AI-based automation for structural design of buildings CILAMCE-2024

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Abstract. With the recent advancement of technology and computational empowerment, processes that were executed manually have the potential to be automated. In Civil Engineering, this is being seen through the implementation of technologies such as Building Information Modeling (BIM), Generative Design, Machine Learning and Artificial Intelligence. The objective of this work is to develop a computational system aiming to optimize the development of architectural and structural projects, implementing technologies such as artificial intelligence and generative design to automate and systematize processes inherent to the project pre-dimensioning phase when designing a building. Using this technology, enterprises specialized in architectural and structural projects will save time, since allocating and pre-dimensioning structural elements are processes that are executed manually. Therefore, engineers are then able to focus on greater challenges involved in structural analysis and architects can simulate the dimensions of elements more accurately.

Keywords: Building Information Modeling; Structural Design Automation; Structural Analysis; Artificial Intelligence.

1 Introduction

Artificial Intelligence (AI) is a subarea of computer science, which proposes the development of computational devices capable of simulating aspects of the human intellect, as described by Silva [1]. In this way, an AI should reason, perceive, make decisions and solve problems by itself. According to Turing [2], a computer can have this name attributed to it when it is capable of imitating human responses under specific conditions.

As claimed by Rafsanjani and Nabizdeh [3], in the world of engineering, civil and structural engineers play an important responsibility in combining architecture with construction. AI, in this case, helps these professionals with rich data analysis, sustainability and productivity. AI focused on structural engineering enables complex and non-linear analyzes of different materials, subjected to different loads, allows efficient monitoring of the health of structures and estimates their useful life, assists in analyzes of dynamic behaviors and can make suggestions on possible solutions for repairs. In the field of geotechnics, it collaborates in the analysis of geological data to understand soil conditions, predict risks and can create foundations. Artificial intelligence can also feed traffic systems to optimize traffic, identify traffic bottlenecks and recommend more appropriate routes. Still in this context, AI can assist in the management of water resources by detecting leaks and optimizing water distribution. As in architectural projects, it can also help with urban planning and the environmental assessment of structures.

Building Information Modeling (BIM) can be understood as a work philosophy, not an activity or specific software, being considered one of the main developments in the architecture, engineering and construction (AEC) industry in the past decades. Its use enables the creation of precise virtual models, which contain the exact geometry and relevant data to support the construction, manufacturing and supply necessary to carry out construction. Eastman [4] mentions that deadlines and costs can be reduced with its use, as a project is modeled with greater ease and visibility, consequently improving execution in the construction phase.

Most structural projects are designed in 2D CAD format, but the calculations are carried out using 3D models, with no connection between the calculation and the two-dimensional drawing. Using BIM, it is possible to achieve this interoperability, since projects are created using software that allows the 3D representation of structural elements. With the increasing complexity of buildings, the need for evolution and adaptation is becoming evident and structural engineers tend to innovate with efficient computational calculation methods. Pires [5] suggests that with the use of BIM modeling software compatible with calculation software, the AEC industry will be modernized.

Ahmed [6] defines *Dynamo* as a visual programming tool present in some *Autodesk* software, such as *Revit*, *Civil 3D* and *Robot Structural Analysis*, created to assist engineers and designers in automating processes inherent to the design phase of a construction. Using *Autodesk Revit* to model elements, there are many repetitive tasks that can be automated with the help of *Dynamo*, as well as carrying out simulations on the model without worrying about errors throughout the process. Nezamaldin [7] emphasizes that this tool allows you to access the *Revit* data structure, change or extract information from it and this can be done with *Python* codes that behave like any other external programming interface. *Dynamo* also allows the import and export of external data, such as *Microsoft Excel* spreadsheets, which is a commonly tool used by engineers.

2 Methods

This chapter will address the methods used to develop the project. The logic of the project is represented in Figure 1, in which, firstly, a user communicates with a chatbot, asking relevant aspects of architectural projects. The chatbot searches the database for a model that fits the mentioned characteristics by the user and returns the *Revit* file. In *Revit*, the architectural model will go through a *Dynamo* script that will create a structural model with columns, slabs, beams and foundation. Following the placement of the elements, another script creates an analytical model with the same properties as the structural model in *Robot Structural Analysis (RSA)*, through nodes inside *Revit*. This script also places loads on the structural elements and retrieves an Excel sheet with all forces generated on specific points. With these forces, the user can calculate the necessary reinforcement and also define the correct cross-section of beams and columns. There is an input in excel that the user can change the cross-section dimensions in Excel and a *Dynamo* script changes the element in *Revit* and recalculate all forces. The step is repeated until the building is viable, ending the program with the presentation of the calculated structure and rendering of the architectural model using *Archviz* 5 in *Unreal Engine*.

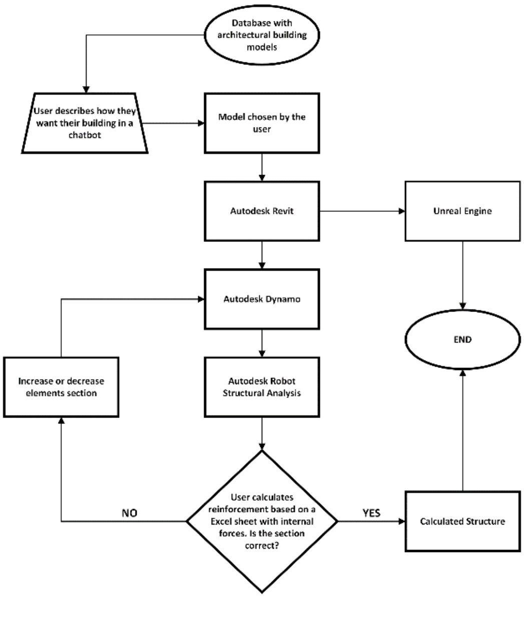

Figure 1. Flowchart of the project

2.1 Database and Chatbot

The first step is to create a database with architectural building models. This was accomplished in a few ways, such as: modeling buildings in *Autodesk Revit* software, obtaining models from online *Revit* libraries and using models that were provided by Instituto Mauá de Tecnologia. These models were processed individually by the authors so that they could have a specific condition, which is having a ground floor, only one standard floor and a roof, as represented in Figure 2.

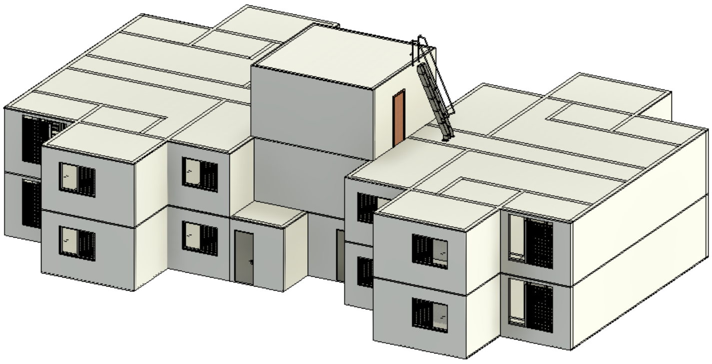

Figure 2. Example of a processed model

Aiming to create a computer system that interacts with the database and simulates a human conversation through text interactions, a *Chatbot* interface was developed. Within this interface, the user can inform characteristics and parameters such as, areas, perimeters, number of apartments, number of floors or, in other words, inputs that would well suit their architectural project. For that to be possible, an AI-powered app was developed and trained to interact in a conversational manner with the user, identifying the parameters asked and searching on a database containing 3D architectural models detailed characteristics, one that matches with the project parameters the user has in mind. The entire application is developed using the Microsoft Power Platform and its tools including the Microsoft Dataverse for database, Microsoft Power Apps for the app and Microsoft Power Automate for automation.

When the AI determines which model matches the user's questions, it displays a plan view of one standard floor and a video of the model. If the person dislikes the model, the conversation continues until another model is found. When the user finally decides his architectural building, a link to a *OneDrive* folder is sent by the *Chatbot*, containing a *Revit* file of the model and *Dynamo* files. With these files, *Dynamo* scripts can be executed on the model to perform structural modeling and analysis.

2.2 Structural modeling using *Dynamo*

The first script in *Dynamo* initiates by selecting all walls present in the *Revit* model, which will serve as a basis for the columns to be allocated. Columns are then positioned on the intersections of walls, disregarding shafts, barriers and architectural finishes. Once this is done, another group of columns is positioned so that the maximum span is 6 meters. In case there is an intersection between columns with doors, windows or any type of opening, the additional structural element is removed.

Having placed all columns, the next step is to insert the beams into the model. To achieve this, the top of each column is identified, and beams are created using lines drawn both horizontally and vertically. Figure 4 represents the script responsible for creating columns and removing the beams located outside the structure, since the lines drawn can arise from two external columns.

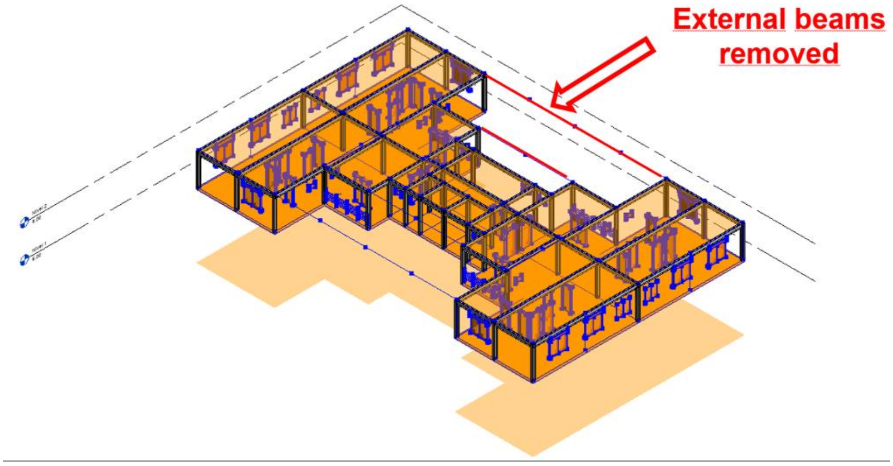

Figure 4. Allocated beams and detail of external beams removed

The next step is to insert the slabs in the region delimited by the beams. This is done by cutting the largest surface of the building, which is the surface formed by the external perimeter of the floor, which will be divided into smaller areas by the beams already positioned. Once this is done, a section of the code identifies the positioning of the building's stairs by removing the area of the slab that corresponds to the projection of the stairs. The finished code and the model with all elements are represented in Figure 5.

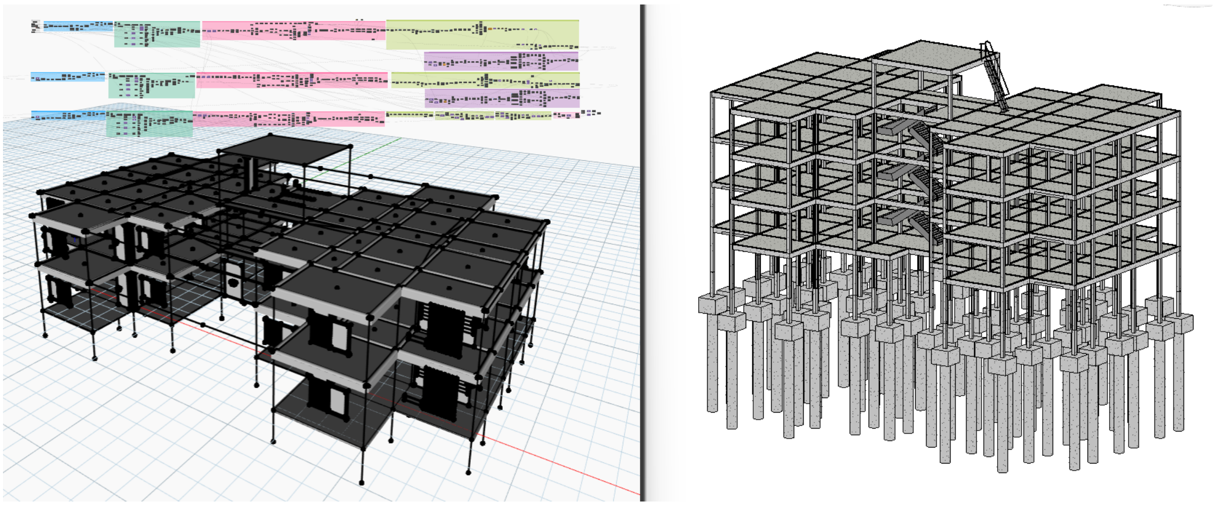

Figure 5. *Dynamo* script for *Revit* (on the left) and structural model (on the right) created from its execution.

2.3 Structural analysis using *Dynamo*

The second script in *Dynamo* creates an analytical model inside *Robot Structural Analysis* from the structural elements placed in the *Revit* project, applying loads and retrieving an Excel sheet with all resulting forces of the components. An issue faced in this study is that the creation of the analytical model was supposed to be made with a simple button present in *Revit*, that transforms the structural model in an analytical model inside *RSA*, and then a script would be created inside the analysis software that would apply loads. However, after further research, it was discovered that this is not possible, because *Dynamo* inside *RSA* only allows loads to be applied on structural elements created inside its software, which is not the case, because the structural elements were created in *Revit*. The way to overcome this factor was by importing a Structural Analysis package that contains nodes which allow the creation of analytical elements and loads inside *Revit*, without having to even open *RSA*.

In this code, analytical bars are created by processing columns and beams, analytical panels are created from slabs and supports are placed according to the foundation. Following this process, loads from the Brazilian standards, NBR 6118 (ABNT, 2023), are applied to the structure. The user can also input data such as, the coefficient for each load, and the concrete f_{ck}. The loads to be considered on the slabs are self-weight, overload of each room and the masonry contained within it. For the beams, self-weight, masonry and the load from the slab are considered. The columns will be loaded with their self-weight and the loads transferred by the beams. At first, horizontal loads, such as wind, should have been considered, although it was not possible to create a load that selected all external walls and was compatible with all models in the database. To simplify the required development, this load was discarded from the analysis. The analytical model generated in *Robot Structural Analysis* is represented in Figure 6.

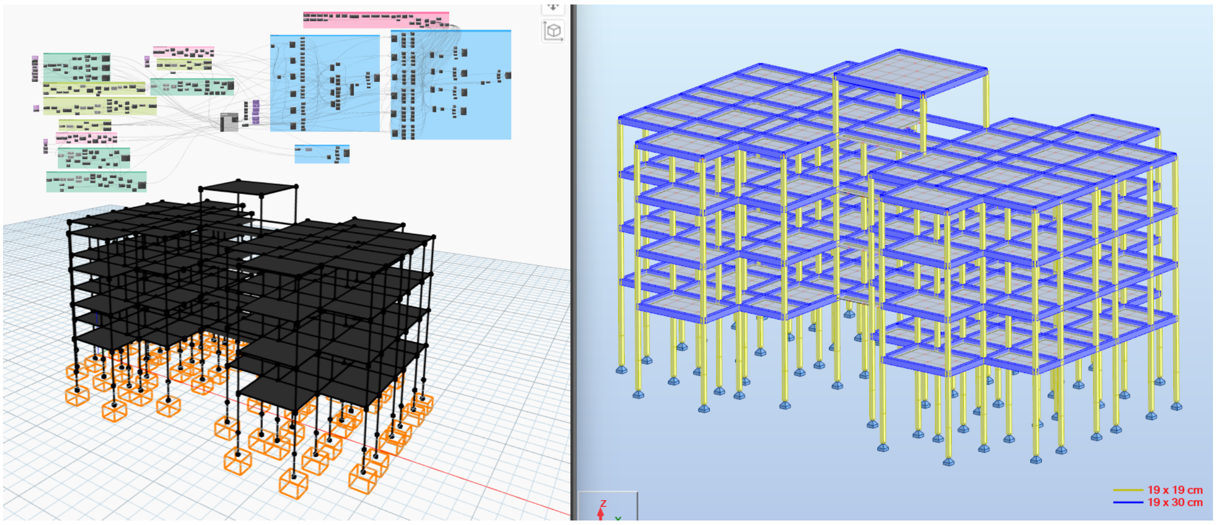

Figure 6. *Dynamo* script for *RSA* (on the left) and analytical model with loads (on the right) created from its execution.

After all loads are positioned, a node calculates the structure and warns the user if there were any errors in the process. A section of the code is then connected to another node which can retrieve forces at specific points of the structural elements. The forces collected are FZ, MX, MY and MZ and the points for columns are the startpoint, endpoint and midpoint. For beams, the points are the intersections between beams and columns, and the gap between these points. The points chosen for these elements represent the maximum and minimum bending moment and shear forces, which are necessary to calculate reinforcement. To organize this information for the user, the data is sent to an Excel sheet, which will have a Macro that positions these points and results correctly and creates diagrams of forces for each column and beam. In this sheet it also appears the section of each column and beam with its respective element ID so the user can see what element is being represented in *Revit.*

The third and final script in *Dynamo* allows the user to change sections of beams and columns in the *Revit* structural model based on the same Excel sheet that was previously sent. It is only necessary to change the value of both sides of the section and execute the script. The code will match the new section of each column and beam based on its Element ID, then the user is able to run the second script once more and compare the results. This process should be repeated until all sections are defined correctly.

2.4 Rendering and finalization of the project

To complete the project, the architectural model is inserted into an interface in *Unreal Engine*, in which it is possible to visualize the building anywhere in the world, by connecting the interface with a plugin named *Cesium*, which allows the insertion of Google Maps API inside the project. Another plugin inserted was *Archviz* 5, that allows the creation of a real estate platform for the visualization of the building's surroundings, amenities and rendered images, if it were to be built.

Unreal Engine was chosen since it is a software that does not require much computational effort and provides a fast and high-quality rendering linked to realistic animations. Additionally, it has plugins for BIM platforms, such as *Revit*, which allows to generate files (*Datasmith*) compatible with *Unreal engine* by downloading *Twinmotion* for *Revit* inside Autodesk's website, within the products section.

3 Conclusions

To validate the structural analysis, a simple structural model was developed in *Revit* and *SAP2000*. The *Dynamo* script that creates an analytical model and applies loads to the structure is executed and a list of the bending moments on beams is presented in the diagram shown on Figure 7. The same model was created in the software *SAP2000*, with the objective of comparing the results after applying the same loads, but manually modeled. The results of the calculation can be observed in the diagram present in Figure 8. Also, it is important to notice that in both models, the slab was discretized in six equal parts. The bending moment results shown on Table 1 represents the comparison between the values obtained from both structural software, considering beams B1 (3,19 m length) and B3 (2 meters length) with the corresponding axial coordinates analyzed.

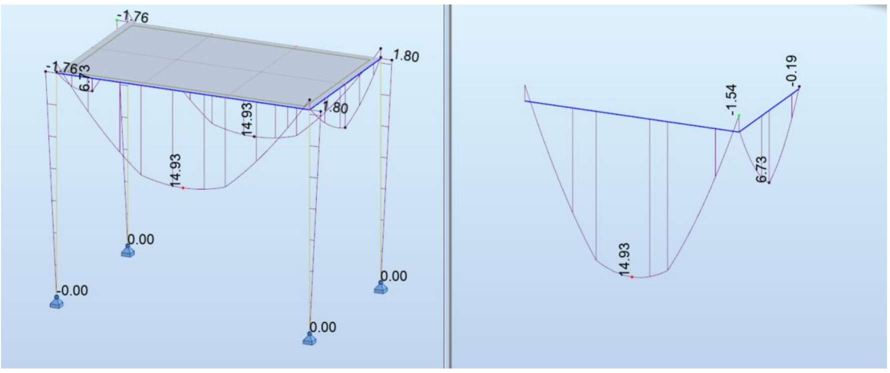

Figure 7. Diagram generated from *Robot Structural Analysis.*

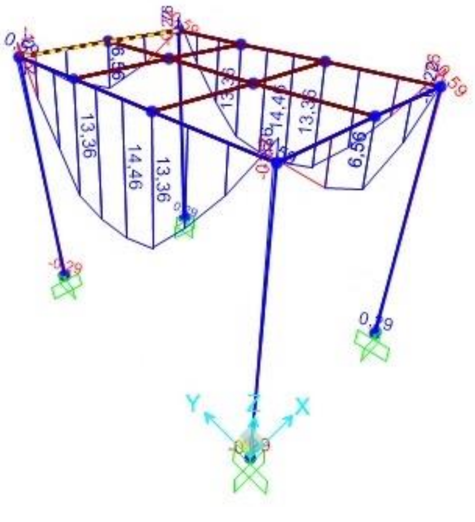

Figure 8. Diagram generated from *SAP2000*.

Table 1. Bending Moment values (kN.m) from RSA and SAP2000 models

		Axial coordinate				Axial coordinate		
Software	Beam	0 m	1,59 m	3,19 m	Beam	0 m	1 m	2 m
RSA	B1	-1,51	14,93	-1,54	B3	-0,19	6,73	-0,19
SAP2000		-1,76	14,46	-1,76		-0,22	6,56	-0,22

The only force chosen for this analysis was the bending moment, due to its significance in the model and aiming keep the analysis brief. Based on the results, it can be noticed that the forces obtained are similar and the error can be explained by the different software utilized, which have different calculation methods. To validate the project, all models in the database should be modeled in different structural analysis software and have the results compared, verifying that the scripts are capable of generating analytical models that accurately represent the real structures.

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