Generative design of modular/ industrial architectural system

https://doi.org/10.21814/uminho.ed.142.24

Wilson Zárate[1], **Bruno de Figueiredo**[3],
Filipe Brandão[4], **Miguel Pires**[2], **Pedro Carneiro**[2]

[1] *BIM A+, Universidade do Minho, Guimarães*

[2] *TOPBIM, Braga, Portugal*

[3] *EAAD, Lab2PT, Universidade do Minho, Guimarães, ID ORCID 0000-0002-3378-0176*

[4] *EAAD, Lab2PT, Universidade do Minho, Guimarães, ID ORCID 0000-0001-8439-7065*

Abstract

The construction industry faces persistent productivity challenges, related to fragmented information flow throughout various project phases and difficulty of communication among stakeholders. To address these issues, the industry has reacted by incorporating solutions such as prefabrication and embracing technologies like Building Information Modelling (BIM). These aim to enhance productivity by facilitating mass customization, improving information flow between project phases and stakeholders, and leveraging software and platforms that enable automation, including processes like Generative Design.

This paper results from an investigation of the application of technologies in prefabrication, with a specific focus on the current use of configurators and the potential for automation in processes related to project development. It presents a methodology to develop a configurator applied to a case study (CREE system, used by CASAIS company). It incorporates researched tools and platforms currently prevalent in the market within the domains of BIM, harnessing the limited parameters of prefabricated elements to automate the generation of design proposals and the acquisition of information about Key Performance Indicators (KPIs).

The research aims to enhance productivity and information flow in the construction industry, leveraging prefabrication and BIM. By using tools associated with configurators, it proposes exploring automation methods, particularly during project initiation phases.

1. Introduction

The construction industry faces persistent productivity issues due to disruptions in the information flow between stages, inefficient resource management, and a lack of clarity regarding the impacts of decisions made in the initial design phases. Hence, the industry is increasingly turning to prefabrication systems as a solution. These systems offer resource optimization, enhance overall project efficiency by reducing scheduling times, and bring greater organization to construction sites. Moreover, they represent a strategic approach for lowering pollution rates and overall construction costs, aligning with a commitment to sustainability and productivity. The integration of Building Information Modelling (BIM) technology further promotes these factors, providing a significant opportunity to improve information flow and automate processes at various levels.

The research revolves around the application of BIM and a prefabrication construction method used by CASAIS, a Portuguese construction company located in Braga. CASAIS is using this hybrid prefabrication system (initially developed by the CREE company) and proposed as a case study. The primary objective is to create a methodology using BIM tools to make a configurator that streamline the generation of design proposals, complete with data and models, quickly and straightforwardly, requiring minimal input from users during the project's design phase.

The paper consists of four main stages. In the initial stage, an exploration is conducted to review existing literature related to the application of BIM in prefabrication for construction. This is followed by an examination of the integration of automation, specifically Generative Design with a focus on configurators, within the design phases of these systems. The second stage explores the proposal of a methodology, which is developed based on the preceding analysis of literature and digital tools. Within this stage, the implementation of a suitable configurator for prefabrication is elucidated, along with the selection of optimal tools to use.

In the third stage, the CREE system is analyzed to identify its main components and the key parameters that need to be taken into consideration. The fourth stage focuses on the implementation of the proposed methodology. This section is centered around the development of code within the Grasshopper Application Programming Interface (API), providing a practical application of the methodology. Finally, it ends with a discussion and conclusions about the exploration made.

2. BIM and Prefabrication

The purpose of prefabrication is to accelerate construction methods, building parts that are assembled off-site in well-equipped manufacturing facilities and under a controlled environment [1]. Subsequently, these prefabricated components are transported from the factory to the construction site, where they are installed and assembled to form the completed parts of the building.

It is worth noting that the design methodology for modular prefabricated elements holds considerable significance for prefabricated systems. The integration of Design for Manufacture and Assembly (DfMA) imply that designers carefully consider the demands of both the manufacturing and assembly stages in the context of industrialized buildings. This approach empowers designers to make informed decisions regarding materials, costs, manufacturability, and assembly processes, ultimately aiming for the creation of the most efficient design [2].

Within this framework, BIM has emerged as a highly effective solution for addressing productivity challenges in the construction sector. The adoption of BIM contributes to enhanced efficiency in the design of prefabricated buildings, their production, and the overall management of construction processes. BIM facilitates simulation and the optimization of information flow. With 3D modeling and the visualization capabilities it offers, a more comprehensive understanding of the entire project is ensured [3].

The integration of BIM in prefabrication, based on literature brings various benefits. It enables early identification of completion delays, streamlines procurement schedules, explores design constraints for fabricators, reduces differences between design and manufacturing models, shortens manufacturing cycles, minimizes coordination errors, improves fabrication quality, and facilitates mass customization. These advantages collectively enhance efficiency, accuracy, and overall project performance [3].

Parametric design stands out as one of the key features of BIM, where entities are represented in parameters and rules. Any modification in one part of the design automatically updates its related parts [4]. Within the BIM environment, buildings are digitally represented with both geometric and semantic information. This representation enables designers to identify key parameters and relationships between various system components [5]. The pre-defined parametric relationships can then be leveraged to generate and optimize building models in prefabrication systems.

With the help of the parametric methods, information from the manufacturing and assembly phases can be included in the design stage. To this end, approaches using automation have been developed, that seek to take advantage of the characteristics of modular systems (they have usually a limited number of parameters and relationships between their components) to improve productivity. In this way, Generative Design is an approach that could use the information of the subsequent phases in the design phase, to increase productivity by automation of design proposals.

In industrialized construction, a strategic approach centered on mass customization has been adopted. The goal is to deliver personalized products at a comparable cost, quality, and speed as the mass production industry. This approach seeks to integrate design flexibility with the advantages offered by mass-produced products. Consequently, standardization and the use of modularity are identified as prerequisites for achieving mass customization [6]. Where the application of newly developed technologies can significantly facilitate the implementation of mass customization. In this regard and according to Far [7], BIM offers substantial benefits across three systemic levels: as a tool, as a platform, and as an environment.

3. Configurators and platforms

Product configurators are a good illustration of product platforms, that were initially used in the manufacturing sector. This emerging technology, akin to the concept of mass customization, aims to enable flexibility in design that adjusts both to customer preferences and to the productivity and capabilities of manufacturers [8]. A product configurator can be defined as a software with the capability to generate, maintain, and utilize electronic product models, facilitating the definition product variations in combinations with minimal input data [9].

Recognizing the significance of tools associated with BIM, a study was undertaken to explore selected platforms with a focus on their functionalities related to automation, information generation, and interoperability. The platforms were chosen based on their market prevalence, availability, and the features they offer, starting from those identified and studied by Brandão [10], and supplemented with additional options. The objective was to gain insights into the primary functionalities and opportunities provided by these platforms and tools, to develop a suitable methodology to make a configurator, incorporating some of them.

The platforms/tools analyzed were the following:

- ShapeDiver [11]: Web-based tool that allows users to create, customize, and share 3D parametric models.
- Hypar [12]: Cloud platform that provides an infrastructure with tools for three-dimensional modeling of buildings using algorithms.
- TestFit [13]: Platform focused on real-estate feasibility, automating site planning for developers, architects, and contractors to maximize site potential.
- PlanFinder [14]: Design app plugin that matches apartment plans to input boundaries using machine learning algorithms to search through a database of building plans.
- Speckle [15]: Platform that focuses on providing interoperability solutions between many different software and applications.
- Rhino Compute [16]: Cloud app for running a headless Rhino application on a server for automating design tasks.

4. Methodology definition

This section describes the proposal of a methodology to make a configurator using some of the tools analyzed. This to generate design proposals, with data and models, considering some KPI’s related with the prefabricated system (CREE). Some of the objectives for the research with the use of these tools and/or platforms in prefabrication for construction are the following:

- The ability to configure a workflow that aligns more precisely with the prefabrication elements of the case study system.
- Automatically retrieving data related to Key Performance Indicators (KPIs) from various design options, with a focus on those most relevant to the system.
- Simplified visualization and configuration of the system, along with the seamless retrieval of results from both models and data, facilitating continuous project development.
- Capability to process information from a server and execute the workflow through a web browser, enhancing ease of interaction.

After analyzing the tools, based on these objectives, it was selected for the implementation of a configurator Rhino compute (due to the flexibility it allows in processing information remotely and the option of being connected to a web browser), and Speckle (due to the possibility it offers of automation in connections between softwares). It was then decided to use Grasshopper (instead of Dynamo, from Revit) to prepare the computational model, due to its easy connection with Rhino compute.

With the use of an implemented web browser, the user can interact with the computational model, allowing him/her to choose within the established parameters, visualize the three-dimensional model as well as obtain data and graphics. The use of the platform Heroku is proposed for the app deployment, and a connection with Revit using Speckle. This allows interconnection with RhinoCompute and the automation workflows. (Figure 1).

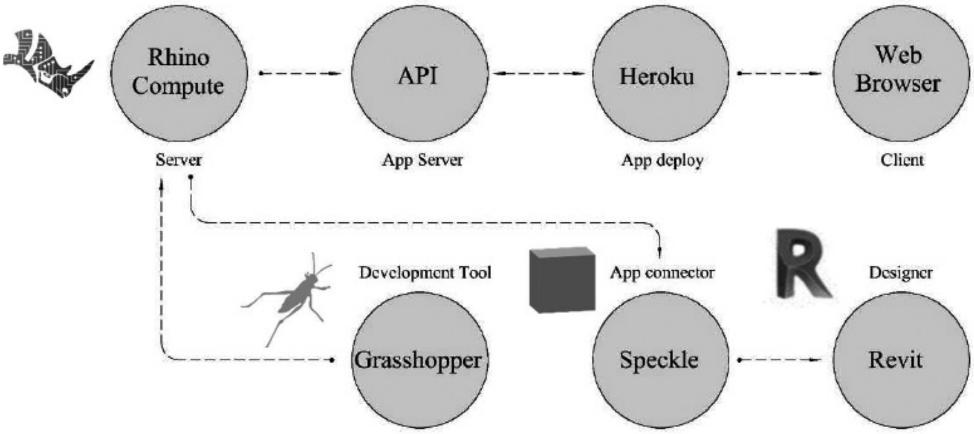
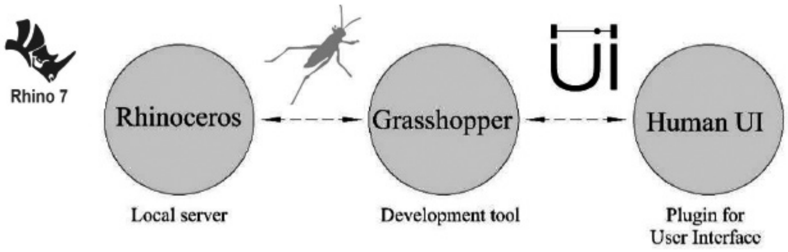


Figura 1
Architecture of the configurator.

The current implementation was focused on the section related to the development of the computational model, elaborated through Grasshopper, leaving the web browser for future implementation. As an alternative for this, it was decided to develop a User Interface through the Grasshopper API, with the use of the plugin HumanUI. In addition, the Rhinoceros software, installed locally, was used as information processor, instead of using the remote version. (Figure 2).

Figura 2
Architecture of the configurator implemented.

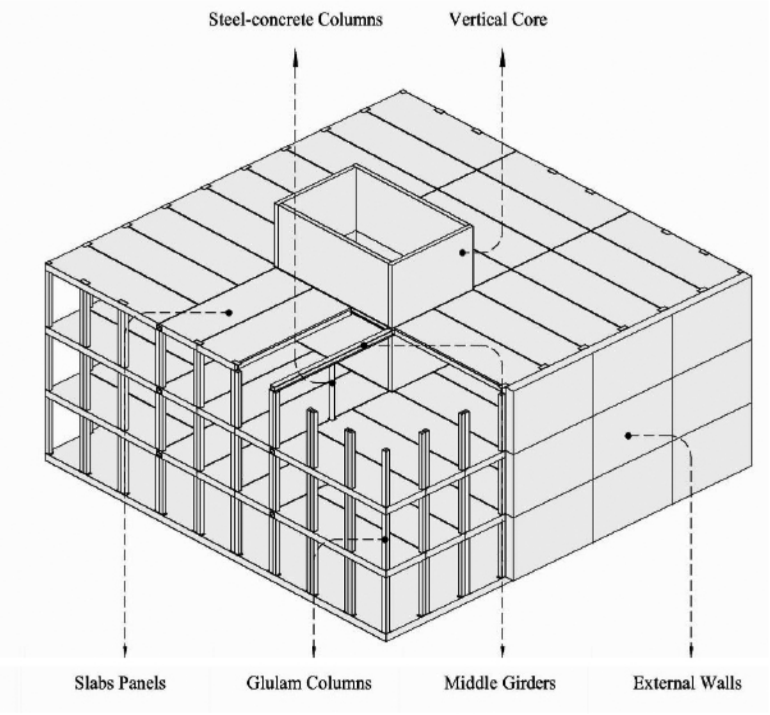


5. CREE system

The CREE System (developed by CREE company) is used as a case study. It is represented by CASAIS Group in Portugal and was proposed by TOPBIM. It is a hybrid prefabrication construction system involving wood and concrete for the construction of versatile high-rise buildings. This system comprises modular elements that enable the off-site construction of virtually the entire building.

To create the computational model in Grasshopper, for the development of the configurator, schemas were developed to represent the key parameters of the prefabrication system, focusing on the components and their interrelations (Figure 3). A set of KPIs, serving as measurable metrics, has been defined to assess the different project options generated. These KPIs are directly aligned with the primary objectives of the case study system, encompassing aspects such as modular quantities of elements, variability in these modules, overall areas, ratios of areas between elements, and maximum and minimum dimensions. Collectively, these KPIs provide an informed understanding of the project's feasibility.

Figura 3
CREE system components and KPIs [17].



Component	KPI
Hybrid slabs	-Dimensions of types. -Quantities by types. -Total areas covered by types.
Cores	-Dimensions of elements. -Areas by element.
Glulam columns	-Quantities by type of grouping. -Quantities by type of section and height.
Steel girders	-Quantities by lengths. -Total length.
L sections	-Quantities by lengths. -Total length.
Steel-Concrete columns	-Quantities by height.
Façade	-Dimensions of types. -Quantities by types. -Total areas covered
Ratio Areas	-Total areas of the components of the system.

6. Generative Design model

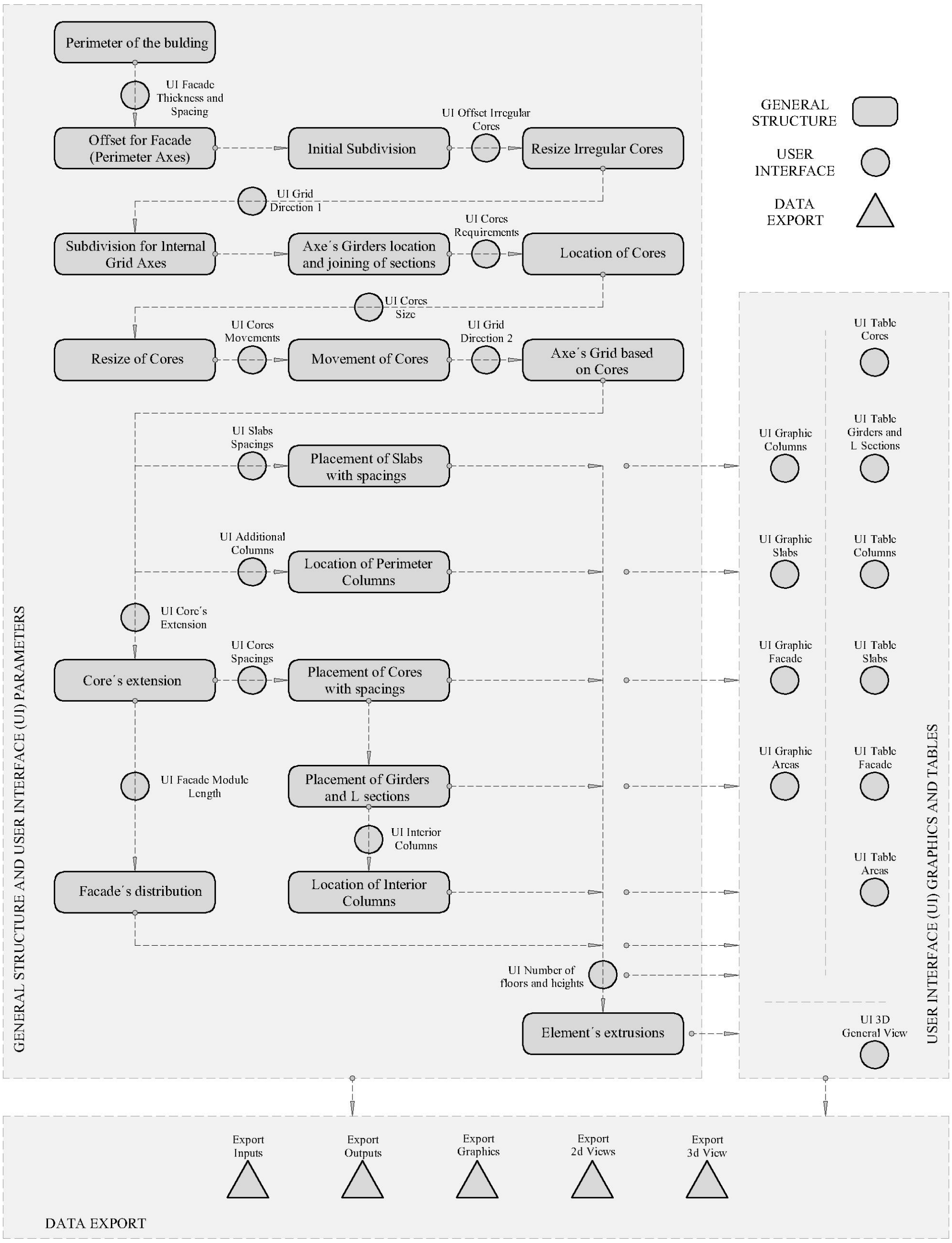
This section presents a prototype of the computational model, developed with Grasshopper and locally processed using Rhinoceros 7 software. It involves three main steps: defining the general structure, creating the User Interface, and processing information for eventual export.

In the general structure of information processing, seventeen steps have been implemented. Starting with the input of the project's perimeter to be designed, these steps enable the automatic definition of the components of the CREE system. It allows user interaction, providing the opportunity for users to assign values to the CREE model parameters as they progress through the configuration (Figure 4).

The order of these steps and their dependencies attend to the relational hierarchies between elements and their parameters. The computational model starts with the location of the perimeter axes of the building, and then, based on this geometry, it looks for an organized 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.

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.

Figura 4
Workflow schema of the computational model.



The second part is dedicated to the creation and integration of the User Interface, achieved using the HumanUI plugin for the Grasshopper API. The management and visualization of the information was organized 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.

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 (Figure 5).

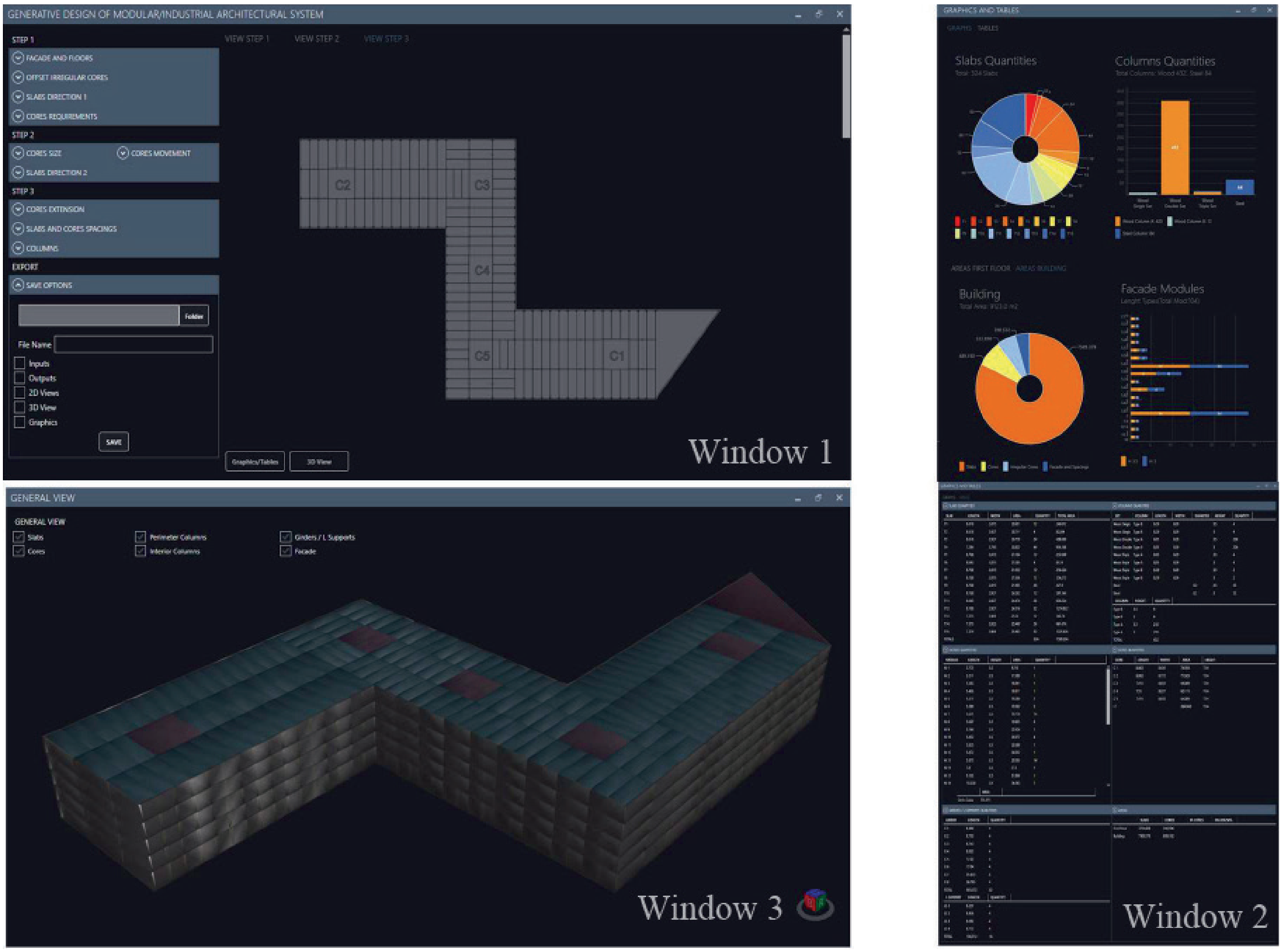


Figura 5
User Interface of the configurator.

The second window contains 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. It 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 prefabricated system. 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, to allow a better visualization.

The third section of the implementation of the computational model involves handling the information generated in the first two sections, to be exported and saved. Thus, the inputs of all the parameters selected, and the outputs of the information generated in tables, would be exported in Excel spreadsheet format. The 2D views, the graphics generated and the 3D visualization window, could be exported in image format.The management of the information to be exported was mainly addressed with the plugin SpreadSheet, that provides components for the organization in tables of groups of information, as well as the possibility of generating screenshots of the graphs and images generated in the user interface.

7. Discussions and conclusions

Although the methodology was defined solely in the section dedicated to the computational model's development (aligned with the research goals and available time), the implementation of the locally developed User Interface successfully resulted in a configurator encompassing the key elements sought: (1) implementation of a computational model for a configurator that automates the generation of data and a model for a prefabrication system, and (2) the provision of user interaction in a simple and systematic manner through the definition of a limited set of inputs. The possibility of implementing a web application for the proposed configurator remains open for future development.

The configurator developed showed 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 in some other examples of building shapes during the process of implementing the computational model to make the necessary adjustments for different building typologies. While 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. Hence, the computational model developed, in theory, can help in the design phases of a project, by allowing the manipulation and automation of information. However, due to time limitations, it has not yet been tested in the CASAIS company to help in the design processes.

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 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.

This research contributed to see the significant advantages that BIM, with its associated processes and tools, brings to the objectives of the prefabrication industry in construction. Concepts such as modularization, DfMA, and mass customization can be efficiently developed through BIM technologies, including those explored in tools like configurators. These tools have proven to be a valuable resource for achieving heightened productivity by enabling automation, smoother information flow during the project design phase, and enhanced collaboration among various stakeholders, with a special emphasis on designers and clients.

Acknowledgements

This research was proposed and carried out in collaboration with TOPBIM, Grupo Casais, which provided resources and openness during the research. This research was supported through the Multiannual Funding of the Landscape, Heritage and Territory Laboratory (Lab2PT), Ref. UID/04509/2020, financed by national funds (PIDDAC) through the FCT/MCTES.

References

[1] Auti, S.D., Patil, J.R., 2018. Prefabrication Technology-A Promising Alternative in Construction Industry. *International Journal of Science and Research*.

[2] Qi, B., Costin, A., 2023. BIM and Ontology-Based DfMA Framework for Prefabricated Component. Buildings 13. https://doi.org/10.3390/buildings13020394

[3] Mahmoud, B. Ben, Lehoux, N., Blanchet, P., Cloutier, C., 2022. Barriers, Strategies, and Best Practices for BIM Adoption in Quebec Prefabrication Small and Medium-sized Enterprises (SMEs). Buildings 12. https://doi.org/10.3390/buildings12040390

[4] Yuan, Z., Sun, C., Wang, Y., 2018. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. Autom Constr 88, 13-22.

[5] He, R., Li, M., Gan, V.J.L., Ma, J., 2021. BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study. J Clean Prod 278. https://doi.org/10.1016/j.jclepro.2020.123505

[6] Bianconi, F., Filippucci, M., Buffi, A., 2019. Automated design and modeling for mass-customized housing. A web-based design space catalog for timber structures. Autom Constr 103, 13-25. https://doi.org/10.1016/j.autcon.2019.03.002

[7] Far, E.R.P., Piroozfar, P.A.E., Robinson, D., 2014. BIM as a generic configurator for facilitation of customization in the AEC industry. Autom Constr 45, 119-125.

[8] Veenstra, V.S., Halman, J.I.M., Voordijk, J.T., 2006. A methodology for developing product platforms in the specific setting of the housebuilding industry. Res Eng Des 17, 157-173. https://doi.org/10.1007/s00163-006-0022-6

[9] Bourke, R. (2004) Product Configurators: Key Enabler for Mass Customization – An Overview, Mindrange Enterprise. 15 July 2004

[10] Brandão, J., 2022. Open reWall: Survey-to-Production Workflow for Building Renovation PhD in Architecture of Contemporary Metropolitan Territories, specialization of Digital Architecture.

[11] Shape Diver. Available at: https://shapediver.com

[12] Hypar. Available at: https://hypar.io

[13] TestFit. Available at: https://www.testfit.io

[14] PlanFinder. Available at: www.planfinder.xyz

[15] Speckle. Available at: speckle.systems

[16] Rhino Developer. Available at: developer.rhino3d.com/guides/compute/

[17] CREE Buildings. Available at: https://www.creebuildings.com/system