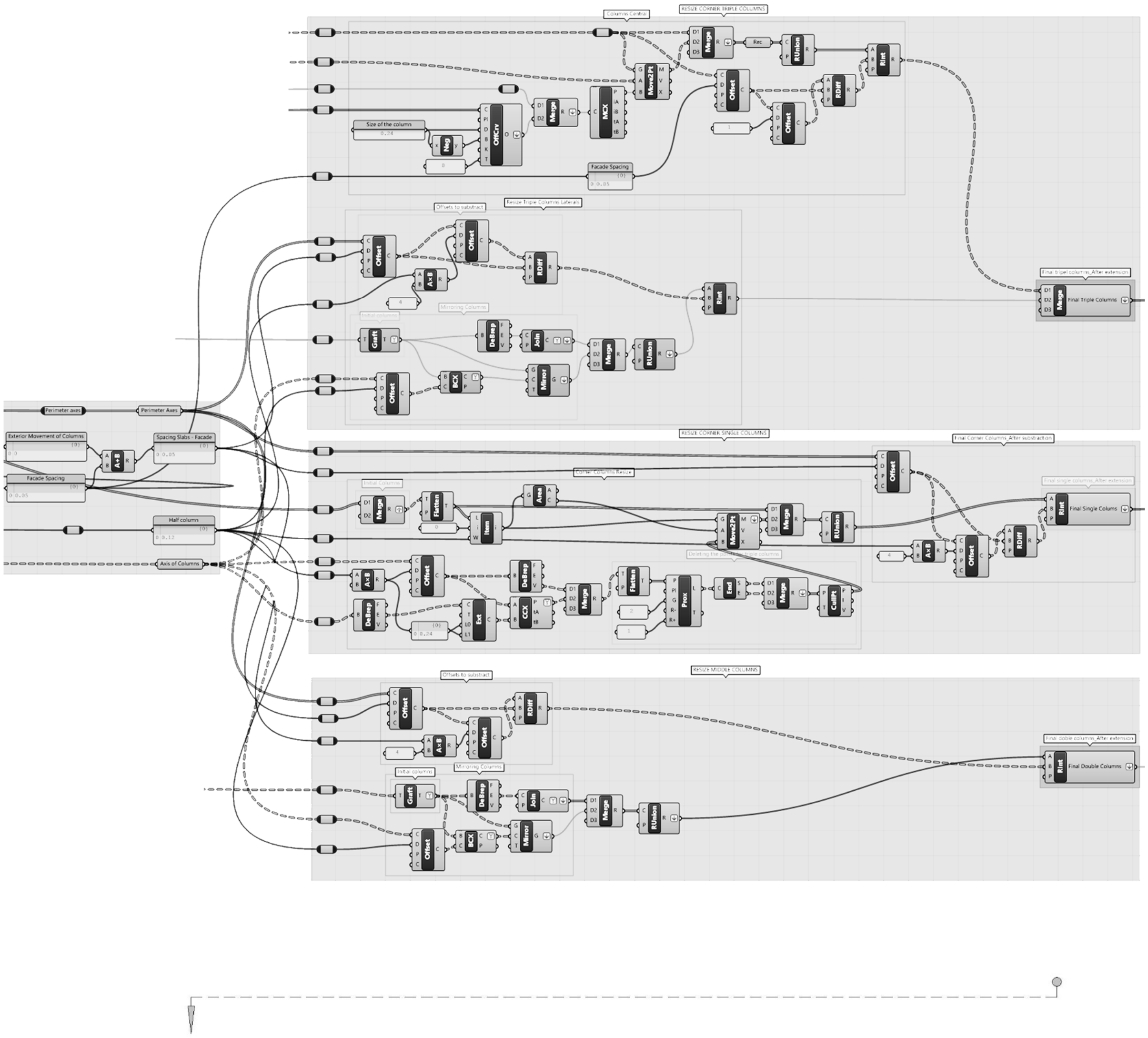
A.


Perimeter Points
Cells of Slabs
Exterior movement of Columns, until axis
Perimeter axes
Section of Columns
Additional Columns
Spacing of Columns to axes
Exterior movement of Columns
Perimeter Points 2

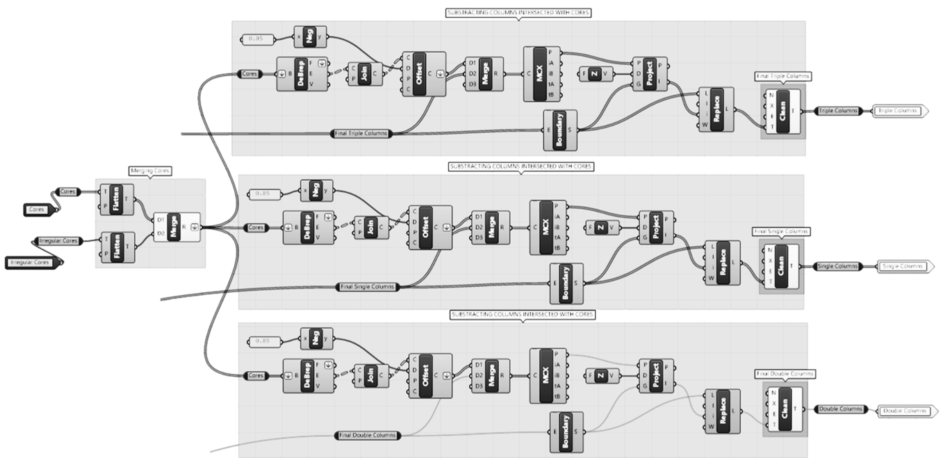
B.


Corner Columns
Offset for Columns Axis
Section of Columns
Facade Spacing
Size of the column
Separation doble colums to the axis
Toggle

C.



D.



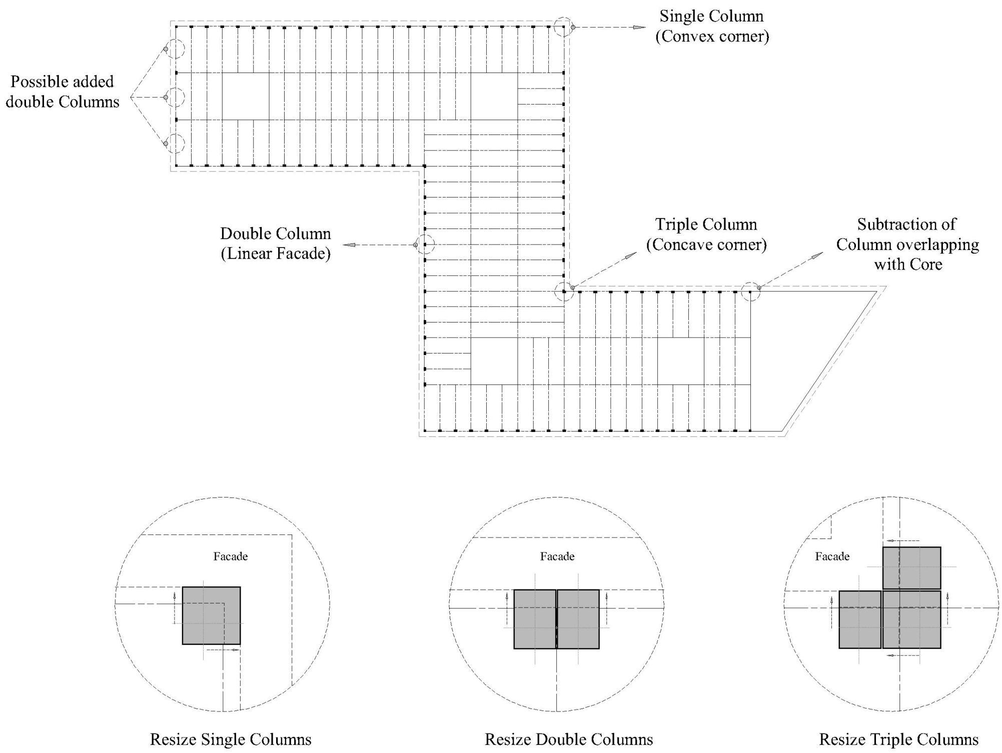


Figure 53- Location of perimeter columns. Visual script and design solution (plan view)

Secondly, once the reference columns were located, the other points were located depending on the type of grouping, thus for the double columns, based on the initial point, two equidistant points were created, separated laterally, and for the triple columns, two additional points were created, displaced in the sense of the sides adjacent to the corner. This process was carried out using offset and line intersections that take into account the spacing between columns. (Figure 53B).

After having all the columns positioned according to the proper grouping, it was given the possibility to resize them. Since these must be attached to the facades, which can be distanced from the perimeter axes of the project, it was necessary to ensure that the growth of the columns followed the distancing of the facades but simultaneously maintained the initial axes of location. For this, each group of columns was treated separately, and by means of offsets of the perimeter axes (based on the distance from facades), displacements of the reference columns and union of regions, in each location, the resized columns were obtained (Figure 53C).

Finally, after obtaining the final columns, classified by type of grouping, the possibility of eliminating those that are superimposed with cores or that are located towards the facades was implemented in the code. For this, by intersecting the geometry of the cores with the list of columns, those to be eliminated are found and removed from the list (Figure 53 D). The final output of this step is all the glulam columns, positioned along the perimeter of the building, classified into the three different types of grouping.

5.2.12. Placements of cores with spacings

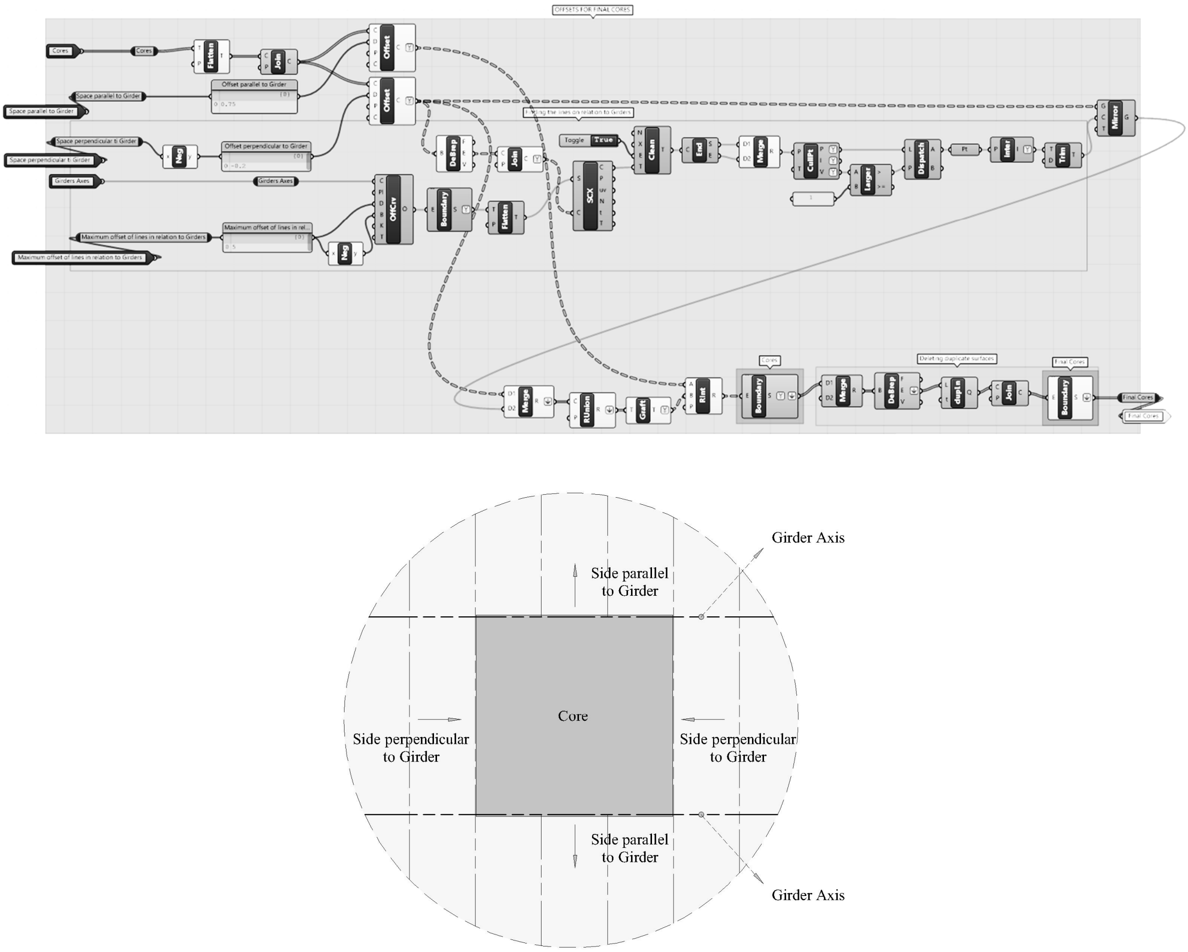


Figure 54- Placement of cores with spacings. Visual script and design solution (plan view)

Once the cores with or without extensions have been obtained (the result of step 10), they must be adjusted according to the spacing requirements of the system. For this, the girders axes are also taken as reference, since it is in relation to these that said spacings can differ. Thus, the sides of the cores that are parallel to the girders must move forward to support the entire core, while the sides that are perpendicular to the girders must move back the required spacing between the walls of the cores and interior axes grid.

The visual script in Figure 54 shows the process in which the sides of the cores are first found, perpendicular or parallel to the girders, to then apply the corresponding offsets. Through union and subtraction of regions, the final shape of the cores is obtained with the required spacings. Finally, a section is implemented in which repeated surfaces are eliminated, if applicable.

5.2.13. Placements of slabs with spacings

Similar to the previous step, offsets are applied to the slabs cells, which make up what has been called the interior axes grid. This in order to generate the final dimensions of the slabs with the spacing required by the system (generally 5 millimeters between slabs and axes).

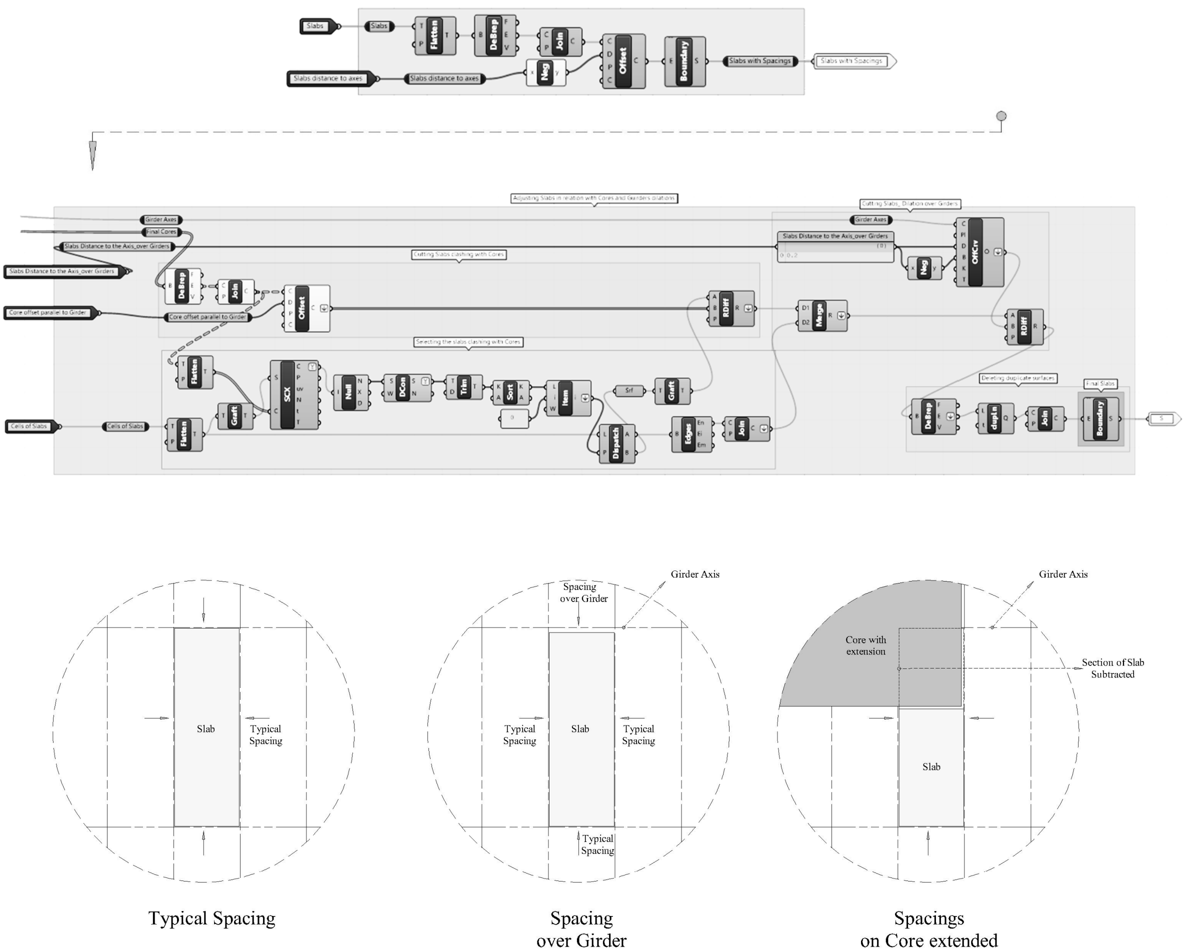


Figure 55- Placement of slabs with spacings. Visual script and design solution (plan view)

Other types of spacing are necessary in this step, and are related to those slabs that are supported on girders, since in these cases a greater space is used (2cm between axes and slabs). In addition, if any extension of cores has been made in step 10, it will be necessary to cut out those slabs that are superimposed on the cores, due to this resizing. The visual script of Figure 55 shows, in the first place, the code implemented for the spacing application described in the previous paragraph, and in the second part, the process used to resize the slabs faced with cores or supported by girders is described.

For this, the computational model begins by locating those slabs that are superimposed on the cores, and the intersected areas are subtracted, also taking into account the necessary spacing between core and slabs for this type of situation (3.5 cm approx.). Then, the slabs resting on the girders are located (through the use of intersections), and subtracted from the regions created with the offsets of the girder axes, The final output of this step is the list of slabs, with all the necessary spacings required by the system.

5.2.14. Placement of girders and L sections

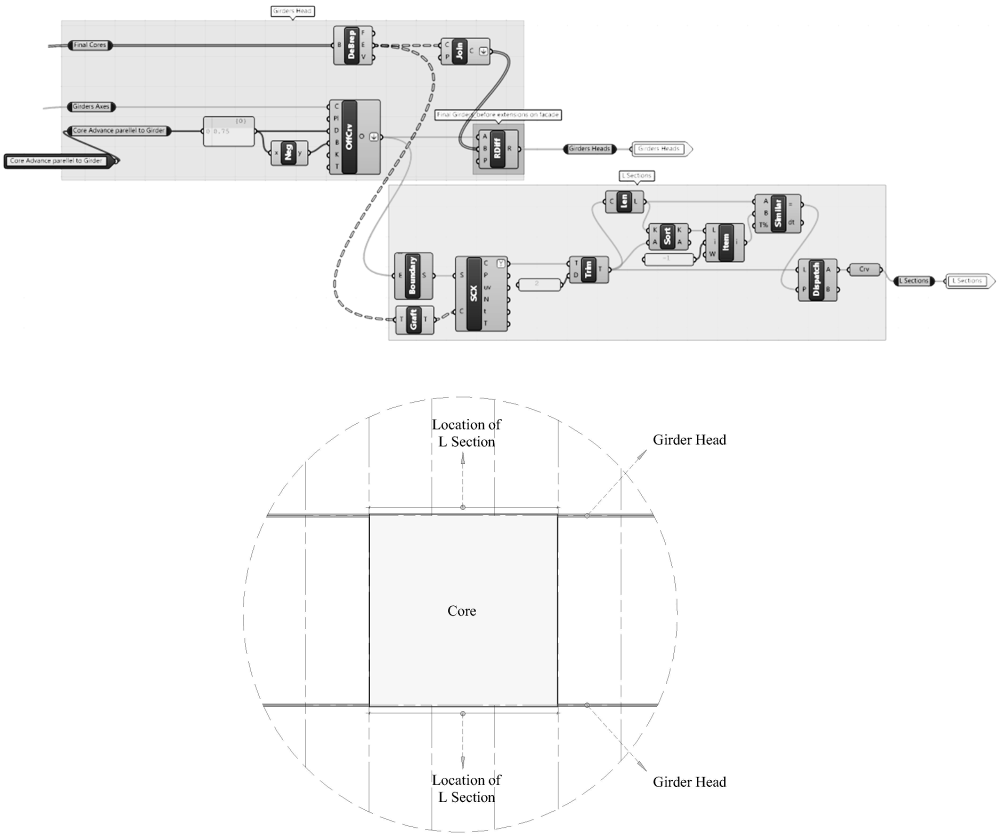


Figure 56- Placement of girders and L sections. Visual script and design solution (plan view)

In order to obtain the surfaces of the girders, starting from the already established axes, and omitting the sections that are superimposed on the cores, the axes were offset to both sides to meet the dimensions of the heads of the girders. Once the surfaces of these were obtained, the regions of the cores that are superimposed were subtracted, resulting in the final elements related to the heads of the girders (Figure 56).

Regarding the location of the L sections, they are anchored to the walls of the cores, to give support to the shorter sides of the slabs that are facing them. For its location, it was started from the surfaces of the girders, found in the first part of this step, and through the intersection with the sides of the cores, the reference lines for the location of the L sections were found, since they are generally located giving continuity to the girders, along the walls of the cores.

5.2.15. Location of interior columns

The interior columns, as previously mentioned, are made of steel-concrete composite with a circular section. These are located inside the project, so that they support the steel girders, in order to allow a greater span of these and thus a greater free area. Among the parameters to highlight in its location would be the diameter of the section of the columns and the maximum distance allowed between them.

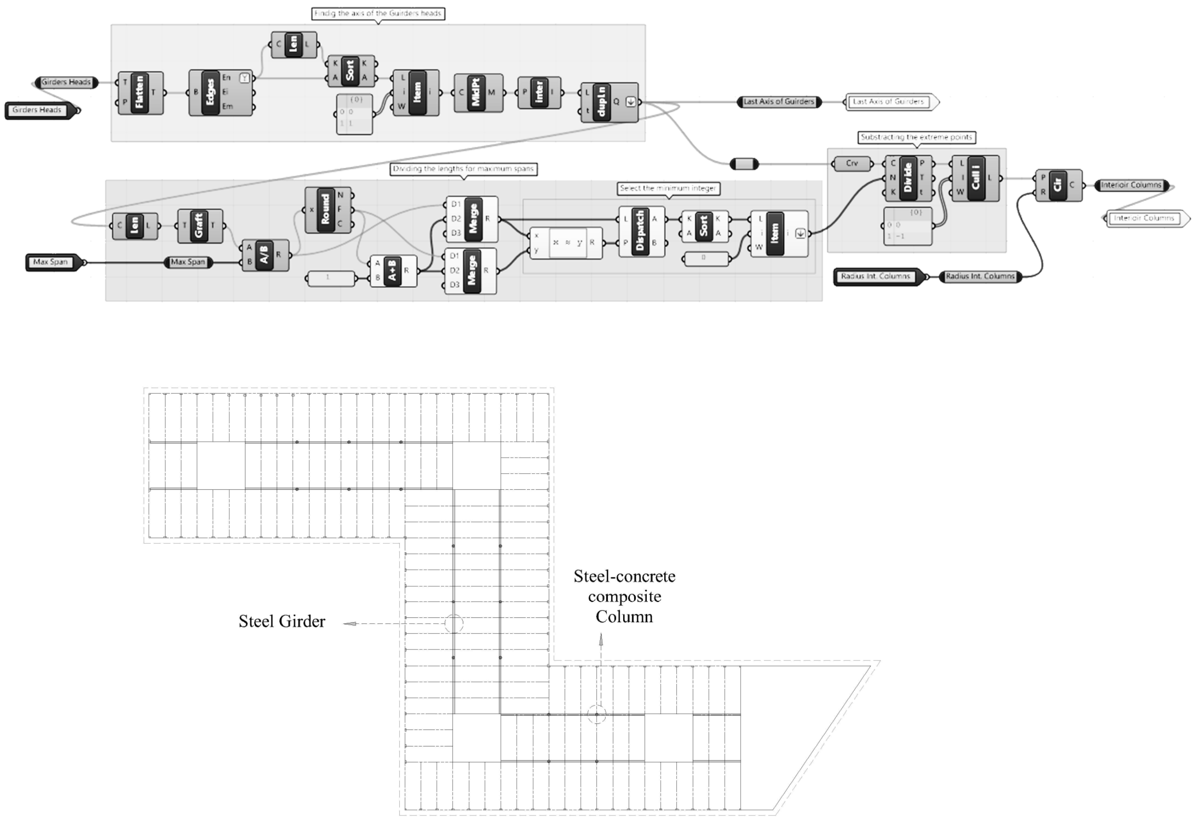


Figure 57- Location of interior columns. Visual script and design solution (plan view)

Figure 57 shows the visual script implemented to locate this type of interior columns. It began with the location of the axes of the surfaces of the girders Heads, which were found in the previous step. With these lines as a reference, the spans are divided in such a way that the subdivisions never exceed the parameter established by the user in relation to the maximum allowed span. Once these subdivisions are obtained, the initial and final points are extracted from the list, since this type of column is not located in them (the girders rest at their ends on glulam columns or on the walls of the cores). Finally, the sections of columns with the established diameter are located, in each of the reference points of the subdivisions.

5.2.16. Façade distribution

As shown in Figure 58, to make the distribution of the façade modules, the total façade surface was generated based on the initial perimeter of the building and its offset towards the interior, using as distance the facade thickness parameter. Since the façade modules are related to the glulam columns, located around the perimeter of the building at the intersections of the interior grid of axes with the perimeter axes, it was decided to take this interior grid as a reference to subdivide the generated façade surface.

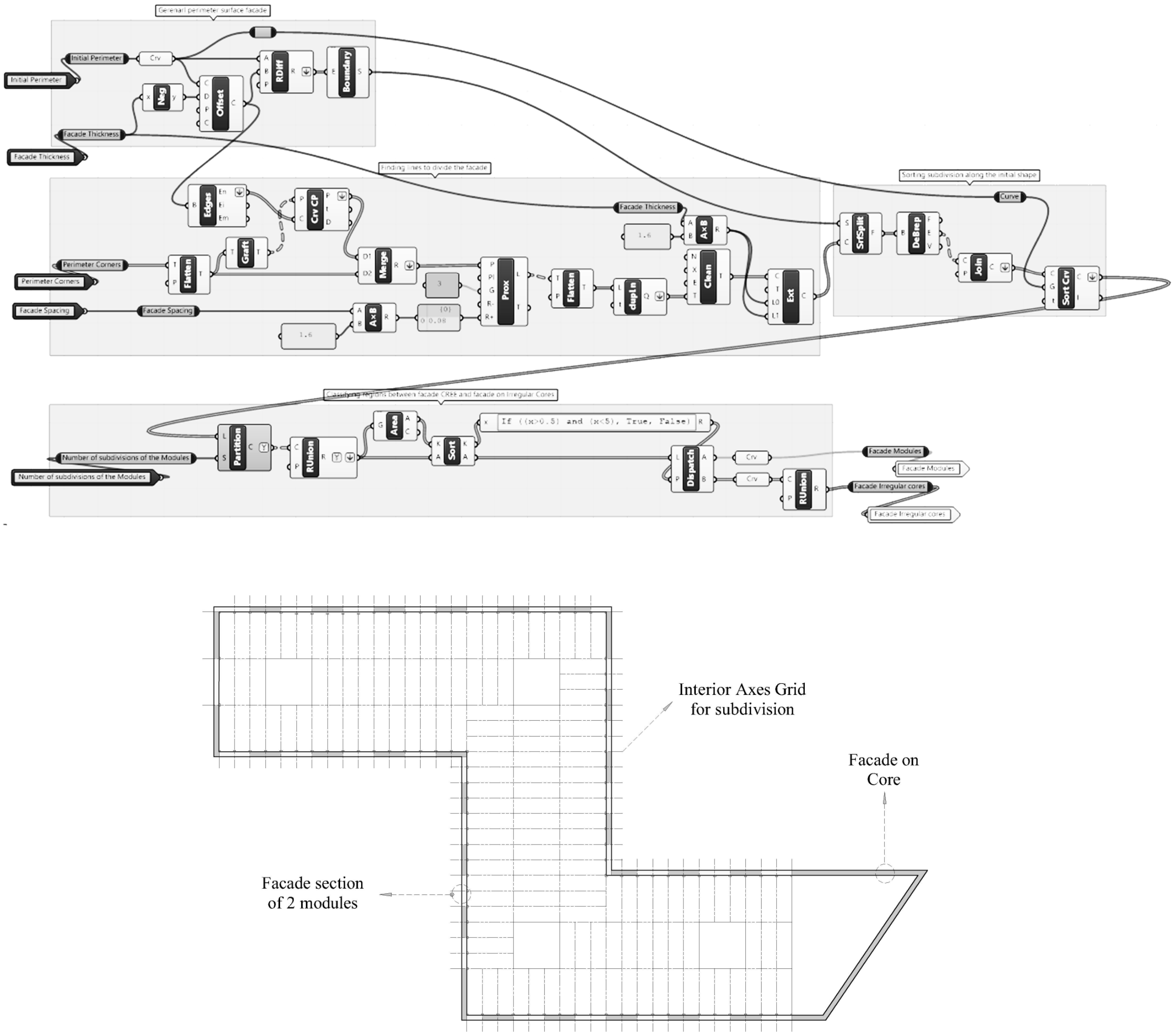
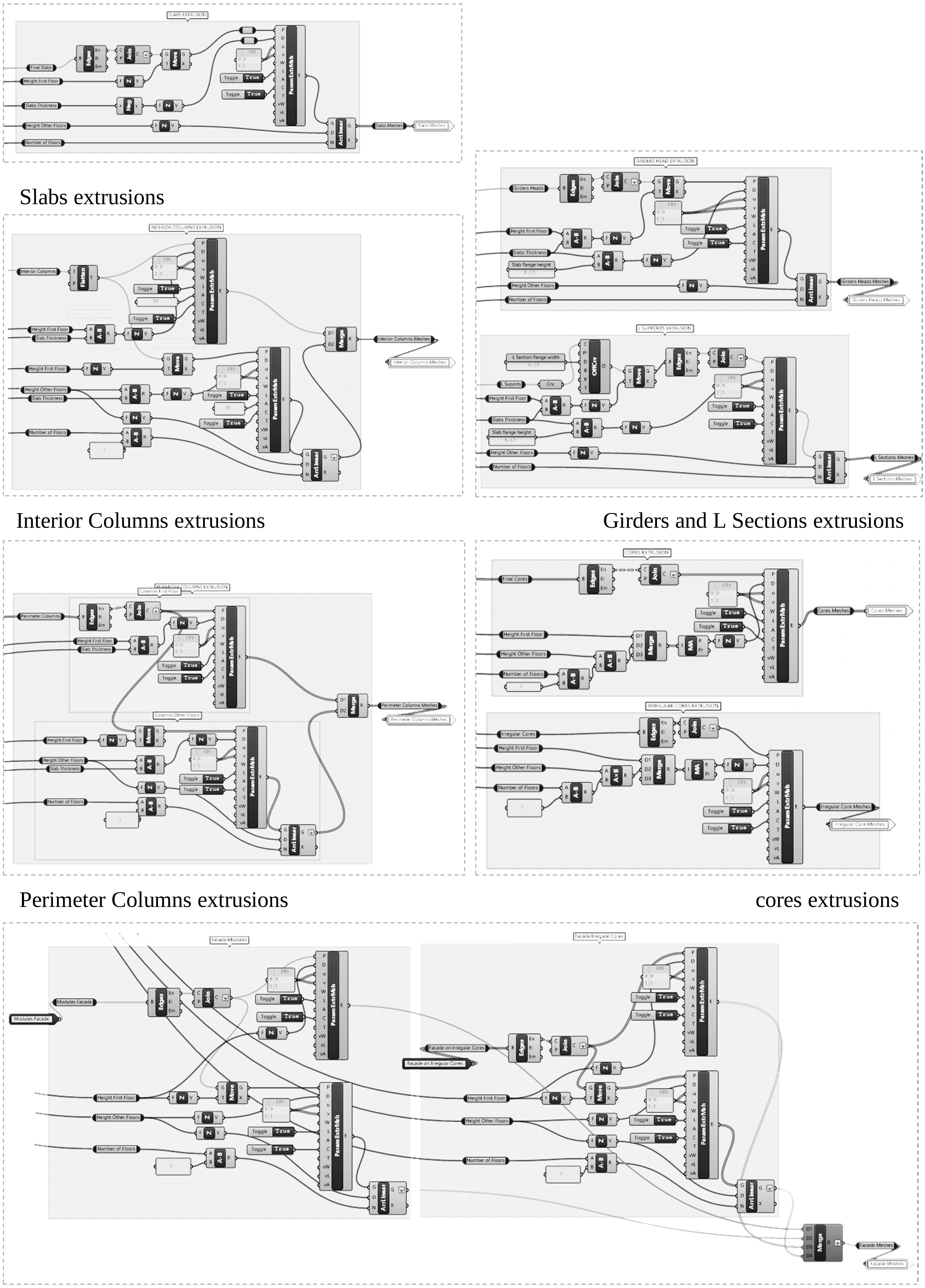


Figure 58- Façade distribution. Visual script and design solution (plan view)

Thus, all the points of intersection between the interior grid of axes and the perimeter axes were located, to then generate lines perpendicular to the façade at each of these points. Once these lines were obtained, they were used to divide the façade surface, thus obtaining modules of lengths linked to the interior axes of the building. A parameter given to the user was generated to define how many of these modules would have the final length of the facade modules, being possible to decide between 1, 2 or 3. In the cases in which they were greater than one, the union was implemented in the code of the consecutive modules, until reaching the desired number, for this it was necessary to organize the order of the modules around the perimeter of the building.

Finally, the façade sections were classified between those related to the glulam columns and those that in certain cases are in front of cores that have been arranged with sides on the façade. There are two final outputs of this step: the facade modules with the lengths defined by the user, and the facade sections in front of cores.

5.2.17. Elements extrusions



Facades extrusions

Figure 59- Visual scripts of elements extrusions

After having all the system elements planned, the corresponded three-dimensional model was generated. For this, the main parameters that intervened in the step were: the number of floors, the height of the ground floor, the height of the other floors and the thickness of the slabs. Based on these parameters, each of the elements was taken, as well as extruded at the appropriate heights.

Figure 59 shows the different visual scripts used for this step in each of the system elements. At a general level, it was necessary to treat the extrusions of the components on the ground floor separately from those located on the other floors, given the possibility of varying heights. For the extrusions, meshes were used, since this type of geometries is compatible with three-dimensional visualisation in the user interface developed with the HumanUI plugin, a topic that will be developed in the next section of this chapter.

The output of this step is the three-dimensional model of the project grouped into different components, which can be visualized through the user interface. In this way, the first part of the computational model is closed, called general structure, which covered all the information processing related to the creation of the system elements, taking the parametric schemas as a reference and with the objective of providing the information about KPIs.

5.3. CONFIGURACION OF USER INTERFACE

The second section of the computational model corresponds to the implementation of the User Interface, also developed using Grasshopper, and the HumanUI plugin. As can be seen in the schema of Figure 60, the management and visualisation of the information was organised in 5 parts: parameters, 2D views, graphics and tables, 3D view, and data export. These parts of the computational model were grouped into 3 different windows for visualisation.

The first window contains the computational model list of parameters, the ones that enable automation and user interaction with the project design. These were divided into three steps, corresponding to the order of the general structure. The first step contains the necessary parameters until reaching the point of locations of cores. The second step contains those parameters that intervene in resize and movements of cores, and axes grid based on cores. Finally, the third step includes the necessary parameters, from the point of core's extension to the extrusion of the project components.

Each of the steps was related to a 2D view, allowing to see the progress made. And each one of them was organized under a tab that could be selected, allowing to witch among the three different views. Finally, the section related to data export was also included in this window.

The second window continues the graphs and tables generated from the information provided by the first section of the computational model. With these it is possible to see the information related to the KPIs, of the decisions made during the project configuration process. This window is activated at the end of the third step in the first window and contains graphs relative to the amounts of slabs, facade modules, columns and general areas of the project. As for tables, it contains all the information, more detailed, of each one of the components of the system.

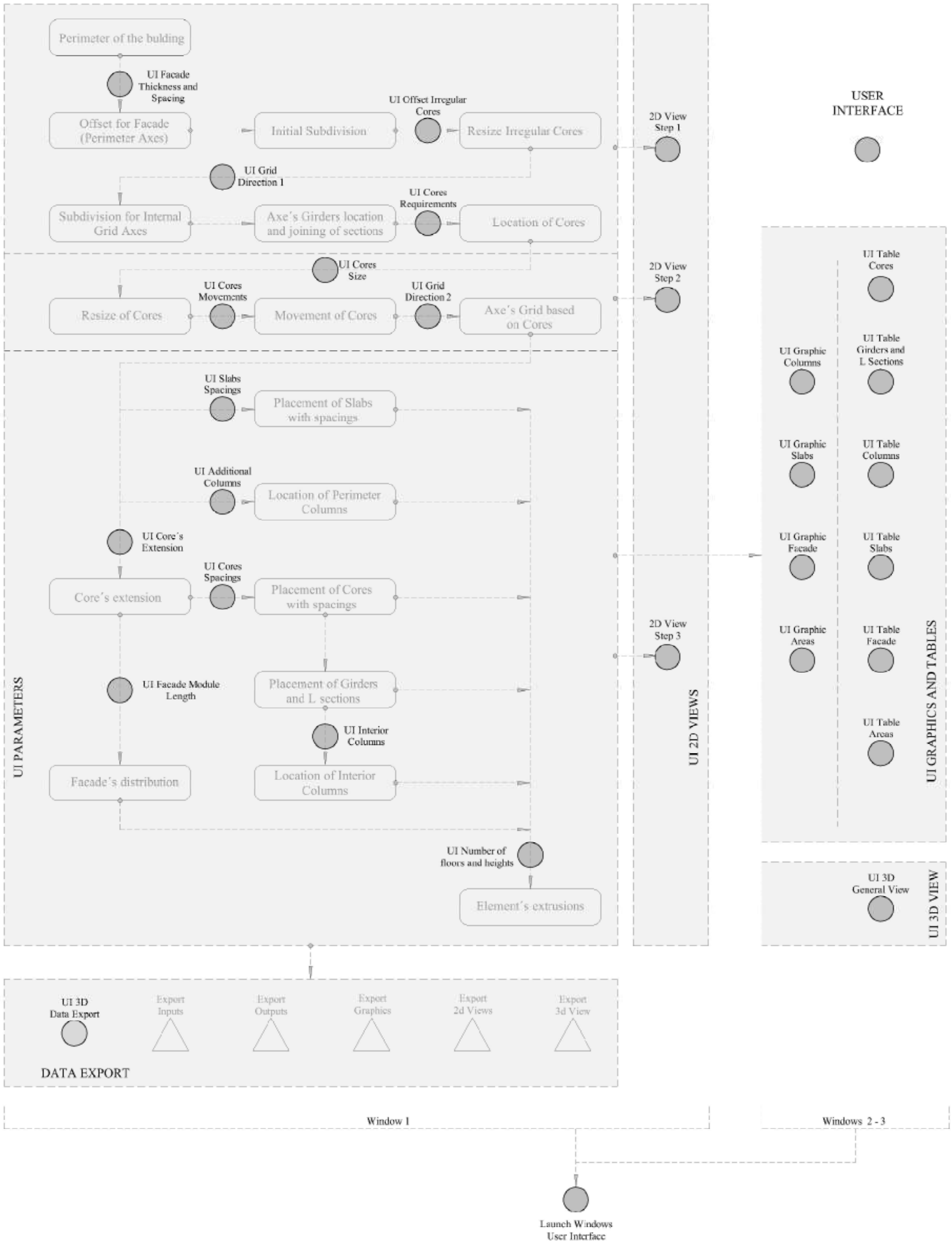


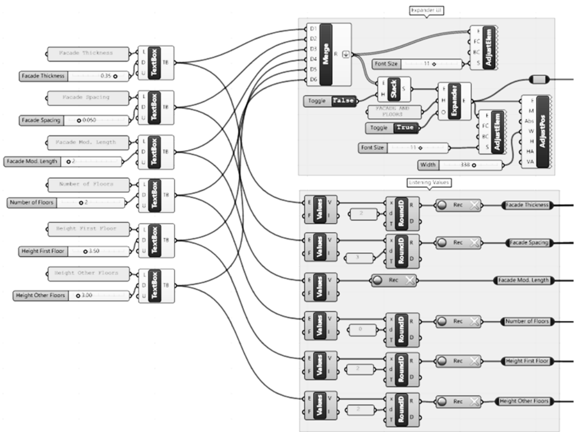
Figure 60- Schema of the second section of the computational model (User Interface)

Finally, the third window contains the three-dimensional model of the project, with all the elements classified by colors according to the type of system component. These can also be hidden by typology, in order to allow a better visualisation of each of the components. Said window can be displayed once the third step of the first window is finished, in the same way that it is done with the graphs and tables window.

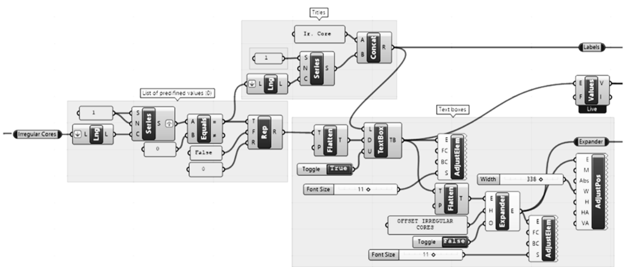
5.3.1. UI parameters

The user Interface displays information regarding the project's parameters, allowing user manipulation and data extraction. These sections were inserted into the general structure of the computational model, in a systematic way, in order to give the possibility of interaction with the user. In each place where they were inserted, they take information from previous steps and allow the manipulation of parameters to define the next steps of the computational model.

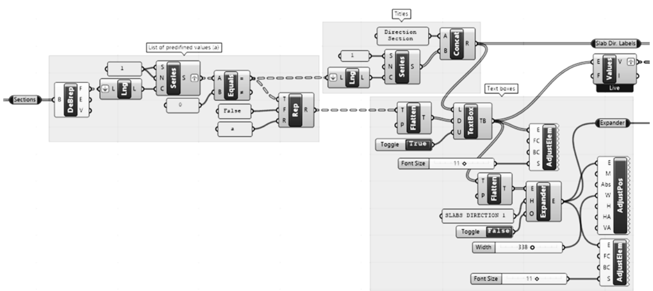
The first step of this section covers the parts called: facade thickness and spacing, offset irregular cores, grid direction 1 and core requirements.



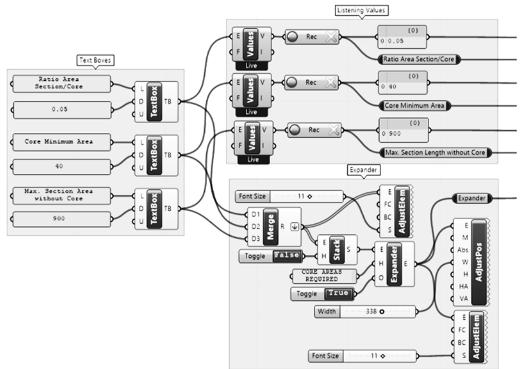
Facade thickness and spacings



Offset irregular cores



Slabs direction 1



Cores requirements

Figure 61- Visual scripts of UI parameters (First step)

All the sections of the script related to the parameters in the User Interface contain components of text boxes, sliders, check lists or buttons, that allows the entry of information or alteration of parameters. After the parameter has been chosen or modified, this information is taken to the next step within the general structure. In this way, there are generally within this type of scripts the elements to be placed within the User interface (with pre-established values), the group of components that read the values assigned by the user, and a group of components that modify the graphics and way of grouping the elements placed inside the user interface.

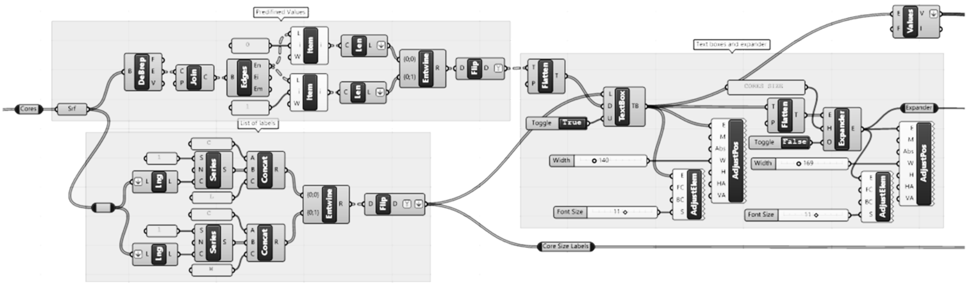
The facade thickness and spacings section generates within the user interface the initial configuration parameters of the project: the thickness of the façade, its spacing with reference to the perimeter axes, the number of floors, the height of the ground floor and the height of the other floors. The parameter of the length of the facade modules was also included.

The irregular cores section takes as input boundary of the irregular cores that can be modified, and generates a list of text boxes that allows inserting their offsets in meters. Regarding the section of slabs direction 1, the list of sections of the first subdivision of the initial perimeter is taken, and values are assigned to the directionality of the slabs in each of them, these being "a" or "b". The user can then define to change these directionalities, whose values are read to modify the model in the general structure.

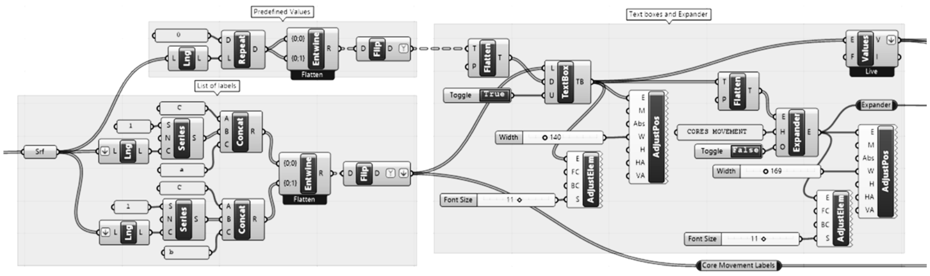
The cores requirements section allows the alteration of the parameters related to the creation of the cores, among these are: the area ratio between cores and the section in which they are inserted, the minimum area of the cores and the maximum distance between each one of them. With this section, the first step of the UI parameters ends. (Figure 61)

The second step contains the parameters related to the modification of the cores (Figure 62), once these have been established by the code automatically, and the generation of subdivisions to achieve the interior grid of axes, based on the new dimensions and core positions. Thus, the section called core size takes the list of length and width dimensions of the cores and generates text boxes that allow the user to modify these dimensions. These values are read and taken by the general structure to scale the elements.

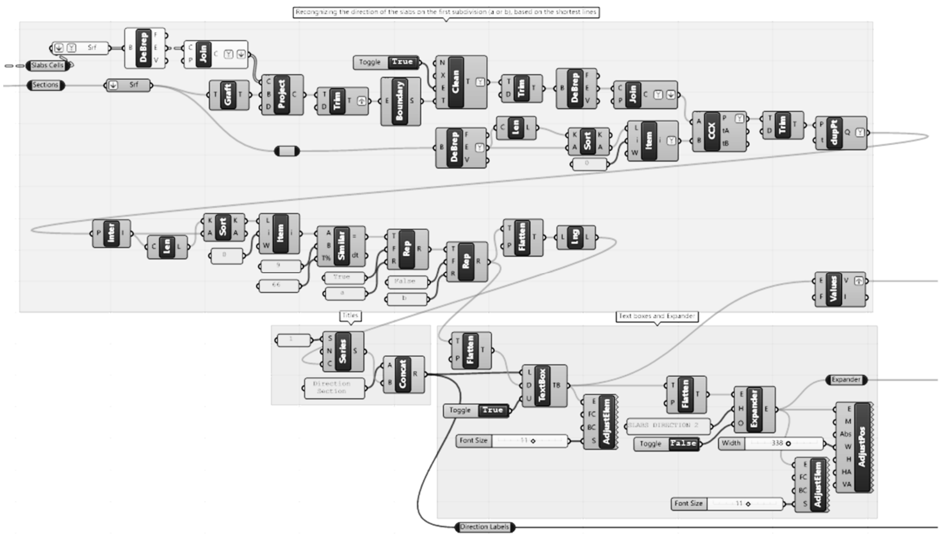
The core movement section generates a list with the positioning of the cores in two directions, “a” and “b”, that can receive positive numbers for displacements in one direction and with negative numbers for the opposite direction. The last section of this step, called slabs direction 2, firstly generates a list with default values of the axes interior grid directionality of all the new subdivisions of the project, which were based on the sides of the modified cores. To do this, the inner grid resulting from the step slabs direction 1 is taken as a reference, so that the default values used in this section are similar to those used in the previous step. In the same way, the directionalities can be alternated between "a" or "b", with the difference that in this step there is a greater number of subdivisions, which allows greater control over the directionality of the slabs.



cores size



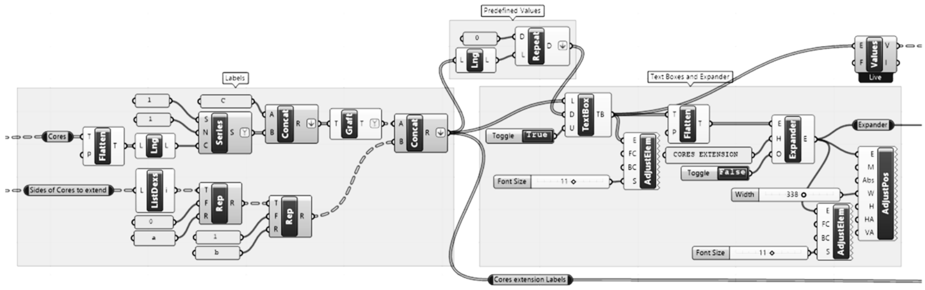
cores movement



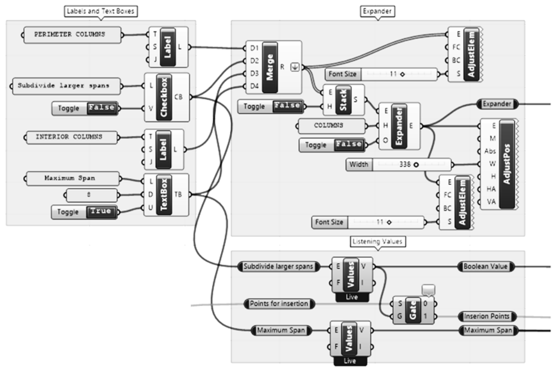
Slabs direction 2

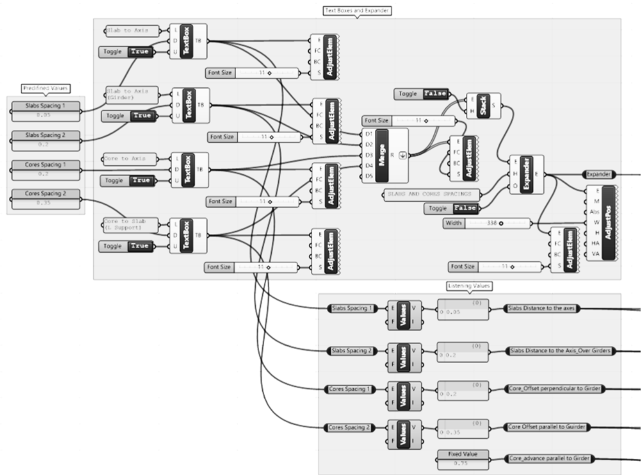
Figure 62- Visual scripts of UI parameters (Second step)

The third step of UI parameters corresponds to all the other parameters related to the final definition of the cores and slabs, taking into account the spacings required by the construction system. In addition, within this step is the definition of some parameters related to the positioning of the facade and interior columns (Figure 63). The core extensions section takes the values generated in the general structure related to the sides of the cores parallel to the girders, which can be extended to increase the size of the core, without modifying the interior axes grid. A list of all these sides of the different cores of the project is generated, with zero values, which can be modified for the extension.



Cores extension





Additional columns

Slabs and cores spacings

Figure 63- Visual scripts of UI parameters (Third step)

The slabs and cores spacings section contains text boxes with the slabs spacing parameters: slabs to axis and slabs to axis over girders (as mentioned, this spacing is generally greater than the first), and cores spacing: core to axis (on the sides perpendicular to the girders) and core to slabs (on the sides parallel to the girders, where the L sections are located). These values are read by the general structure and used to develop the final sizes of the cores and slabs. The additional columns section has a parameter for the glulam columns and one for the steel-concrete composite columns. For those located on the façade, the location of an additional column is allowed in the center of the spans close to 9.0 m, and for the interior columns, the maximum separation distance between them can be decided.

Within this part of UI parameters, it was decided to also place the export parameters of the project data related to inputs, outputs, 2D views, 3D view, graphs, and tables (Figure 64), which will be explained in the next chapter. In this step, related to the User Interface, a check list was generated to select the type of information to be saved, xlsx and jpg being the formats established. It was also necessary to configure the script to allow the entry of the file names by the user and the search for the location where they would be saved.

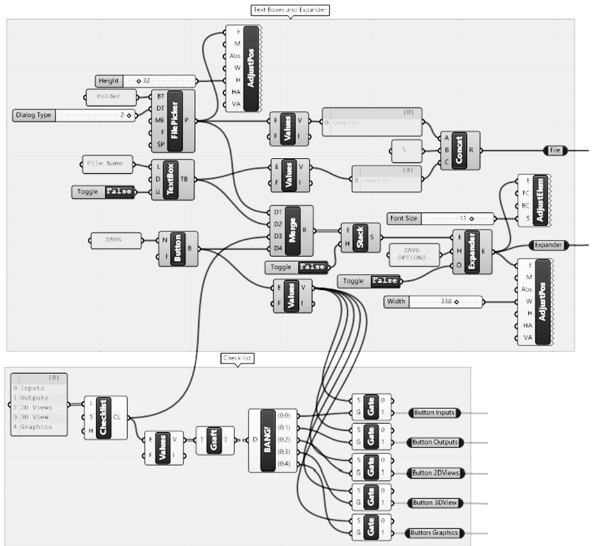


Figure 64- Visual scripts of UI export data

Figure 65 shows the display in the User Interface of the previously described section of UI parameters, which is organised into the three project configuration steps and the part related to data export. Each one of these parts contains expanders with the different parameters to be inserted or selected, which depending on the project can vary in length, since they depend on the number of elements of each one of the components of the prefabricated system.

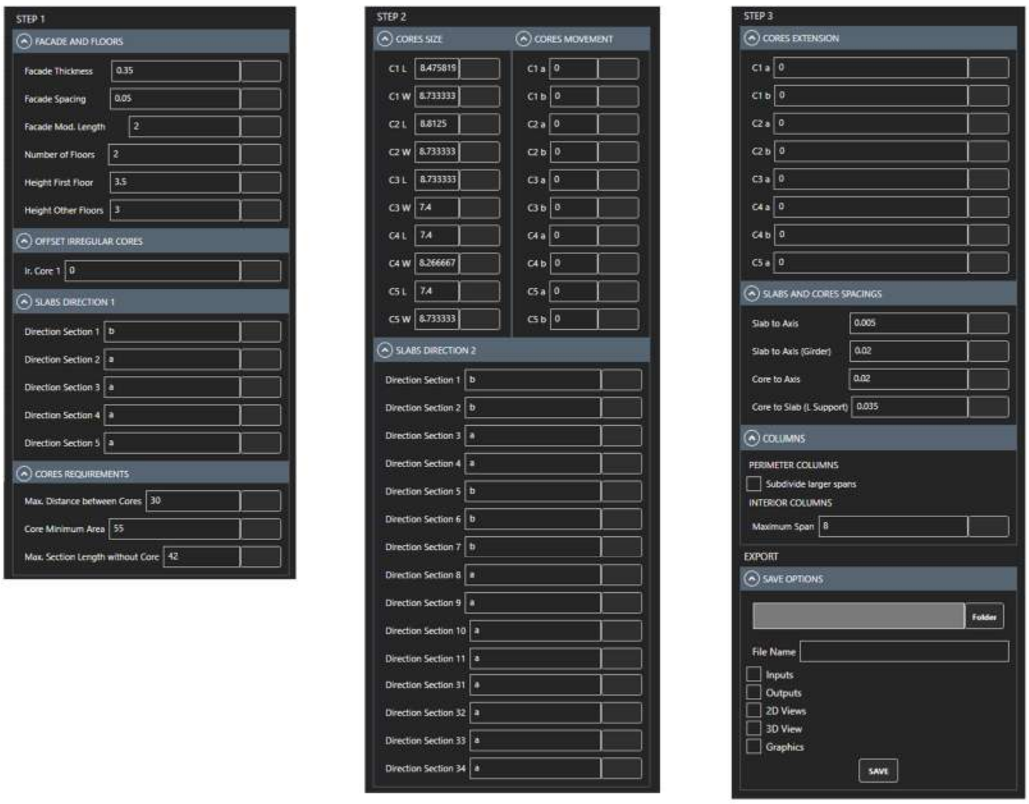


Figure 65- User Interface parameters and exporting data

5.3.2. UI 2D views

In order to allow the user to visualise the project with the decisions of the parameters described above, which are generated either automatically or defined by the user, a section with three different 2D views was implemented in the User Interface of the first window, one for each of the steps mentioned in the UI parameters section. These visualisations, being related to the three steps discussed, are increasingly specific in the type of information they present and are accessed through tabs that must be selected, depending on the step in which the user is establishing parameters.

The first 2D view is open by default in the User Interface and presents the information related to the first step of UI parameters. It contains the perimeter axes of the project, the grid of interior axes and the first subdivision of the project, if it has a compound shape. Figure 66 shows the visual script for the implementation of this view, where it can be noted that in addition to the collection of the information described above, to be placed in the User Interface, nomenclatures were placed on the subdivisions of the project, classifying them between regular (used for the location of slabs) and irregular (used as cores) (See Figure 67). In this way, the visualisation of the subdivisions for the change of directionality of the interior grid of axes is made easier.

The second 2D view corresponds to step two of the UI parameters, and it shows the modifications made in terms of the sizes and displacements of the cores, as well as the subdivisions of the project, generated from the new sizes and positions of the these. It was necessary for this view to place nomenclatures to the cores and the subdivisions, in order to make it easy to locate the elements to be modified. In it, the interior axes grid is also visible with the directions in each of the subdivisions, parameters that can be modified. Figure 68 shows the visual script developed for this 2D view and Figure 69 contains the final appearance in the User Interface.

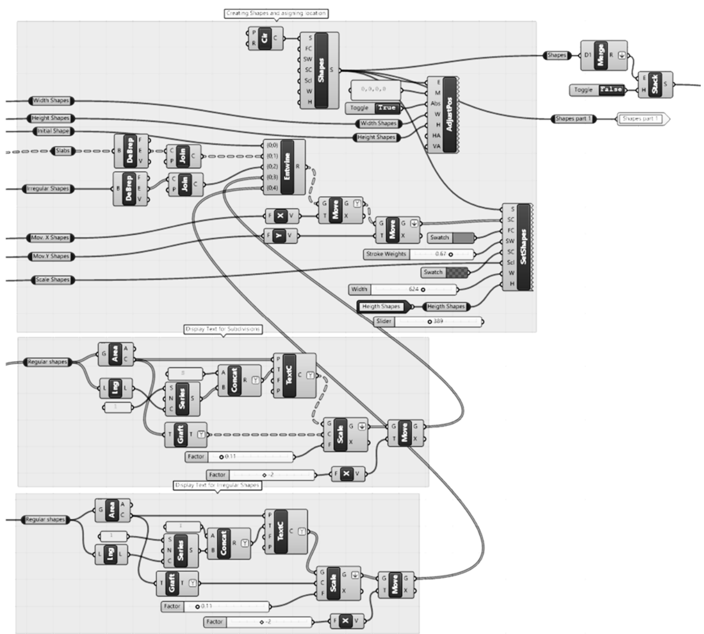


Figure 66- Visual scripts of UI 2D view (First step)

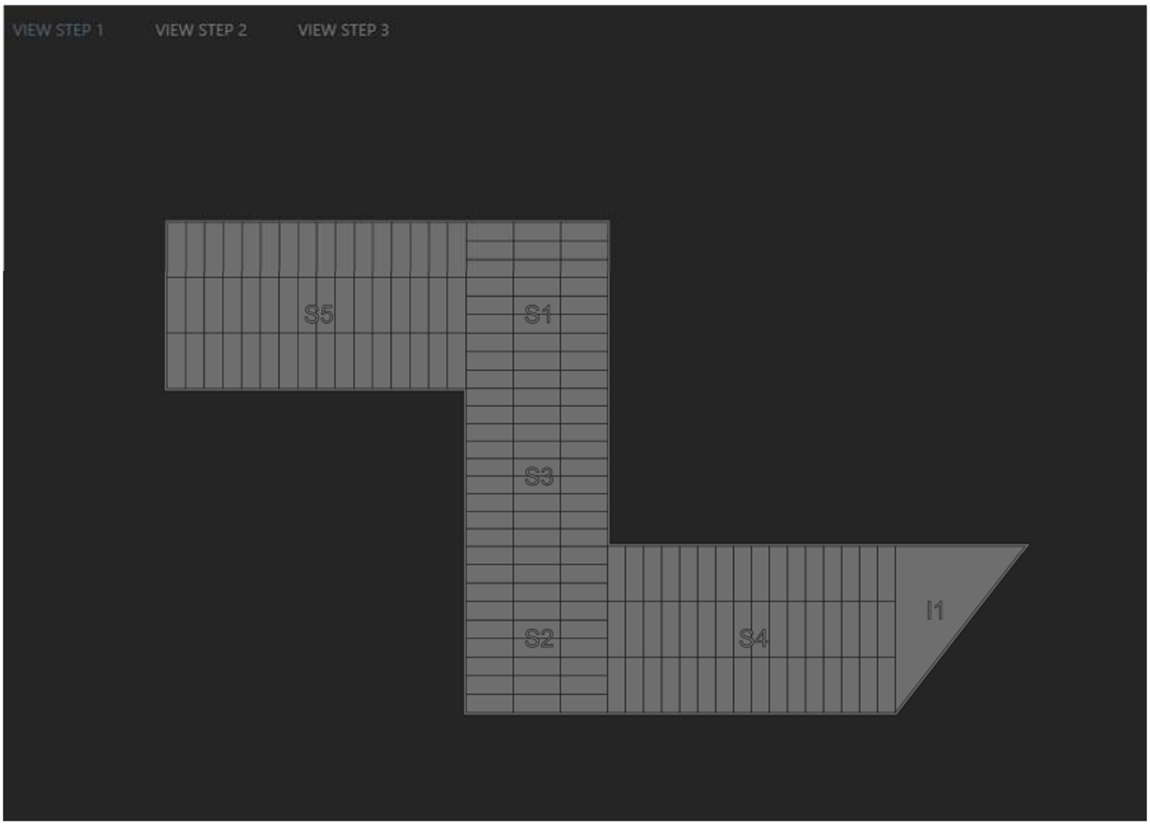


Figure 67- User Interface 2D view (First step plan view)

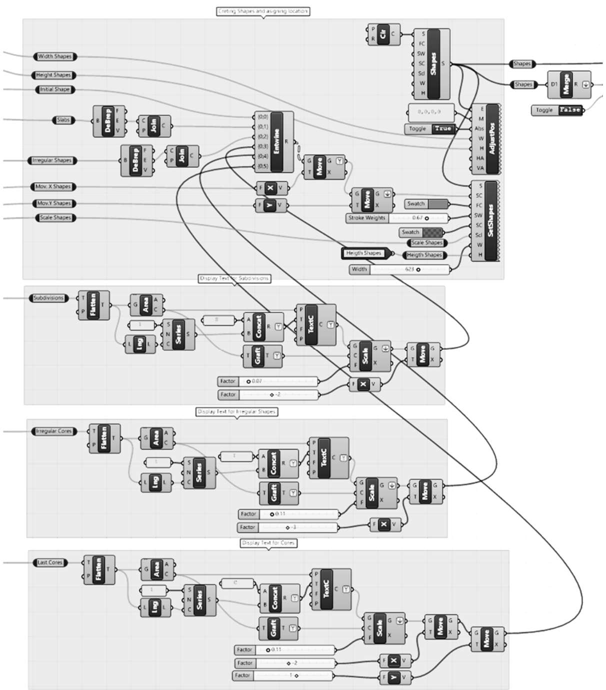


Figure 68- Visual scripts of UI 2D view (Second step)

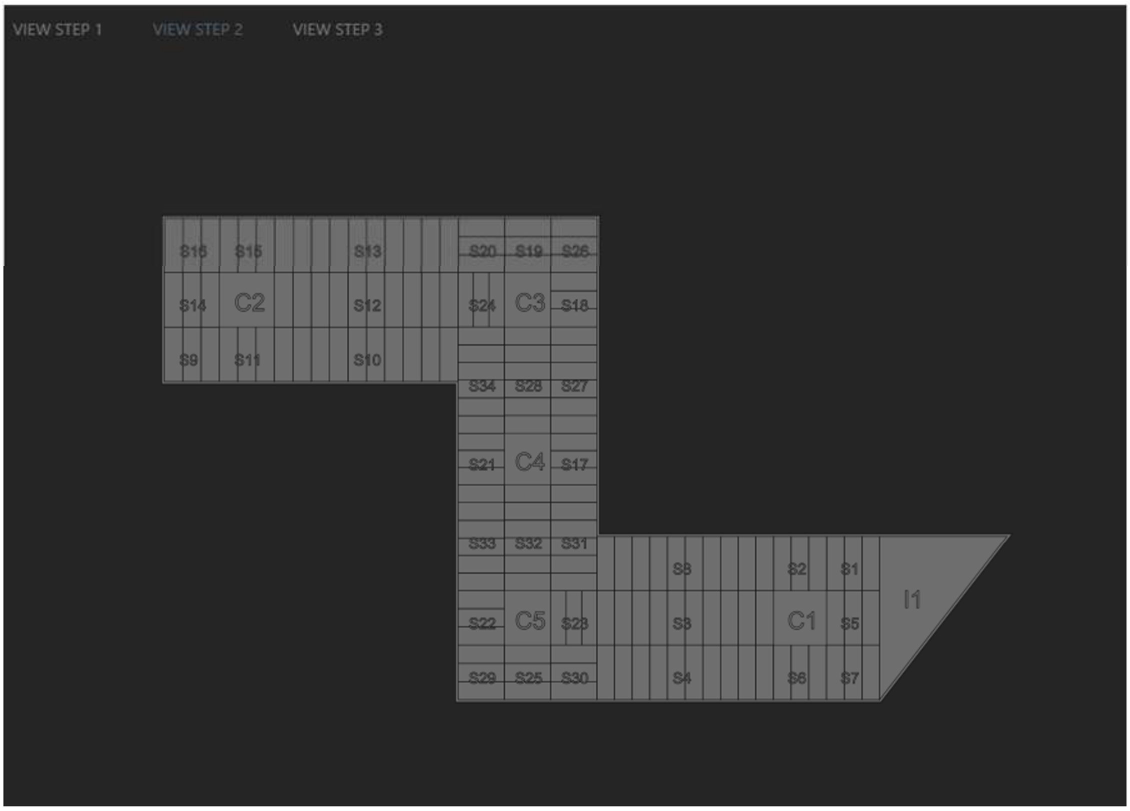


Figure 69- User Interface 2D view (Second step plan view)

The last 2D view (Figures 70 and 71) contains the visualisation of the decisions made in the parameters of the third step of UI parameters, and it shows the final cores and slabs, the location of the glulam columns in the perimeter of the project and the steel-concrete composite columns inside. Nomenclatures were assigned to the cores in this step, to allow their location in the modification of their size related to the cores extension parameters.

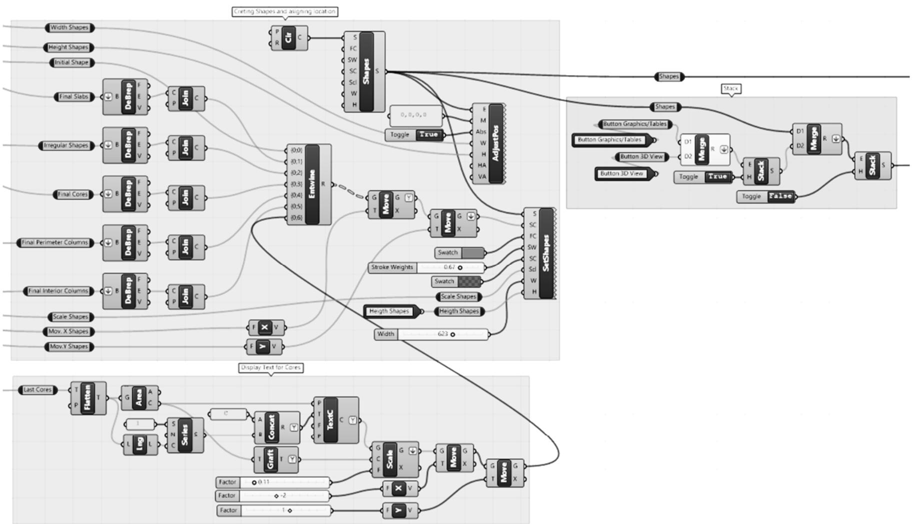


Figure 70- Visual script of UI 2D view (Third step)

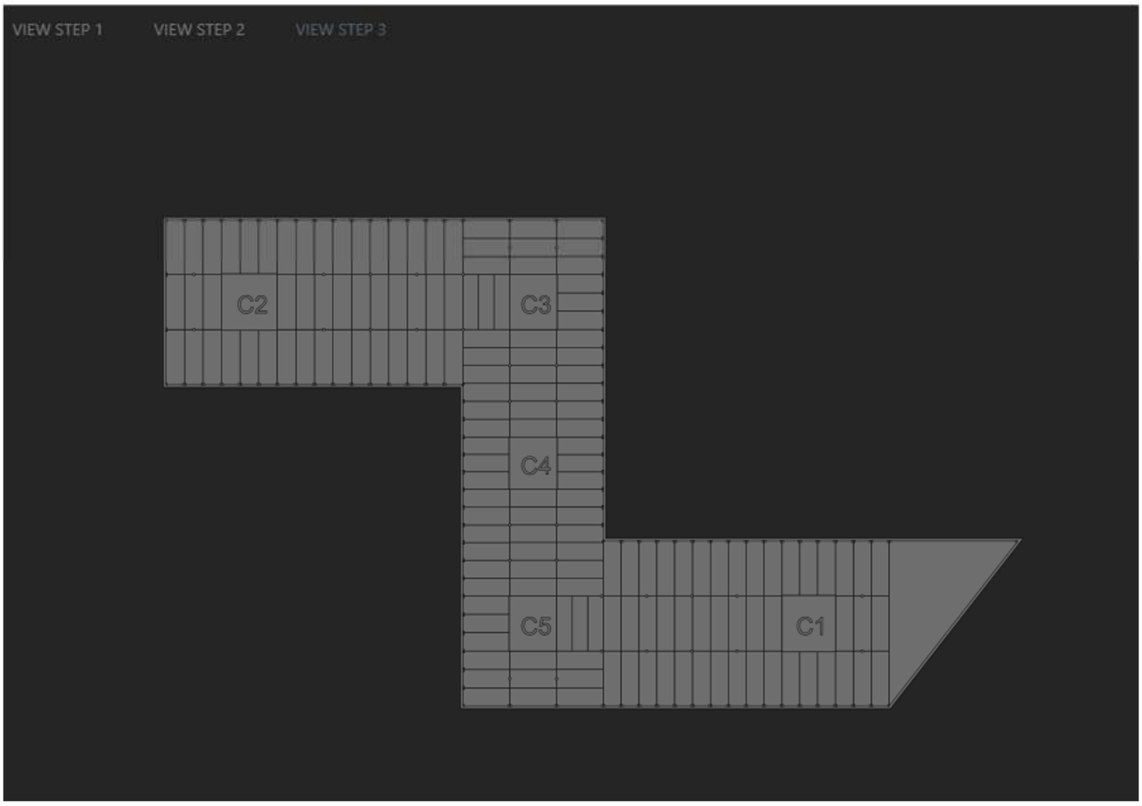


Figure 71- User Interface 2D view (Third step plan view)

Since with this 2D view, the steps of the UI parameters are finished, two buttons were included that allow the launching of the second and third windows of the User Interface. The second window contains the graphs and tables displaying all the information of the configured project components and the third window shows the project 3D view classified by types of system components. Figure 72 shows the general display set of window 1.

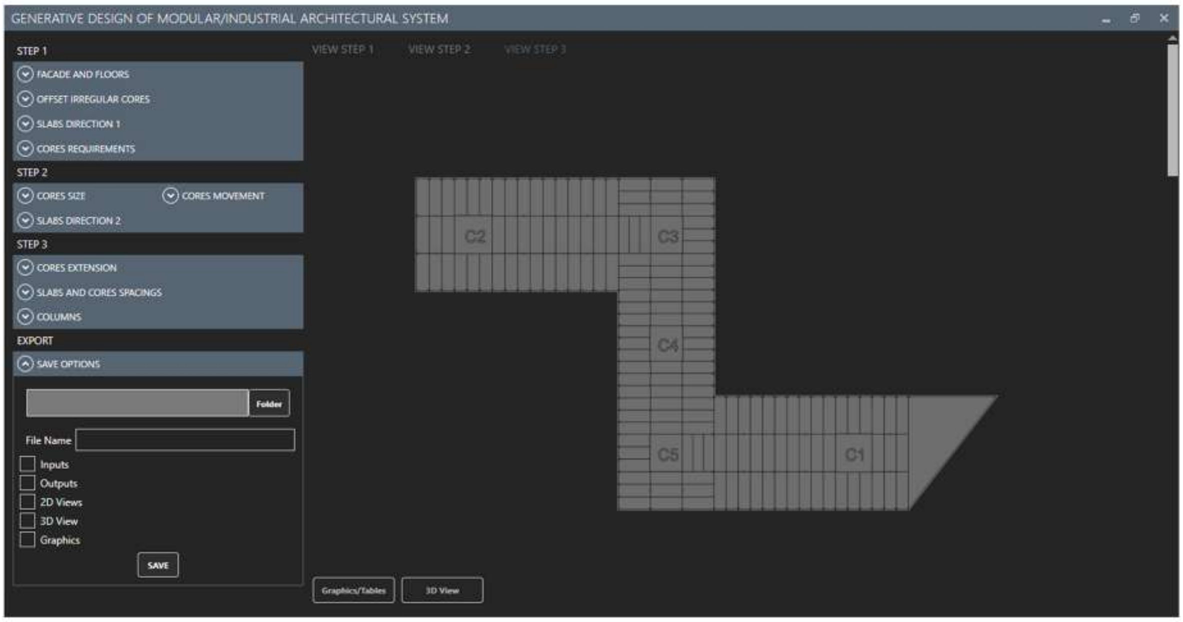
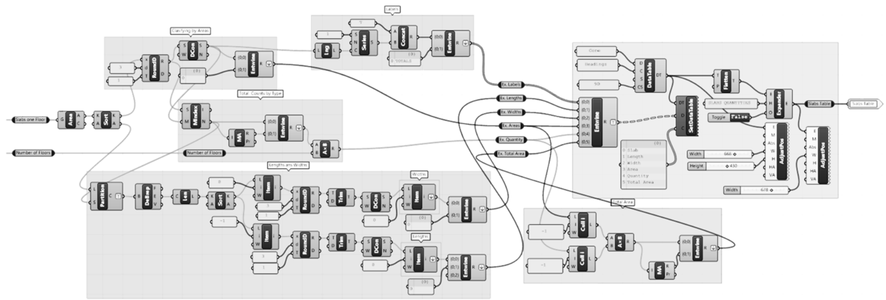


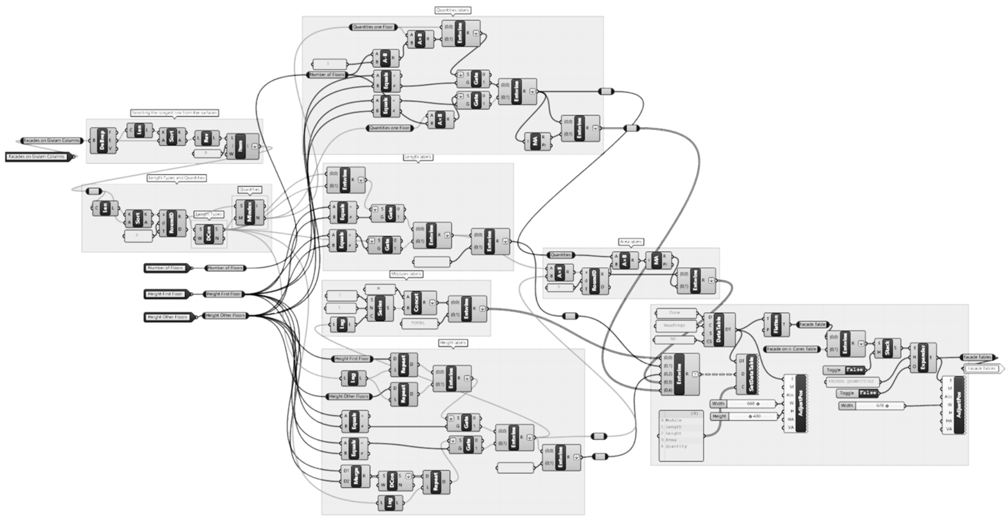
Figure 72- User Interface Window 1

5.3.3. UI graphics and tables

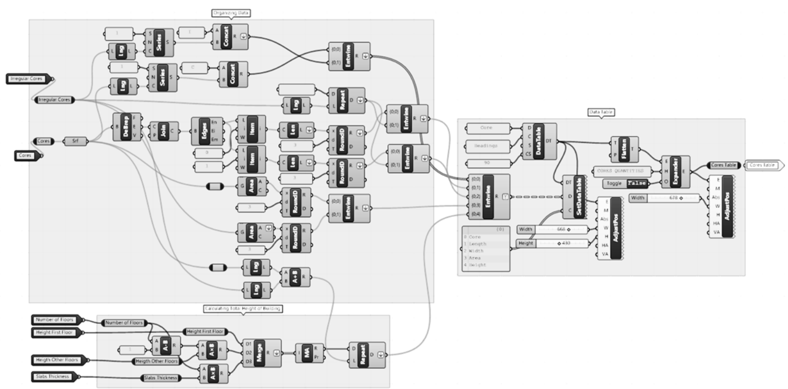
The second window of the User Interface is divided into two parts that can be accessed through a couple of tabs. One part contains four graphics that show the results of the data collected from the main elements of the project in relation to the KPIs. The other part of the window contains the list of tables of all the elements of the system, with detailed information in relation to quantities, lengths, areas, types, etc.



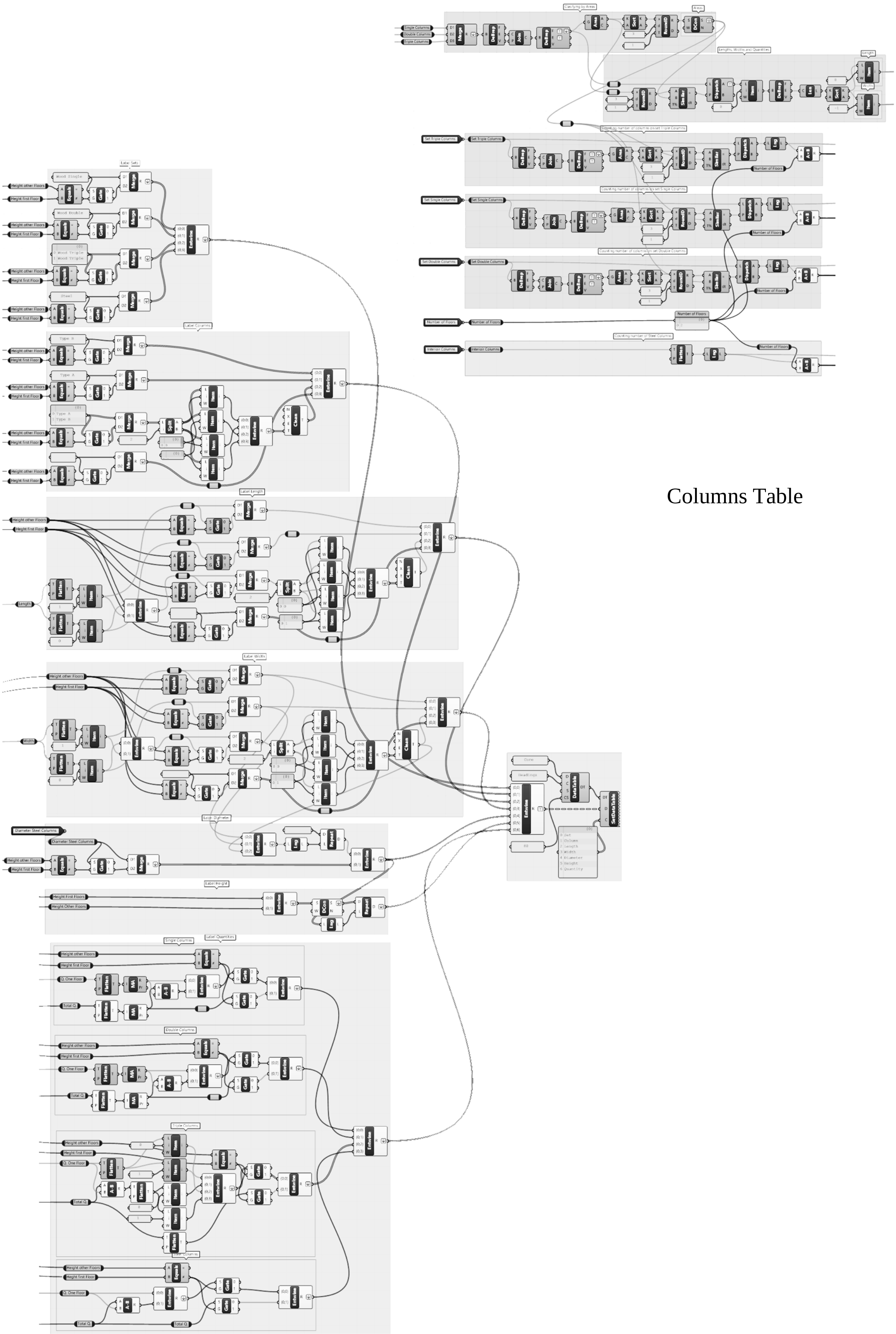
Slabs Table



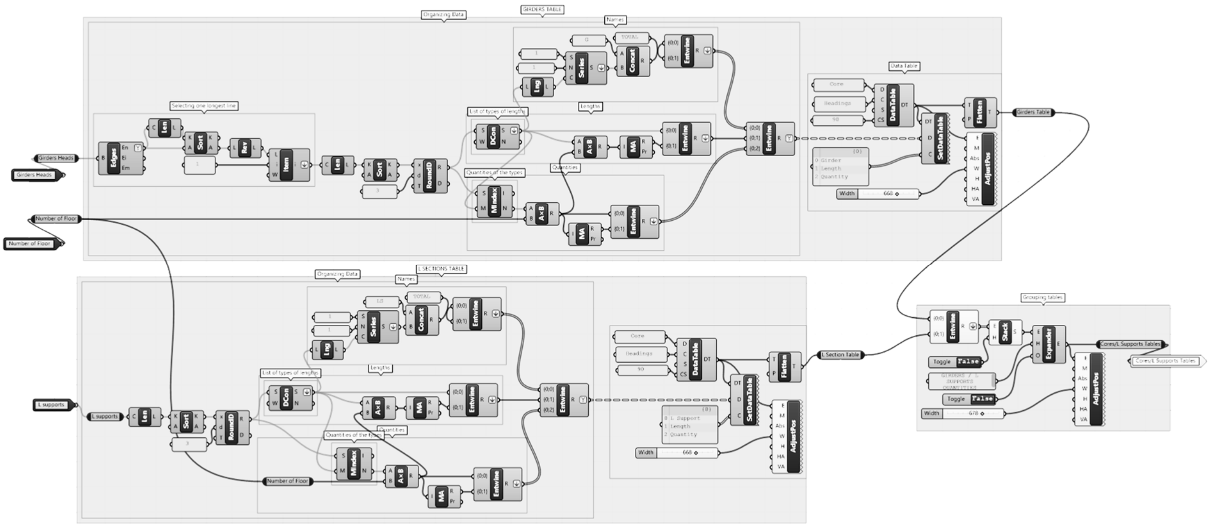
Facade Table



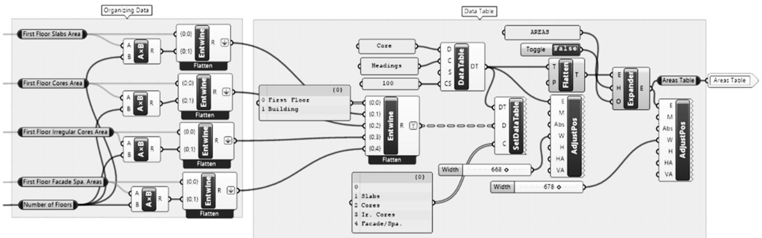
Cores Table



Columns Table



Girders and L Sections Table



Areas Table

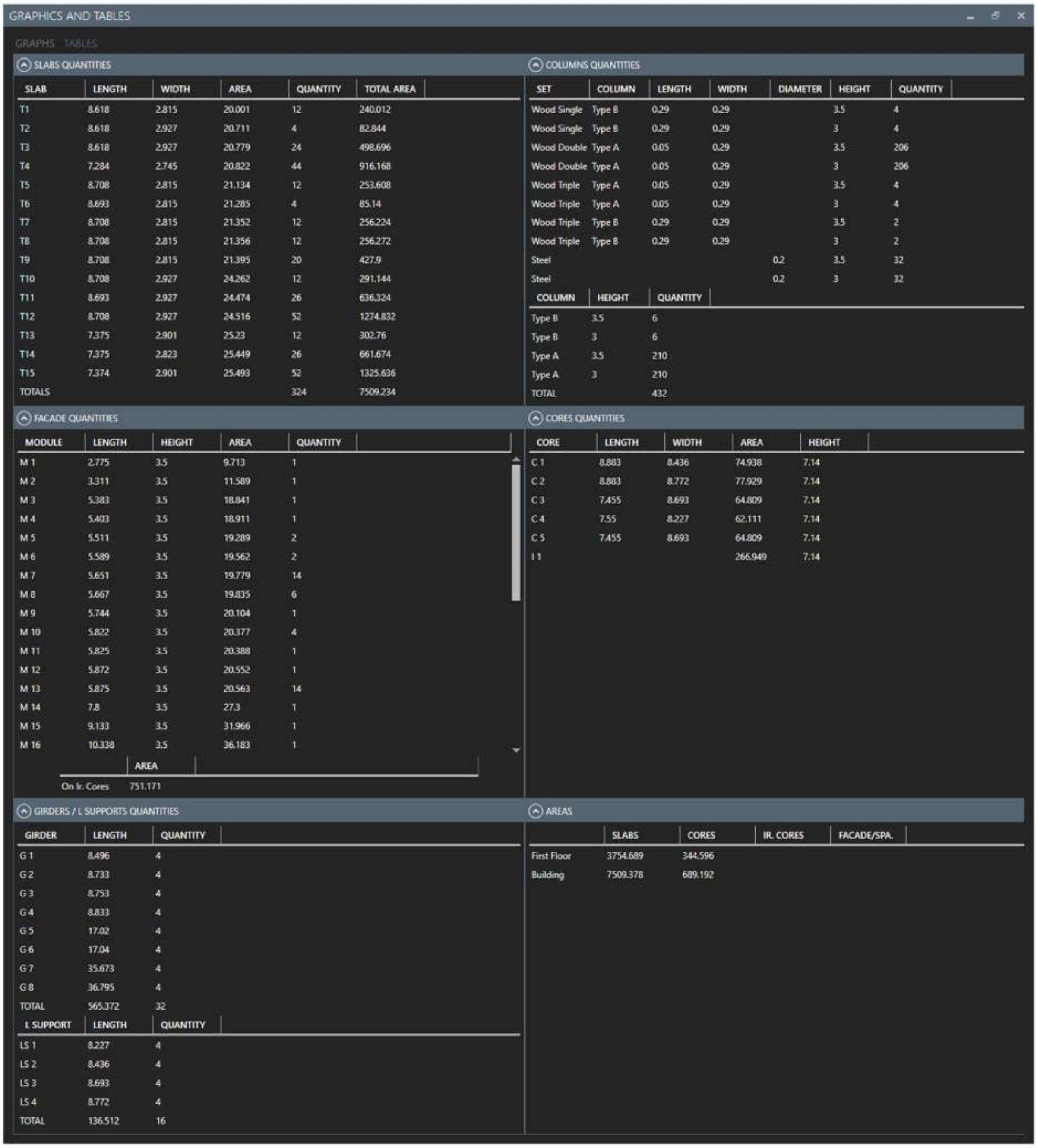
Figure 73- Visual scripts of tables

Six different sections of tables were generated that display the information of the system components: slabs, columns (perimeters and interiors), cores, facade, girders and L sections, and a last one with the general areas of the project. In Figure 73, it is possible to see the different scripts implemented for the collection, classification, and display of information in each of the implemented tables.

For the slabs table, the project's slabs were first classified according to their area, to then extract their lengths and widths. The quantities of each slab typology were then counted and the total number of slabs in the entire project wasgiven. In relation to the columns table, the information was classified according to the type of column (perimeter or interior) and the grouping typologies (single, double or triple glulam columns). In second place for the perimeter columns, they were classified according to their section. Since there are always two types of sections, these were found by classifying the columns according to their area and then extracting the length and width. Once having this classification, the amounts by type and section are generated.

The facade table was classified between facades in relation to the glulam columns and the facades in front of cores, when these are aligned on one of their sides with the perimeter of the building. Regarding the modules of facades attached to the glulam columns, they were classified in the first instance by the length in plan, to generate typologies to which in the second instance they were classified by type of height. Finally, the areas of each typology are extracted and the quantities of each one are found, as well as the totals of the entire project. In relation to the facades in front of cores, a total area of these in the building is given.

The cores were listed in the table cores, one by one with their respective lengths, widths and areas, as well as the total height taken from the ground floor level to the last level of slabs. As for the irregular cores, the areas and heights of each of them are given. The girders and L sections table contains the quantities of these elements classified by type according to length, and the total quantities in meters. Two separate tables were made, which were then joined under the same set to generate this table.



GRAPHICS AND TABLES

GRAPHS TABLES

SLABS QUANTITIES

SLAB	LENGTH	WIDTH	AREA	QUANTITY	TOTAL AREA
T1	8.618	2.815	20.001	12	240.012
T2	8.618	2.927	20.711	4	82.844
T3	8.618	2.927	20.779	24	498.696
T4	7.284	2.745	20.822	44	916.168
T5	8.708	2.815	21.134	12	253.608
T6	8.693	2.815	21.285	4	85.14
T7	8.708	2.815	21.352	12	256.224
T8	8.708	2.815	21.356	12	256.272
T9	8.708	2.815	21.395	20	427.9
T10	8.708	2.927	24.262	12	291.144
T11	8.693	2.927	24.474	26	636.324
T12	8.708	2.927	24.516	52	1274.832
T13	7.375	2.901	25.23	12	302.76
T14	7.375	2.823	25.449	26	661.674
T15	7.374	2.901	25.493	52	1325.636
TOTALS				324	7509.234

COLUMNS QUANTITIES

SET	COLUMN	LENGTH	WIDTH	DIAMETER	HEIGHT	QUANTITY
Wood Single	Type B	0.29	0.29		3.5	4
Wood Single	Type B	0.29	0.29		3	4
Wood Double	Type A	0.05	0.29		3.5	206
Wood Double	Type A	0.05	0.29		3	206
Wood Triple	Type A	0.05	0.29		3.5	4
Wood Triple	Type A	0.05	0.29		3	4
Wood Triple	Type B	0.29	0.29		3.5	2
Wood Triple	Type B	0.29	0.29		3	2
Steel				0.2	3.5	32
Steel				0.2	3	32

COLUMN	HEIGHT	QUANTITY
Type B	3.5	6
Type B	3	6
Type A	3.5	210
Type A	3	210
TOTAL		432

FACADE QUANTITIES

MODULE	LENGTH	HEIGHT	AREA	QUANTITY
M 1	2.775	3.5	9.713	1
M 2	3.311	3.5	11.589	1
M 3	5.383	3.5	18.841	1
M 4	5.403	3.5	18.911	1
M 5	5.511	3.5	19.289	2
M 6	5.589	3.5	19.562	2
M 7	5.651	3.5	19.779	14
M 8	5.667	3.5	19.835	6
M 9	5.744	3.5	20.104	1
M 10	5.822	3.5	20.377	4
M 11	5.825	3.5	20.388	1
M 12	5.872	3.5	20.552	1
M 13	5.875	3.5	20.563	14
M 14	7.8	3.5	27.3	1
M 15	9.133	3.5	31.966	1
M 16	10.338	3.5	36.183	1

	AREA
On Ir. Cores	751.171

CORES QUANTITIES

CORE	LENGTH	WIDTH	AREA	HEIGHT
C 1	8.883	8.436	74.938	7.14
C 2	8.883	8.772	77.929	7.14
C 3	7.455	8.693	64.809	7.14
C 4	7.55	8.227	62.111	7.14
C 5	7.455	8.693	64.809	7.14
I 1			266.949	7.14

GIRDERS / L SUPPORTS QUANTITIES

GIRDER	LENGTH	QUANTITY
G 1	8.496	4
G 2	8.733	4
G 3	8.753	4
G 4	8.833	4
G 5	17.02	4
G 6	17.04	4
G 7	35.673	4
G 8	36.795	4
TOTAL	565.372	32

L SUPPORT	LENGTH	QUANTITY
LS 1	8.227	4
LS 2	8.436	4
LS 3	8.693	4
LS 4	8.772	4
TOTAL	136.512	16

AREAS

	SLABS	CORES	IR. CORES	FACADE/SPA.
First Floor	3754.689	344.596		
Building	7509.378	689.192		

Figure 74- User Interface of tables

Finally, a table was developed with the areas of the cores, slabs, and facades (in plan, taking into account spacing). Figure 74 shows all the tables previously described, in the User Interface. Each one of them was designed to be contained in expanders in order to allow a more optimal management of the data that wants to be made visible.

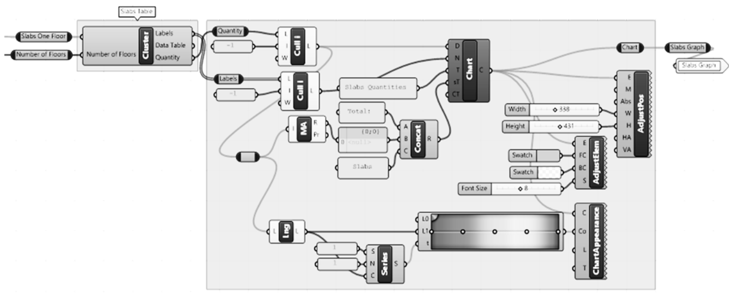
The next part of this second window contains the four graphs mentioned above. The main components of the system were chosen, treated as objectives to be displayed for the KPIs. Figure 75 shows the visual scripts implemented for the development of the graphs corresponding to quantity of columns, quantity of slabs, quantity of facade modules and the project areas both on the ground floor and throughout the building.

For the slabs graph, the classified information from the slabs table was taken, and a circular graph was produced with all the different types of slabs in the project, and their quantities. This allows to visualise mainly the variability of the slabs, being one of the objectives to maintain the largest number of these elements of the same dimensions. The different visual scripts of these graphs (Figure 75) show the configuration in terms of information classification as well as the types of colors and types of representation to be implemented in the User Interface of the elements.

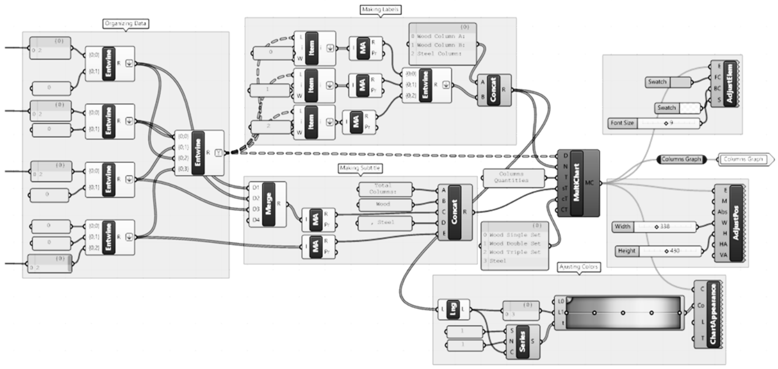
For the development of the columns graphic, a bar graph was implemented, with the three grouping typologies of the glulam columns and the steel columns. The bars related to the interior columns are managed in such a way that they are divided between the two types of column sections. With this type of graphic, it is possible to easily compare the amounts of glulam columns, with respect to steel-concrete columns. It also allows to quickly see the implications of the initial shape of the project, in relation to the amounts of the three types of grouping of the glulam columns.

For the quantities of façade modules, a bar graph was also implemented, which classifies the modules by typology based firstly on lengths and then on heights. This graph allows to see the variability of module types, which, like the slabs, also seeks to have a greater number of elements of the same dimensions. Since the variation in heights basically depends on whether the height of the ground floor differs from that of the other floors, it was decided to group these two variances within the same quantity bar for each of the types of modules

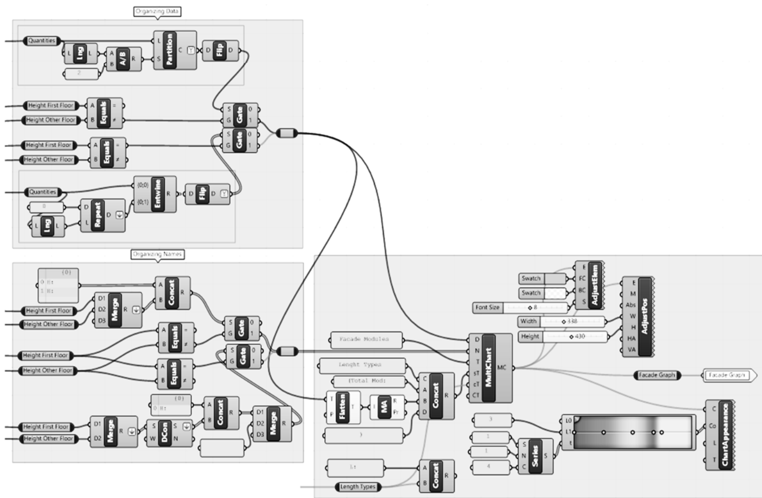
Finally, to show the areas of the project, two circular graphs were made, one containing the main areas of elements that make up the ground floor (slabs, cores and facade with spacings) and the other with the areas of these elements in the entire project. It is possible to choose which of the two graphs to view with the use of a couple of tabs located at the top of the window. These types of graphics allow to size the ratios between the areas of the system components that occupy the most space and determine if the configuration decisions meet the expectations in terms of occupation and distribution of elements. Figure 76 shows the four graphs described.



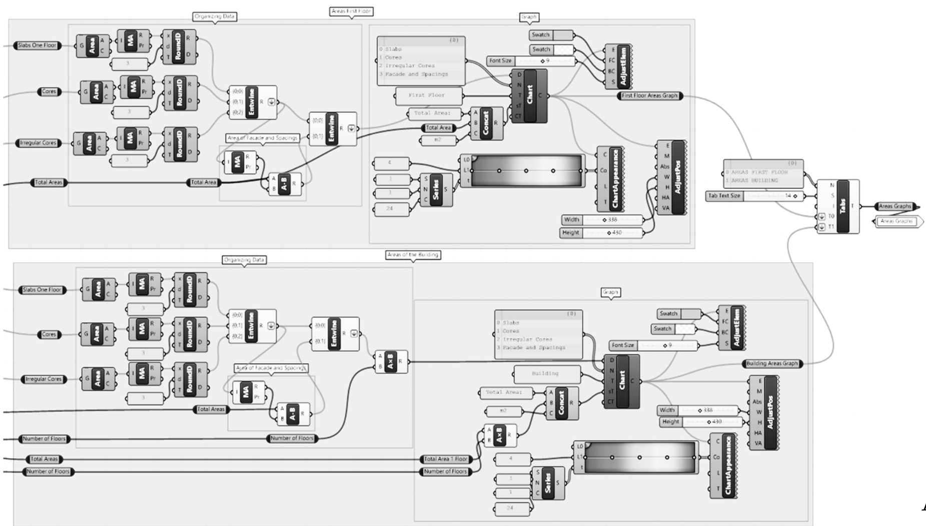
Slabs Graphic



Columns Graphic



Facade Graphic



Areas Graphic

Figure 75- Visual scripts of graphics

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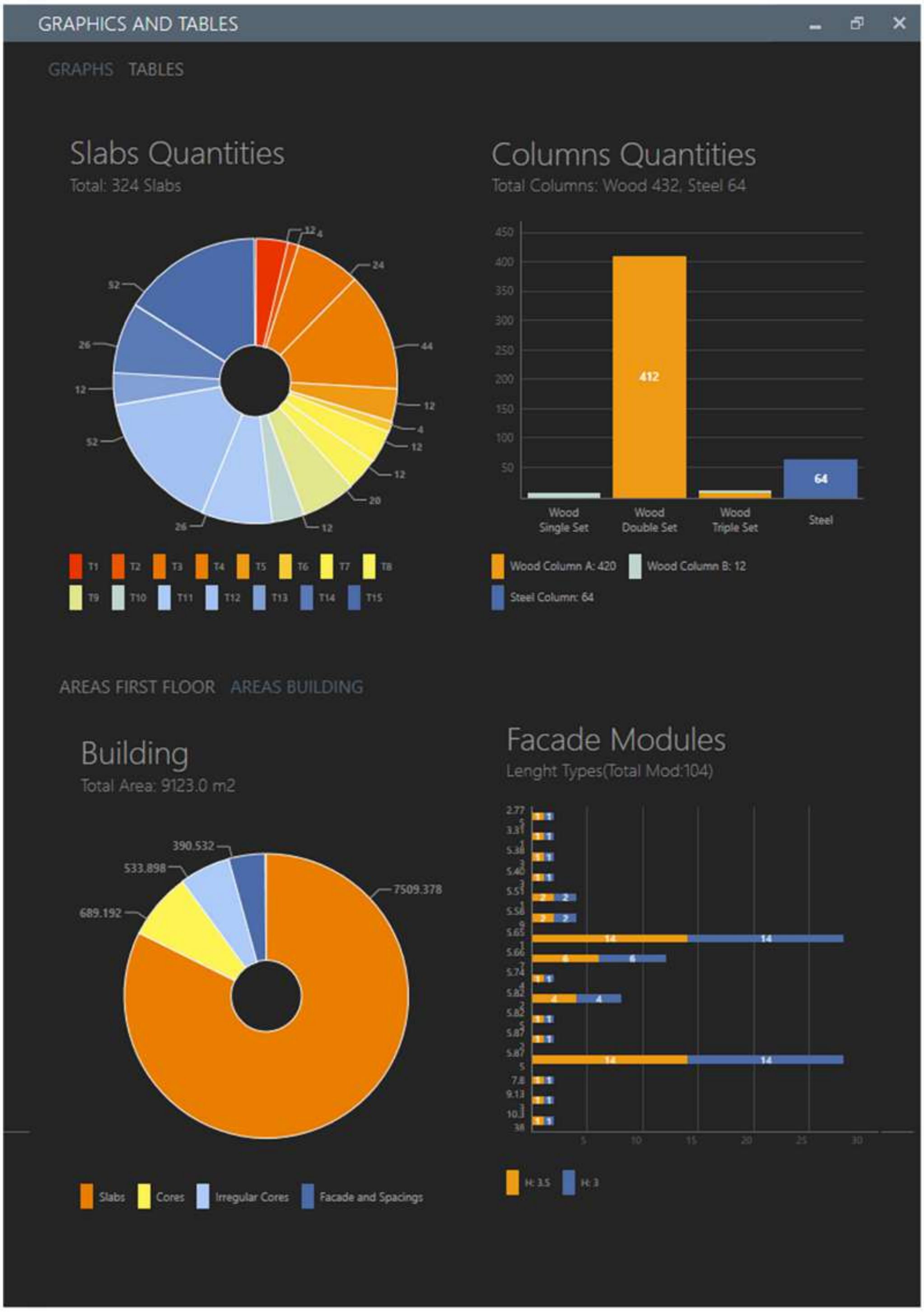


Figure 76- User Interface graphics

5.3.4. UI 3D view

The third window of the User Interface, contains the 3D visualisation of the configured project. In this, all the elements of the CREE system that were modeled automatically and with the intervention of the user through the previously explained list of parameters are shown. For its configuration, it was decided to show each of the groups of components with a different color and also allow, through a check list, the selection of these groups to be displayed. In this way, only what the user wishes to analyze can be isolated, which allows, together with the graphs and tables window, to have more complete, detailed and easy-to-understand information on each of the components and the KPIs for decision making in the design process.

Figure 77 shows the visual script implemented for the configuration of this window, in which three main parts were established. First, all the meshes built in the extrusions step of the general structure are taken as input, information that is passed through gates connected to the user interface checklist. In this way, the passage of the information to be shown in the final window is allowed or not. The last part contains all the code components for the launch and the graphical configuration of the window and the elements to be displayed. Figure 78 shows this third window of the User Interface with the 3D view.

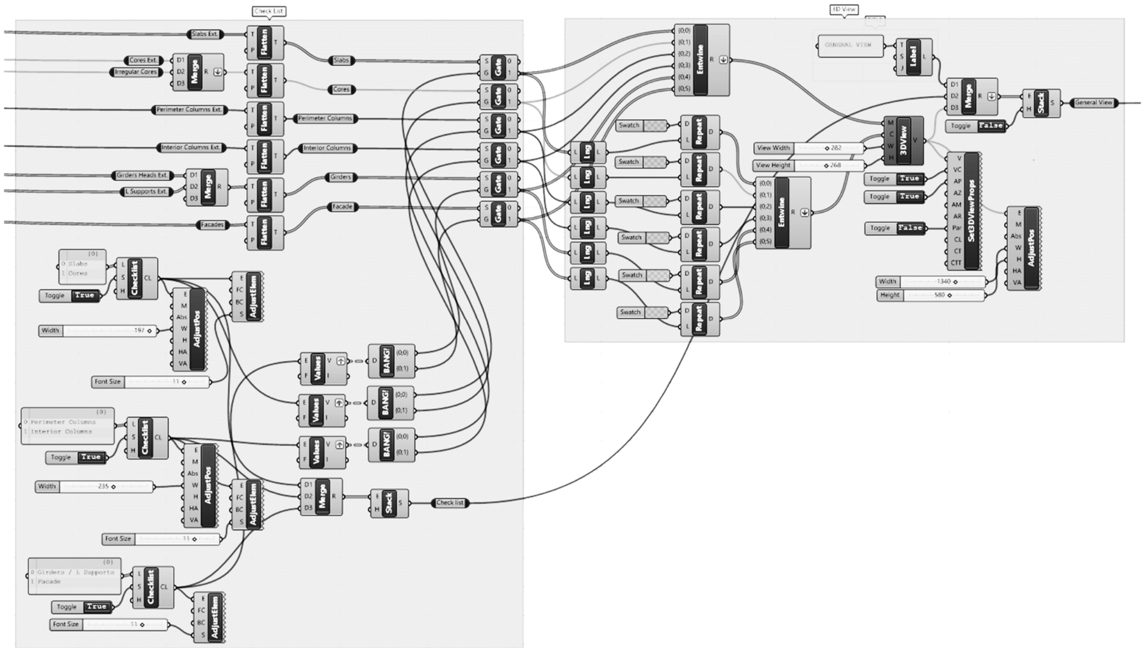
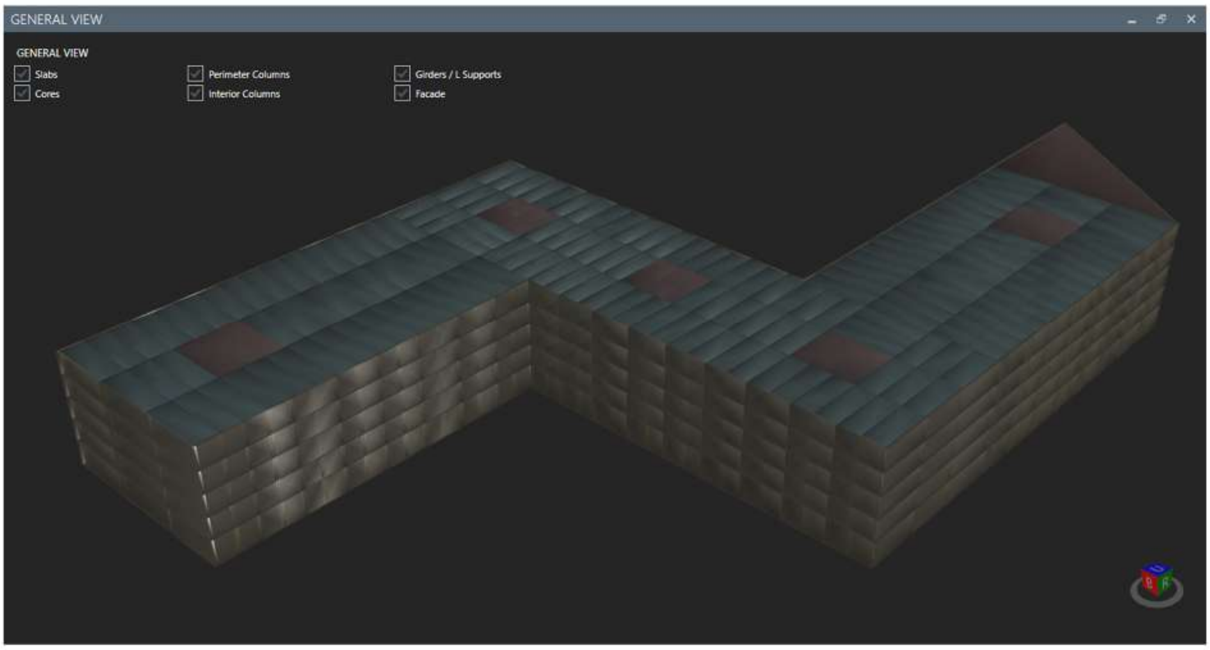


Figure 77- Visual script of 3D view



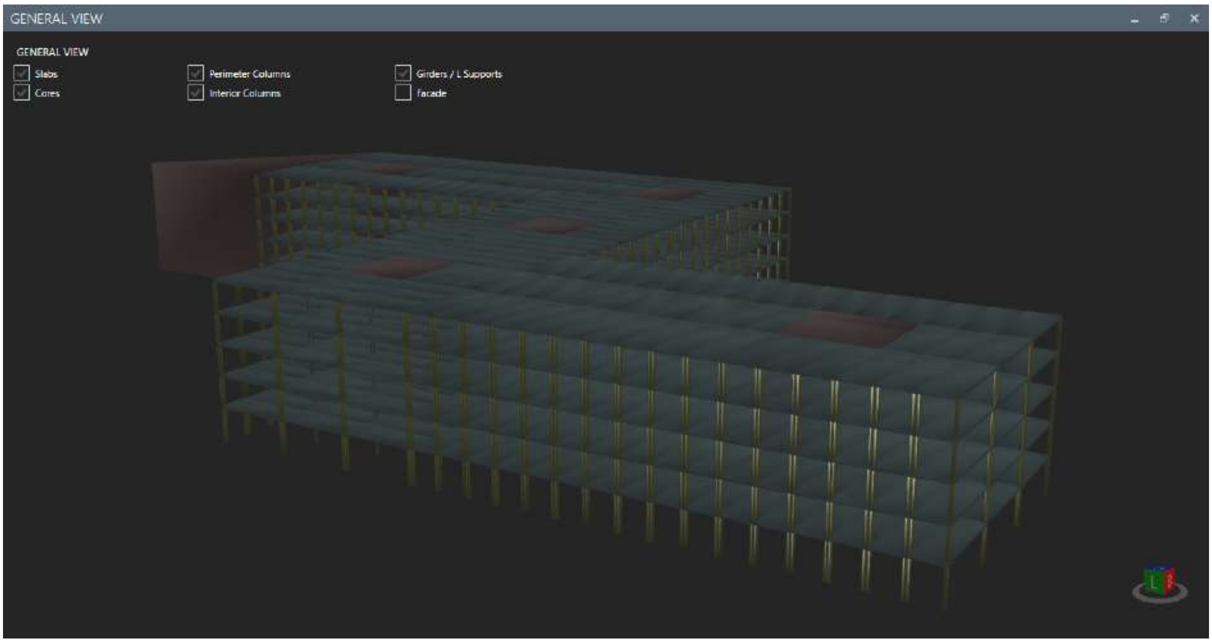


Figure 78- User Interface 3D view

5.4. CONFIGURACION OF DATA EXPORT

The third section of the implementation of the computational model involves handling the information generated in the first two sections, called General Structure and User Interface, in order to be exported and saved. In this way, it would be possible to have a database of the selected configurations of the projects and give continuity to the design in later stages.

For this, it was decided to take five components within the information of the computational model, which would be exported in .xlsx or .jpg formats, depending on the type of data (Figure 79). Thus, the inputs of all the parameters established in the UI parameters section, and the outputs of the information generated in the UI tables section, would be exported in Excel spreadsheet format. The three 2D views corresponding to the three steps of the workflow, the four graphics generated in the UI graphics section and the 3D visualisation window, could be exported in image format.

The previous section, corresponding to the implementation of the User Interface, covered the development of the visual script used to create the export options, grouped together with all the other parameters in the UI parameters section (just after the third and last step). There it was mentioned that the option was given to select which of the five information components described would be exported and the general name given by the user to save the files. In this subchapter, the management of the information to be exported will be addressed, for which a Grasshopper plugin called SpreadSheet was mainly used, that provides components for the organisation in tables of groups of information, as well as the possibility of generating screenshots of the graphs and images generated in the user interface.

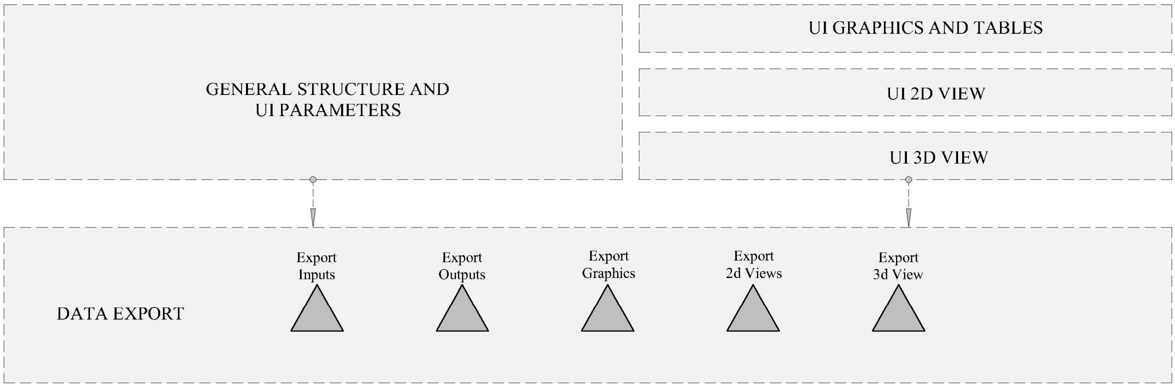


Figure 79- Schema of the Third section of the computational model (data export)

5.4.1. Export inputs and outputs

Regarding the information of all the inputs of the parameters established by the user or given automatically by the computational model, it was decided to export in xslx format in a spreadsheet with three sheets, corresponding to the three steps of the workflow, mentioned in the UI parameters section. Each of these sheets then contains the parameters and the values assigned to each of them, grouped under each of the three steps.

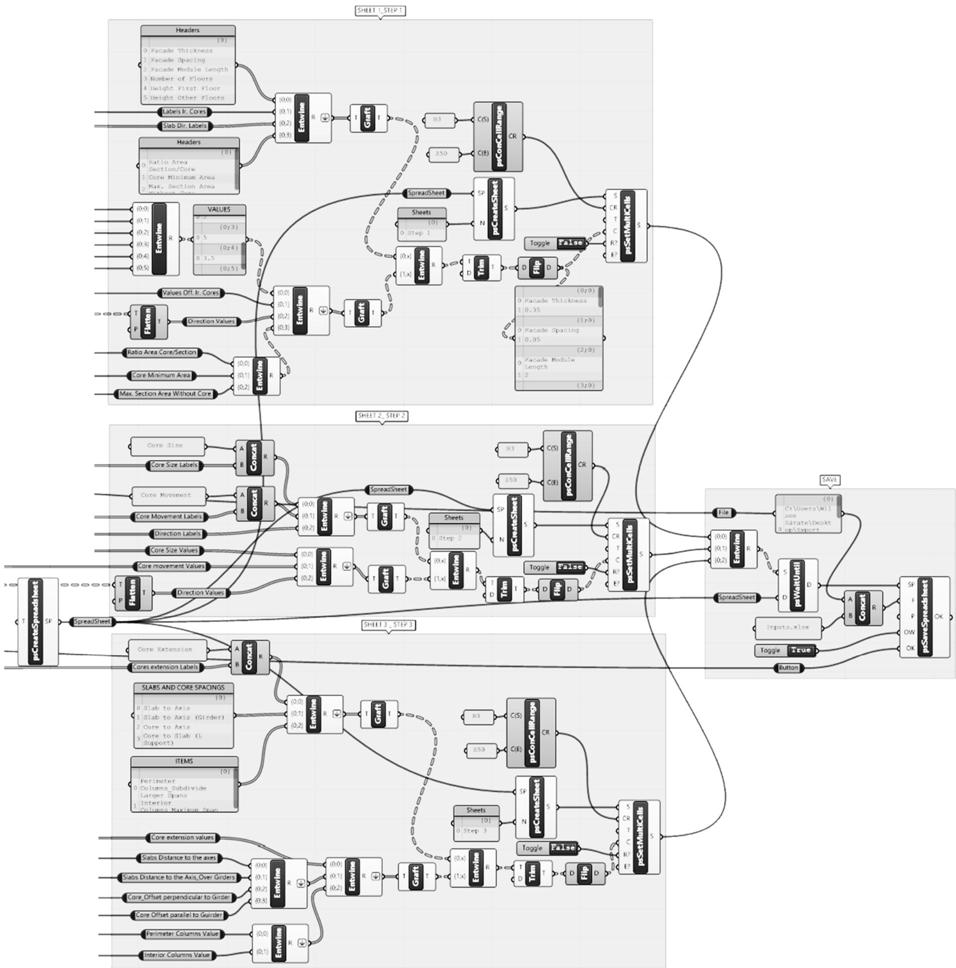


Figure 80- Visual scripts of exporting inputs

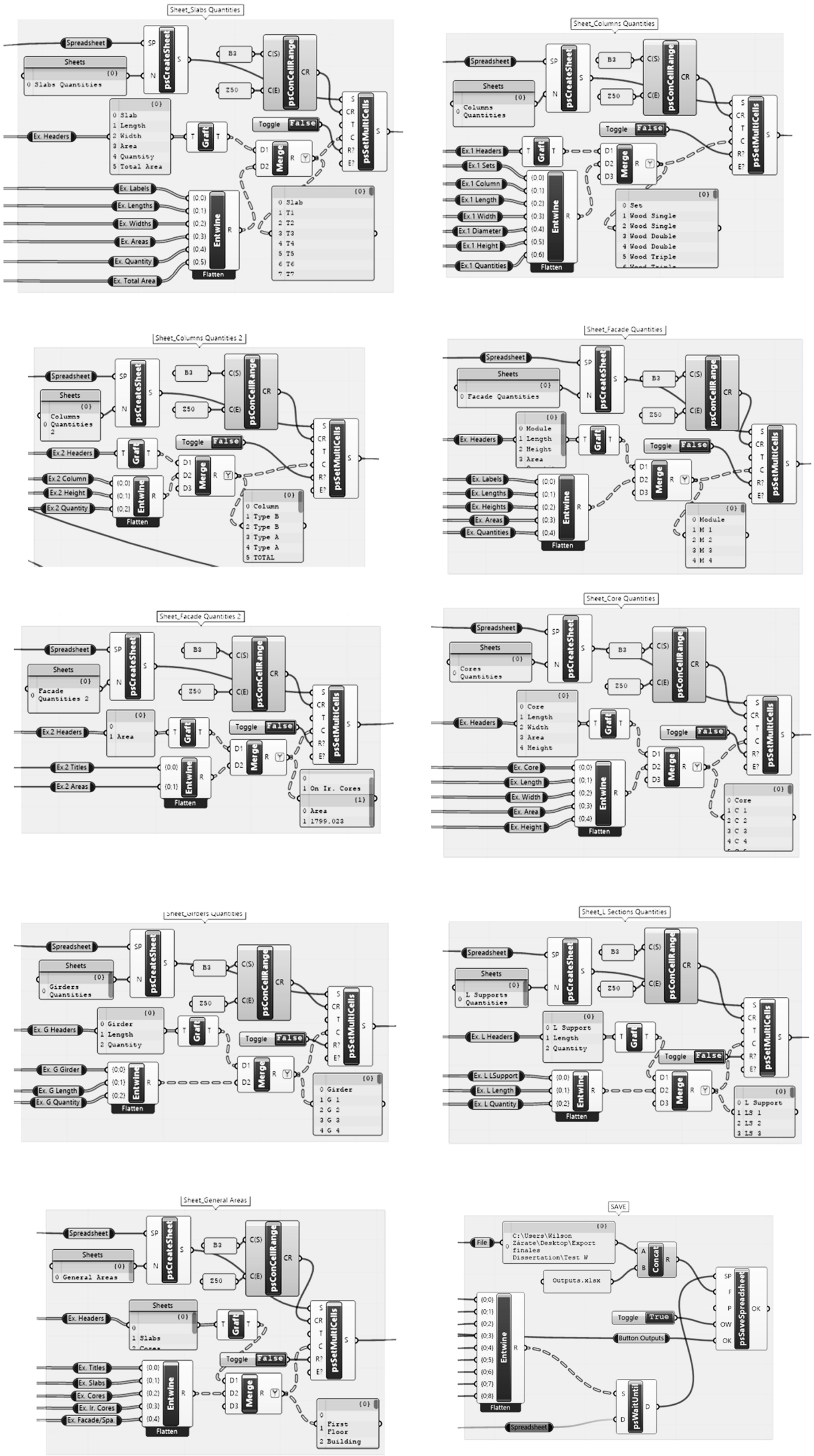


Figure 81- Visual scripts of exporting outputs

The final information exported in the spreadsheet was organised in such a way that, in later developments, it could be read back through a computational model, in order to be used automatically, to generate the exact configuration that was achieved. of the project, through the set of parameters. Thus, all the parameters were listed horizontally along the same row, and their corresponding values, in the row immediately below it (See Annexes).

Figure 80 shows the implemented visual script, in which all the information in terms of parameter names and all their corresponding values is collected, to later be organised in the three different sheets mentioned. After having the final list of information organised, it is associated with a Spreadsheet that can be exported with the option implemented in the User Interface.

The set of information of outputs, generated by the computational model to export, corresponds to the groups of components that were elaborated in the tables of the UI graphics and tables section. So, in this section, the information generated for that visualisation was taken and organised in such a way that each of the tables was on a sheet of an Excel spreadsheet. Figure 81 allows to see the visual scripts developed for the creation of each of the tables, these being: slabs quantities, columns quantities (this one with two tables, one organised by column grouping typologies, and the other organised by column sections), facade quantities (one table for facades associated with glulam columns and another for those facing cores), cores quantities, girders quantities, L sections quantities, and general Areas.

Once all the sheets have been organised with the information of the system components, they are joined to be exported in a spreadsheet, through the option that is given in the check list of the User Interface, under the export section. The final exported result can be seen in the annexes.

5.4.2. Export 2D views, graphics and 3D view

In order to have the most complete information, regarding the different project configurations developed in the configurator, it was decided to have the possibility of also exporting the graphic components that were implemented through the computational model, these being: the three visualisations in 2D, corresponding to each of the steps of the configuration process, the four graphs that summarize the results of quantities and areas of the project, and the 3D visualisation of the general model with all the components of the system.

For this, components of the SpreadSheet plugin were also used in the visual script, which give the possibility to activate and export screenshots of the selected elements, in jpg format. Figure 82 shows the three codes used for the export configuration of the 2D views, the graphics, and the 3D view, in which three inputs can be seen mainly for the image capture: The information to be exported, the configuration of the name of the file to be saved, and the activation button of the component.

Regarding the information to be exported, it was taken directly from the visual script components corresponding to the User Interface, since they were the ones that processed the information and generated the images and graphs. The only difference between the elements to be exported, was the list that had to be made of the 2D views, to allow the exportation of the three images at the same time, with the appropriate names. Regarding this configuration of file names, the User Interface option is given for the user to select the first part of the name, and by default this is associated with a second part that contains the specification of the type of exported element.

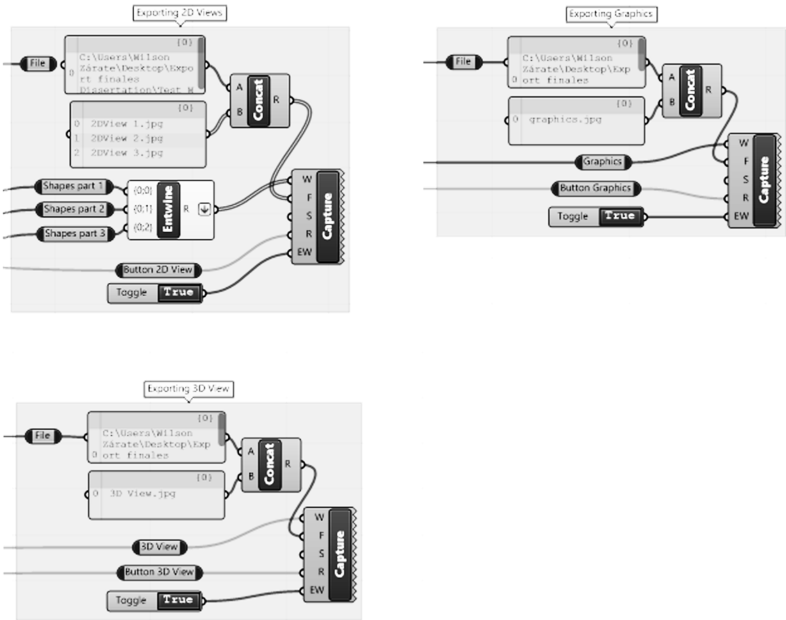


Figure 82- Visual scripts of exporting 2D views, graphics and 3D view

Finally, the activation button is connected to the checklist given to the user in the export data parameters, in which he can choose the information he wants to save and activate the process. Figure 83 shows the final result of all the saved files, with the predefined names and the file type (inputs, outputs, 2D views, graphics and 3D view).

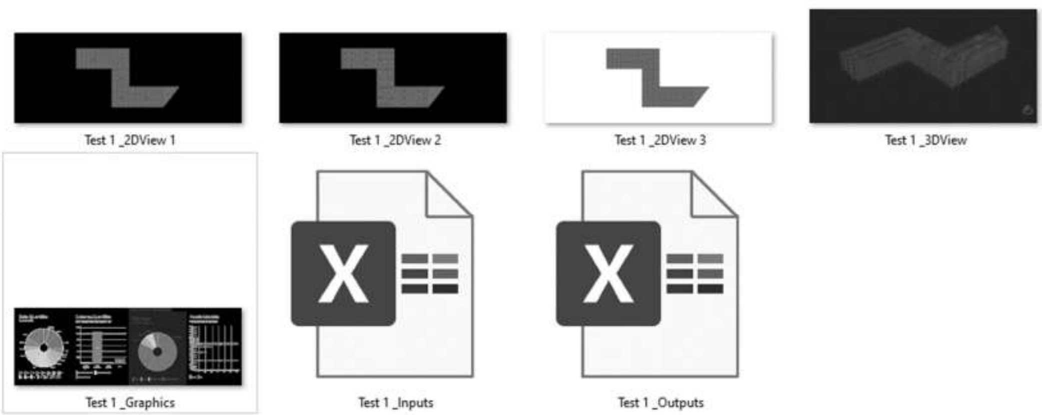


Figure 83- Files exported

6. DISCUSSIONS

The configurator developed during the dissertation proved to be beneficial in obtaining information related to the proposed KPIs and the visualization of the results in tables and graphs that would allow a faster understanding of the feasibility of the project configurations. It was tested on other examples of building shapes during the process of implementing the computational model in order to make the necessary adjustments for different building typologies. One of the difficulties that arose in this regard was the appropriate handling of composite figures that had sections that were not orthogonal to each other, since the interior subdivisions then had to be treated separately in the computational model. A great advance was achieved in this regard, however, the way to develop it in a more optimized way remains for future research.

The interior cores that are proposed to be located automatically on the longitudinal axes of the subdivisions of the initial figure, can be moved in the two main directions of the subdivision in which they are located. This approach allows freedom in the location of the cores, however it presents some difficulties in cases where the cores must be located towards the facades, since the exact displacement would have to be calculated. This could also be improved, perhaps adding some more parameters that would allow the cores to be automatically located towards the facades chosen by the user.

Although the results in terms of graphs, tables, 2D Views and 3D views are obtained automatically, it was found that the processing time is quite high, mainly due to the use of the Human UI plugin components. Specifically, in the computational model developed, it was found that when modifying the parameters, and recalculating to make the results visible in the User Interface, the exact point of bringing this information back to the interface is the one that takes a long time to process. This is a marked limitation of the use of the HumanUI plugin, which allowed to see until what point this could be useful. For the present dissertation it allowed to process the information and obtain results, however for the effective use of a configurator that allows the processing of information more quickly, it would be more convenient to develop the proposed general framework, with the use of Rhino Compute and the implementation of a Web Browser.

It was for this reason of processing speed that it was decided to divide the User Interface into three different windows, so that the first one contained only the parameters to be modified by the user and the 2D views of the plants with the modifications made. When the modifications are completed, it is possible to launch the activation of the other two windows to produce the graphs, tables and 3D visualization, which takes considerable time. In this way, it was possible to optimize the user's interaction with the configurator to a certain extent, however, in order to achieve efficient use, it was evident that the Human UI plugin presents marked limitations.

Hence, the computational model developed, in theory, can help in the design phases of a project, by allowing the manipulation and automation of information for different configurations, which was tested in the example given in the dissertation. However, due to time limitations, it has not yet been tested in the CASAIS company to help in the design processes, where mainly architects, designers, clients and developers could be the beneficiaries.

For the future, the workflow of the proposed computational model could be used, and instead of the User Interface made through HumanUI, a web browser could be implemented that allows the use of the configurator within the company and remotely. This would make it easier to use by clients, who could send proposal information (which they themselves would explore and which would initially adjust to their requirements) to the designers of the CASAIS company, who in turn could take this information and continue developing proposals. Communication in this way would be greatly improved between clients and designers. For now, with the developed configurator, despite the time it takes to process the information, it could still be used to obtain information on the main KPIs of the system and have a clearer perspective of the feasibility of different design proposals.

Among the advantages that could be highlighted of having a configurator like these, would be the possibility of having said information organized in tables and graphs in an automatic and coherent way that, even despite the processing time, would be much faster and more efficient than if it were not used. The possibility of having a model created automatically also makes the project more easily understandable from the first design decisions. The information generated, which can be exported in .xslx and jpg format, can be easily shared between the different stakeholders of these first phases of the project, facilitating communication and also allowing it to be used as a database for future design approaches.

In a future development, the use of exported information could also be implemented, to be automatically read by the configurator and continue with explorations in past project configurations. This would allow even more efficiency within the company with possible project design exchange between different designers in a more fluid way. With this configurator implemented, it was possible to obtain an adequate workflow in the computational model that specifically adjusts to the prefabrication construction system of the case study, and to the way in which the design process is carried out in the company in general, that is, starting from the initial perimeter of the project, then defining the location of slabs and cores that finally allow the location of the rest of the system components. Other workflows could continue to be explored, in which automatic optimization systems could be included that would allow having, from the beginning, several automatic options that would be shown to the user to choose.

It could also be highlighted that a good level was achieved in terms of ease of use of the tool by people who may not have professional knowledge in design. Although the first input from the configurator still requires the direct use of Rhino, which perhaps makes its use difficult in a certain sense, the rest of the process is carried out from the User Interface. This could be handled in the future, with the implementation of the complete framework using a web browser that would allow drawing within it the initial perimeter input of the building, as it is done in some of the tools investigated and taken as references.

7. CONCLUSIONS

The use of prefabrication in the AEC sector, as recognised through the researched literature, introduces advantages for the industry in terms of productivity, costs, material waste, constructive quality workers safety, sustainability, among others.

To achieve these benefits, prefabrication systems incorporate principles of DfMA, and in this way take into account factors and requirements of the manufacturing and assembly phases of the projects, from the first design phases. Thus, from those moments, predictions can be made about the most efficient ways of handling materials, costs, design, manufacturing, and assembly of prefabricated elements of buildings.

A great advance is achieved with the integration of information between the different phases of design, production, and construction. However prefabrication processes initially taken from mass production had to be modified over time, to meet the requirements of building construction, whose elements tend to be unique in terms of design and production. For this reason, the implementation of mass customisation becomes relevant for this sector.

An important characteristic of mass customisation processes is the search for flexibility and variety in design. So, depending on the degree of customer involvement, it is possible to have a higher or lower level of customisation, and at the same time incorporate the modular characteristics of prefabricated systems. In this way, advantages are obtained from both poles, always seeking the best productivity through the repeatability of the elements while also allowing the search for unique products, a characteristic widely sought by customers.

In this context, it was found that through the use of BIM and the prefabrication industry, it is possible to benefit from characteristics of modularization, mass customisation and DfMA in an even more efficient way, closing the productivity gap and maintaining a more fluid flow of information between design phases and a greater cooperation, among the professionals involved and clients.

It was found that the implementation of BIM in prefabrication industry brings enormous benefits, allowing building data and model information to be shared and transmitted throughout the entire life cycle of project processes. This increases the quality of the designs by allowing a greater degree of visibility of integration between the components as well as the coordination between the designer and the manufacturer. Other benefits within the design stage are: the detection of collisions between the different components and locate the causes, better understanding of the entire project leading to greater precision and consistency of the information, with the integration of 4D and 5D it makes possible to take design decisions based on more objective data.

In relation to the benefits in other phases of the construction cycle, it could be mentioned: the virtual reality model improves the management of the construction site for the assembly work of the components, allowing optimizing operation problems, detecting problems more easily in the construction processes and schedules, improving management of safety in production and construction, simulating different manufacturing strategies to identify the best prefabrication plan, and locating elements or equipment that are not in good condition within the building for their maintenance.

One of the greatest benefits of BIM found was the possibility of automating processes in the different phases of the projects, which leads to reduction of time, costs and efficient obtaining of information. Within the design phase it becomes possible to automate processes, taking advantage of BIM´s parametric nature. Since models are made of elements with clearly defined relationships and parameters, changes are automatically propagated. This is where research into the use of product configurators associated with BIM became relevant, since, with the adaptation of this type of tools to the prefabrication industry, efforts have been made to automate design processes through the use Generative Design.

Much of the uses of BIM in the prefabrication industry have focused on post-design phases, however with the use of configurators, the ability to obtain a large number of options and variations of a product has been explored, with the use of a limited number of inputs, which allows its use to be easy to handle, even for non-professional users. Within the literature and tools investigated in this regard, it was found that through their use advantages are enhanced such as greater efficiency and coordination in projects, preservation and reusability of the knowledge generated for future products, reduction of time and costs, increase of flexibility in design and greater involvement by different stakeholders, including clients.

It was very useful the classification of these tools, based on the researched literature, according to the phase of the project on which they focus and the main users to whom they are directed. Which made possible to see that the majority of these tools focus on the planning and design phases, that is typology 1 and 2 configurators, which involve planners, designers, manufacturers and clients. The tools that were investigated in this regard allowed to see that good solutions have been generated that involve, to a greater or lesser extent, certain technical knowledge for their use, but that in general seek the ease of obtaining design configurations through automation and a limited number of inputs.

Being then clear that this type of tools could be useful for the integration of BIM in the prefabrication industry, a way was sought to adapt some of these in a methodology that could be used in a specific case study. Some of them allowed to a certain point flexibility in the integration of new functionalities, but not in their configuration in terms of easy navigation and visualisation. Others had better options to add functionalities that were a little more specific to the case study, but their complexity increased or they did not have the possibility of being open source. Other tools focused on interoperability or the possibility of remote information processing, which made them a good option.

It was then possible to take some of them for the development of the general framework, since they could be integrated with each other, allowing the flexibility of adaptation that was sought in terms of the parameters and functionalities to be developed, as well as the ability to generate information related to KPIs specific to the case study. Other tools analysed largely served as references for the development of the configurator workflow, or for the way of obtaining data and tables, or for the form of presentation and visualisation that was most suitable for users.

The proposed framework entailed the creation of a web application in which the user can easily interact with a computational model developed through visual code and processed remotely. The information generated at the model level can be taken to a BIM software, through a connector, in order to be used in later design phases. It was found that this type of framework for a configurator could be applied to the CREE prefabricated system, it allows the configuration of the User Interface that also adapts to the requirements of the case and makes possible to obtain information automatically.

However, for this dissertation it was necessary to define (given the goals of the research and the time available for it) the methodology only in the section related to the development of the computational model. This was made through locally processed visual code and generated a User Interface using these same tools. This part being the central point of the implementation of a configurator methodology that adapts to the case study. The rest of the framework was proposed for possible future development, although at a general level, through the implementation of the User Interface developed locally, it was possible to obtain a configurator that included the main elements sought from the dissertation: (1) implementation of a computational model that automates the generation of data and model of a prefabrication system, and (2) the possibility of interaction in this process by the user in a simple and methodical way through the definition of a limited use of inputs.

It was evident that, for the development of a computational model of this type, the definition of the parameters and relationships between elements of the precast system was of crucial importance. The better defined the elements of the system and the greater its modularization characteristics, the more clearly it can be explored in automation and Generative Design methods, since there is a limited number of parameters allowing the user to obtain relevant information about the feasibility of the project, in terms of KPIs, with the insertion and selection of few inputs.

For this purpose, the definition of the information that was wanted to be achieved (KPI's) also played an important role, since the development of the computational model and the configuration of a User Interface depended on it, which would allow the information to be displayed quickly, simple and readable for decision making. In this sense, the case study explored (CREE System) allowed parametric schemas of the relationships between its components to be created, and the KPIs to be obtained from the configurator to be defined from these, thanks to its marked modularization characteristics.

To reach the final configuration of the computational model, several alternatives were explored regarding a workflow that automates the generation of information, but also allows the user to participate in the design configuration. To achieve this, a process divided into steps was then chosen, to define increasingly specific parameters of the project, until reaching a final design solution from which the data sought for decision-making could be obtained. This type of approach was quite convenient, in terms of achieving a good level of project definition, considering all the main components of the system and still maintaining simple handling of the configurator by users.

In the specific case of this prefabrication system, the definition of the dimensions of the slabs had one of the greatest hierarchies in comparison with the rest of the components, since these were the base elements for the definition of modular guidelines, seeking the greatest number of slabs modules repetition. For this, it was necessary to define a grid of axes based on their repetitive dimensions and subsequently to locate all the other components of the system. This method took advantage of modularization benefits but also maintained certain flexibility in terms of the location of other defining elements at a spatial level, such as the cores (vertical circulations).

More parameters within those proposed in the methodology were included to give greater definition to the components, for example, the cores were determined based on areas and some necessary basic dimensions, which could be extended to have parameters that would enable the generation of even the internal elements that are also prefabricated in concrete. Regarding the slabs, there could be the possibility of defining their typology, according to their positioning within the project and some components that serve as a connection between systems could be included. However, with the parameters that were used, it was possible to obtain the most relevant information about the project, for the focus of the dissertation in the initial design phase.

The use of the Grasshopper API for the implementation of the computational model, proved to be an asset for this work since it allows architects with limited knowledge in programming to implement and manipulate the script. Due to its widespread use, a wide range of plugins have been developed with functionalities that were very useful for the development of the implemented code, among them RoomSurveyor, HumanUI and SpreadSheet could be mentioned, which provided tools for geometric organisation, implementation of the User Interface and export of information in Excel formats.

The developed configurator focused on the code implementation section for the case study, and as an alternative to the general framework, it developed a User Interface processed locally, in order to obtain the information related to the KPIs. This configurator is based on a definition of parameters that are easy to use and visualise by the user, largely achieving the objectives set at the beginning of the dissertation. That is to say, based on an initial input of the perimeter of the building and the determination of a set of parameters, the user can automatically obtain the generation of information, displayed as a tables, graphs and 3D model, in order to allow more objective decisions regarding the feasibility of the projects. This information can be exported and saved for continued design development.

As a continuation of the exposed configurator, the reading of saved configuration inputs could also be implemented, in order to have them as a basis for later designs. The proposal is also open for the development of the general framework of the configurator, which can be used as a Web Application, with the processing of the data remotely and the possibility of exporting not only the data but also the 3D model to a BIM software, for the continuity of the development of the components of the prefabrication system.

In this way, this dissertation helped to see that BIM, allows to achieve the objectives sought in the prefabrication industry in construction. Modularization, DfMA, and customisation are concepts that can be developed more efficiently through BIM, including those explored in tools such as configurators. These proved to be a good resource to achieve a higher level of productivity in the industry, by allowing automation through Generative Design, greater flow and obtaining of information in the project design phase, and greater cooperation between different stakeholders, especially designer and clients, who are largely the beneficiaries of this search to make project information accessible and easy to use. In addition, the making of important decisions by the main people involved in the initial phases of the buildings becomes more objective and efficient, by getting the most relevant KPIs automatically.

Although in general during the research a good amount of information was found in relation to BIM applied to the prefabrication industry in construction, this was not the case when the focus was on finding applications mainly in the initial design phases. Apparently, this is an area that still has a lot to be explored, which makes research into tools such as configurators relevant. Regarding these and their application in prefabrication, both in the literature consulted and, in the platforms and/or tools investigated and tested, no single examples were found that were easily adaptable for a specific case study. This allowed to see the need to create a methodology based on different tools.

One of the biggest difficulties in this regard was the lack of knowledge in programming languages that would allow me to make connections between the tools selected for the development of the initial framework. The implementation of a web application for the proposed configurator, which makes use of the remote information processing capabilities of Rhino Compute, based on a computational model, remains open for further development of the dissertation. The interoperability possibilities allowed by the Speckle platform could be widely used to bring the information generated from the model to other BIM tools, which would allow the development of the design at a higher level of detail.

With respect to the computational model developed, other geometric approaches could be explored for the definition of the elements of the case study system. What was proposed was an option that allowed design automation and user interaction to a good degree, but the code processing time was longer than expected, which is an obstacle to its efficient use. Also, those codes that were implemented could be taken to a higher level of definition, in order to obtain, for example, the prefabricated elements of stairs and circulations inside the cores, different typologies of slabs depending on their position in the building, and better definition of the facade modules. The code used for the User Interface through Grasshopper API cannot be used in a web application, however, the applied methodology can be taken as a basis for a later implementation that allows its use on the Internet.

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LIST OF ACRONYMS AND ABREVATIONS

AEC	Architecture, Engineering, Construction
API	Application Programming Interface
A.slab	Area of grid cell based on slabs
BIM	Building Information Modelling
CAD	Computer-Aided Design
Cw	Column width
d	Spacing of the facade to perimeter axis
D.axis 1	Column axis parallel to perimeter axis
D.axis 2	Column axis perpendicular to perimeter axis
D.axis 3	Column axis perpendicular to perimeter axis in cases of triple columns
Dcg1	Maximum dimension of cell grid in first direction
Dcg2	Maximum dimension of cell grid in second direction
DfMA	Design for Manufacturing and Assembly
f	Facade thickness
Int.L1	Interior length (between perimeter axes) in first direction
Int.L2	Interior length (between perimeter axes) in second direction
KPI	Key Performance Indicator
Max.L.C	Maximum distance between cores
Max Ssc	Maximum span on steel-concrete composite columns
Min.Area.C	Minimum core Area
ns1	Number of subdivisions in first direction
ns2	Number of subdivisions in second direction
SCpl	Spacing core-axis on the sides perpendicular to girders

SSg	Spacing slab-axis over girder
SSl	Spacing slab-core on L sections
SSt	Typical spacing slab-axis
Sub.L1	Final dimension of slab in first direction
Sub.L2	Final dimension of slab in second direction
UI	User Interface
W.G.	Width of girder
W1.G	Width of the girder´s head

APPENDICES

APPENDIX 1: EXPORTED DATA OF INPUTS

First step

facade Thickness	facade spacing	facade Module Length	Number of Floors	Height First Floor	Height Other Floors	Ir. core 1	direction section 1
0.35	0.05	2	2	3.5	3	0	a

direction section 2	direction section 3	direction section 4	direction section 5	Ratio Area section/core	core Minimum Area	Max. Sesctio Length Without core
a	a	A	a	30	55	42

Second step

core size C1 L	core size C1 W	core size C2 L	core size C2 W	core size C3 L	core size C3 W	core size C4 L	core size C4 W
8.475819	8.733333	8.266667	7.4	8.733333	7.4	8.8125	8.733333

core size C5 L	core size C5 W	core movement C1 a	core movement C1 b	core movement C2 a	core movement C2 b	core movement C3 a	core movement C3 b
8.4875	8.733333	0	0	0	0	0	0

core movement C4 a	core movement C4 b	core movement C5 a	core movement C5 b	direction section 1	direction section 2	direction section 3	direction section 4
0	0	0	0	b	b	b	a

direction section 5	direction section 6	direction section 7	direction section 8	direction section 9	direction section 10	direction section 11	direction section 12
b	b	b	a	a	a	b	a

direction section 13	direction section 14	direction section 15	direction section 16	direction section 17	direction section 18	direction section 19	direction section 20
b	a	a	a	a	a	a	a

direction section 21	direction section 22	direction section 23	direction section 24	direction section 25	direction section 26	direction section 27	direction section 28
A	a	a	b	b	a	a	a

direction section 29	direction section 30	direction section 31	direction section 32	direction section 33	direction section 34
a	a	a	a	a	a

Third step

core extension C1 a	core extension C1 b	core extension C12	core extension C2 a	core extension C2 b	core extension C3 a	core extension C3 b	core extension C4 a
0	0	0	0	0	0	0	0

core extension C4 b	core extension C5 a	core extension C5 b	slab to axis	slab to axis (girder)	core to axis	core to slab (L support)
0	0	0	0.005	0.02	0.02	0.035

perimeter columns_Subdivide Larger Spans	interior columns_Maximum Span
FALSE	8

APPENDIX 2: EXPORTED DATA OF OUTPUTS

Slabs Quantities

slab	Length	Width	Area	Quantity	Total Area
T1	8.618	2.815	19.892	4	79.568
T2	8.618	2.815	20.001	8	160.008
T3	8.618	2.815	20.009	4	80.036
T4	8.618	2.815	20.113	2	40.226
T5	7.284	2.901	20.123	4	80.492
T6	7.284	2.901	20.207	6	121.242
T7	7.285	2.73	20.247	8	161.976
T8	7.285	2.901	20.269	8	162.152
T9	8.618	2.927	20.312	4	81.248
T10	8.618	2.819	20.375	4	81.5
T11	8.618	2.819	20.418	2	40.836
T12	8.618	2.819	20.779	12	249.348
T13	8.708	2.815	20.822	24	499.728
T14	8.708	2.815	21.134	12	253.608
T15	8.708	2.815	21.352	6	128.112
T16	8.708	2.815	21.395	12	256.74
T17	8.708	2.815	24.037	12	288.444
T18	8.708	2.815	24.078	24	577.872
T19	8.241	2.456	24.262	12	291.144
T20	8.241	2.456	24.296	12	291.552
T21	7.375	2.823	24.474	6	146.844
T22	7.359	2.823	24.516	52	1274.832
T23	8.708	2.927	25.23	12	302.76
T24	8.708	2.927	25.449	24	610.776
T25	8.708	2.927	25.493	48	1223.664
TOTALS				322	7484.708

Columns Quantities

(By grouping)

Set	column	Length	Width	Diameter	Height	Quantity
Wood Single	Type B	0.29	0.29		3.5	4
Wood Single	Type B	0.29	0.29		3	4
Wood Double	Type A	0.05	0.29		3.5	196
Wood Double	Type A	0.05	0.29		3	196
Wood Triple	Type A	0.05	0.29		3.5	4
Wood Triple	Type A	0.05	0.29		3	4
Wood Triple	Type B	0.29	0.29		3.5	2
Wood Triple	Type B	0.29	0.29		3	2
steel				0.2	3.5	25
steel				0.2	3	25

Columns Quantities

(By section)

column	Height	Quantity
Type B	3.5	6
Type B	3	6
Type A	3.5	200
Type A	3	200
TOTAL		412

Façade Quantities

Module	Length	Height	Area	Quantity
M 1	2.775	3.5	9.713	1
M 2	2.938	3.5	10.283	1
M 3	5.403	3.5	18.911	1
M 4	5.511	3.5	19.289	2
M 5	5.55	3.5	19.425	3
M 6	5.589	3.5	19.562	1
M 7	5.651	3.5	19.779	14
M 8	5.658	3.5	19.803	1
M 9	5.667	3.5	19.835	3
M 10	5.744	3.5	20.104	1
M 11	5.767	3.5	20.185	1
M 12	5.822	3.5	20.377	2
M 13	5.875	3.5	20.563	14
M 14	7.8	3.5	27.3	1
M 15	8.217	3.5	28.76	1
M 16	9.133	3.5	31.966	2
M 17	11.022	3.5	38.577	1
M 18	2.775	3	8.325	1
M 19	2.938	3	8.814	1
M 20	5.403	3	16.209	1
M 21	5.511	3	16.533	2
M 22	5.55	3	16.65	3
M 23	5.589	3	16.767	1
M 24	5.651	3	16.953	14
M 25	5.658	3	16.974	1
M 26	5.667	3	17.001	3
M 27	5.744	3	17.232	1
M 28	5.767	3	17.301	1
M 29	5.822	3	17.466	2
M 30	5.875	3	17.625	14
M 31	7.8	3	23.4	1
M 32	8.217	3	24.651	1
M 33	9.133	3	27.399	2
TOTAL			1929.61	100

Cores Quantities

core	Length	Width	Area	Height
C 1	8.436	0.095	75.764	7.14
C 2	8.883	8.772	77.929	7.14
C 3	8.883	8.447	75.042	7.14
C 4	7.55	8.227	62.111	7.14
C 5	7.55	8.693	65.635	7.14
I 1			266.949	7.14

Girders and L section Quantities

girder	Length	Quantity
G 1	0.095	4
G 2	7.325	4
G 3	8.287	4
G 4	8.496	4
G 5	8.733	6
G 6	8.753	4
G 7	8.833	4
G 8	16.67	4
G 9	17.04	4
G 10	26.478	4
G 11	28.178	4
TOTAL	573.018	46

L section	Length	Quantity
LS 1	8.227	4
LS 2	8.447	4
LS 3	8.693	6
LS 4	8.772	4
TOTAL	153.942	18

General Areas

	slabs	cores	Ir. cores	facade/Spa.
First Floor	3742.429	356.481	266.949	195.641
Building	7484.858	712.962	533.898	391.282