Integrated design of reinforced concrete buildings in a BIM environment

Matheus L. Peres[1], Elisa Sotelino[1], André Fregolente[1]

[1]*Dept. of Civil and Environmental Engineering, Pontifical Catholic University of Rio de Janeiro*
Marquês de são Vicente street, 225, Gávea, 22451-900, Rio de Janeiro, Brazil
matheuslperes@gmail.com, sotelino@puc-rio.br, andrefregolente@gmail.com

Abstract. A lean solution demands that not only the final result must be efficient, but the whole process also needs to have its efficiency improved. The collaboration between engineers and architects in the design process within BIM methodology is a way of achieve this objective. However, much of the research effort has focused in the development and usage of 3D modeling software packages rather than in the direction of integrating the design teams. In this work, a design process is proposed to facilitate the integration between the structural and the architectural designs at early stages of the process. To help the implementation of the proposed process an Autodesk Revit plugin, named ConDA, was developed. It allows the architect to perform preliminary verifications of reinforced concrete structures at an earlier stage in the design process, which avoids the conception of unfeasible structures and facilitates the communication between architects and structural engineers. Introducing ConDA to the design workflow has the potential to reduce the number of design reviews and, consequently, the time spent during design.

Keywords: BIM, reinforced concrete design, integrated design, parametric design, plugin.

1 Introduction

According to Coelho [1], when attempting to adopt the BIM design methodology, three main types of barriers are encountered: Process, Technology and People. The adoption of BIM influences the workflow between design teams. As there is a compartmentalization of disciplines in the usually adopted design workflow, the use of parametric tools during building modeling will not improve the information exchange amongst the design teams. In an attempt to help improve the much-needed integration, this research proposes a project design workflow that fosters better integration between architects and structural engineers. The principles used for this integration can be easily extended to the integration between others disciplines, such as architects and Mechanical, Electrical and Plumbing (MEP) engineers. The main idea of the proposed workflow is that the architect makes a preliminary design considering the space distribution and at the same time considering the characteristics of the structural elements. After this stage, each specialist team receives the preliminary design and proceeds to develop their respective basic design. This is when the first project compatibilization would be performed.

This work develops a mechanism to anticipate the compatibilization between these two designs areas by enabling the architect to perform a structural verification in the preliminary design phase. The insertion of the structural verification in the early stage of the design process promotes design compatibility inherent to the process.

The implementation of the proposed design process demands a broader knowledge from the professional, which may be difficult to achieve, especially when it comes to unexperienced architects. To make this feasible, tools are necessary to aid the architect during the design process without loss of efficiency. In this research work, a plugin for Autodesk Revit, named ConDA (Concrete Design Assistant), was developed to supply this demand. The developed tool allows the architect to perform preliminary verifications of reinforced concrete structures, and, thus, helps them make better structural decisions. This optimizes the design process and reduces rework produced by late integration and compatibilization. Thus, it is a step towards overcoming the perceived process and technological barriers. It is important to point out that the developed tool does not replace the structural engineer who will be responsible for conceiving the final structural system. The goal is to facilitate the communication between architect and structural engineer, thus, making the workflow more efficient.

2 Structured Literature Review and analysis

In order to identify gaps of knowledge in the literature and direct further research on the subject of interest, the first step in this study was to conduct a Structured Literature Review (SLR). Furthermore, it is necessary to understand how the involved areas relate to each other in order to propose a workflow for BIM methodology implementation. Thus, in this work the literature review focused on structural and architectural building design, and their relation with BIM.

To start the SLR, the first attempt was to filter research works that simultaneously study the three main areas (architecture, structural engineering and BIM). In this first attempt, few papers were found, so, the first SLR conclusion is that there is a gap in knowledge and this combination of areas needs more studies. The next step was to verify how deep or shallow this gap is, so, it was necessary to combine the words into strings as can be seen in Table 1.

Table 1: Strings of Keywords

Groups	Keyword strings
Structural engineering + BIM	structural engineering AND (structural conception OR reinforced concrete OR preliminary design OR optimization OR load distribution OR structural analysis or code checking) AND BIM AND (principles OR software engineering OR data modeling OR parametric modeling OR interoperability OR information management or plug-in OR workflow)
Structural engineering + architecture	structural engineering AND (structural conception OR reinforced concrete OR preliminary design OR optimization OR load distribution OR structural analysis or code checking) AND architecture AND (design process OR sustainability OR conceptual design OR building functionality OR space transformation)
BIM + architecture	BIM AND (principles OR software engineering OR data modeling OR parametric modeling OR interoperability OR information management or plug-in OR workflow) AND architecture AND (design process OR sustainability OR conceptual design OR building functionality OR space transformation)

The third step of the SLR was to filter the papers that could contribute to answer one of the following questions:

- How do BIM Methodology, Architecture and Structural Engineering interact in design development to achieve better results?
- How can BIM functionalities and methodologies contribute to structural conception in an Architectural and Structural Engineering workflow?

The next subsection discusses the main papers selected during the SLR and the main conclusions based on the literature review.

2.1 Literature Research Results and Finding

Lavette and Stoker [2] and Fenves [3] were the first authors to investigate the usage of computers in structural design. Both works emphasizes that systems capable of creating and maintaining database during design life would improve the design process. Lavette and Stoker [2] observed, in their case study, two areas for improvements by computer assistance: building structural system selection considering the architectural and mechanical constrains, and development of a framework for the entire design process instead of discrete design tasks. Fenves [3] concluded that the interaction with architecture occurs when the design problems are first considered as a building problem instead of a structural problem, and the computer should be a tool which helps architects and engineers, to make decisions considering the two disciplines.

After the work of Lavette and Stoker [2] and Fenves [3] some other authors focused on study how the different discipline could use computer to achieve better compatibilized projects. Schnellenbach-Held et al. [4], for example, created a BIM knowledge-based environment applying fuzzy logic for the integration between the building layout, the structural system and the HVAC (heat, ventilation and air conditioning) system designs using a sensibility analysis. However, they did not consider the interoperability of the developed system with others traditional software packages which hinders improvements in the whole design process. Hu et al. [5] focused on the interoperability between architectural and structural software packages; and between different structural software packages. Although Hu et al. [5] developed their studies in the three main topics (BIM, Structural Engineering and Architecture), they did not discuss the design process, which is the focus of the present research.

Other researchers, as Carrasco [6], Abrishami et al. [7], Sharafi et al. [8], studied the development of tools that would assist the structural design. Although these works contribute to automize some verifications, they do not impact the design process in relation of the information exchange among the stakeholders.

Differently from the previous papers presented before in this section, in which the contribution focused on late design stage, this work focused on make improvements on early design stage. This approach was choose because BIM methodology was not currently used at this stages yet (Holzer [9]), and due the fact that improvements implemented in this stage have higher probability of impact the whole process.

In short, the research works have given more attention to how BIM affects the architecture or the structure design than how architecture and structural engineering interact in the design process. It is also possible to analyze the principal terms in the papers filtered during the SLR using the VOSviewer, a paper management software. The results extracted from the VOSViewer are presented in Figure 1.

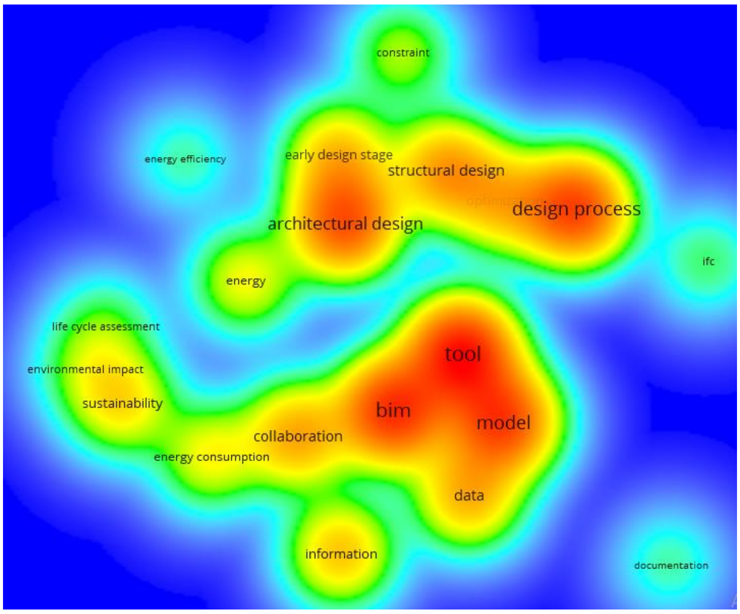


Figure 1: Keywords Density Visualization.

Figure 1 shows the topics concentrated in two main regions: BIM and design. It can be observed that there are two points that with further development can connect these regions. One of the points is the sustainability topic and the other is the development of tools to integrate BIM and the design process. Despite the fact that there are some papers talking about different computational tools, none of them integrates architecture, structural design and BIM. Therefore, the present research proposes a BIM design workflow that increases the structural considerations at the very early architectural design stages, with the help of the Concrete Design Assistant (ConDA).

Figure 1 also shows the most effective way to integrated structural and architectural design is increasing the information exchange during the early design stage. Therefore, the solution proposed by this research is in agreement with the best practices reported in the literature.

3 ConDA Plugin

The reliable use of ConDA requires user attention to the geometrical and mechanical information of the structural elements modeled. Thereby, the suggested approach depends on the use of Revit families configured with realistic parameters. Other information that needs user input is the geographical localization parameters of the building. This information is necessary for the considerations of environmental aggressiveness class and of wind conditions.

For better understanding of ConDA’s workflow, Figure 2 provides a brief presentation of its toolbar and Table 2 describes the buttons’ usage.

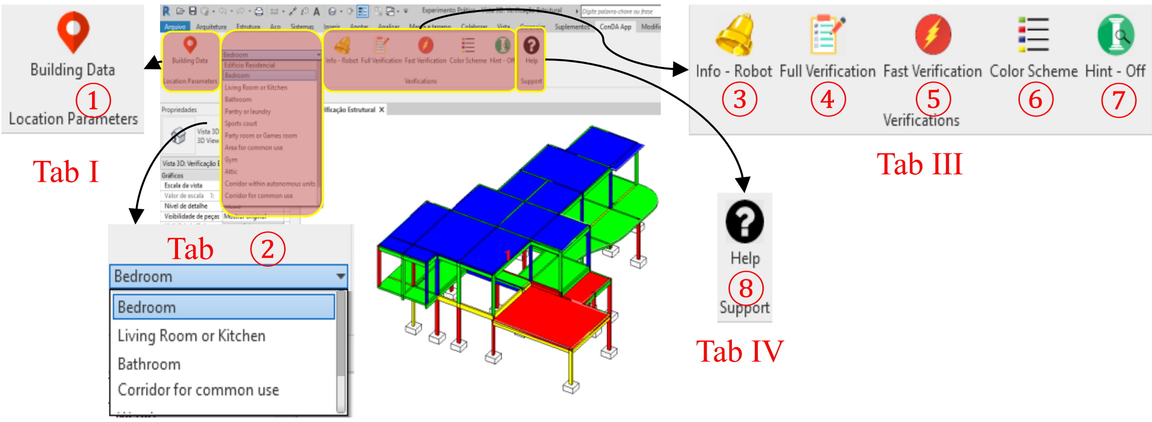


Figure 2: ConDA's toolbar.

Table 2: Tab and button descriptions.

Tab	Button	Description
I	①	Input location parameters that will be used to consider the aggressive environmental and the wind effects (according to the Brazilian Code ABNT NBR 6123:1988).
II	②	Dropdown list with room classification for the creation of the occupation load over the room's area (according to the Brazilian Code ABNT NBR 6120:2018).
III	③	Description of the steps that the user needs to follow to perform the interoperability between Revit and Robot, which is necessary during the full verification.
	④	Full verification process: information exchange, structural analysis and verification.
	⑤	Fast verification: structural verification based on existing structural analysis results.
	⑥	Description of the color scheme for the structural element's verification results.
	⑦	Suggestions for the user´s consideration on how to alter a structural element´s size in order to achieve a more feasible and economical structural solution.
IV	⑧	Support information on ConDA´s considerations and suggestions.

3.1 ConDA Scope

Using ConDA the user is able to perform structural verifications of reinforced concrete structures. The plugin is intended to improve the design process, making it possible for the architect to conceive a feasible structural system in the early design phase. As mentioned previously, the structural engineer, who will be responsible for conceiving the final structural system, is not replaced in the proposed design process. The goal of the plugin is to facilitate the communication between architect and structural engineer, thus, making the workflow more efficient.

For accurate verification, the user must to follow some steps:

1) Model the columns, beams and floors as structural elements.
2) Model the walls considering all its layers.
3) Define the rooms´ classifications according to their occupancy.
4) Enter the information related to the location of the building.

With this information, the plugin is able to consider the effect of the gravity and the wind on the structure during the structural verification.

ConDA considers the gravity effect in two ways. First, it considers the weight of columns and beams as a distributed linear load acting on the instance. The weight of the walls is considered as a distributed linear load over the floor that supports the wall and the weight of the floor as a distributed area load acting on the instance. The NBR 6120 (2018), classifies this type of load as dead load.

The density of the instance's material defines the magnitude of these loads. In cases in which no material is specified by the user for the instance or the material does not have any density specified, the plugin sets the material's density to a default value based on two criteria. If the instance or layer that has a non-specified density material is a wall, the system sets the density value as 1500kg/m³ based on the values presented in NBR 6120

(2018) for masonry wall. If the material is concrete, the density value is set to 2500 kg/m³, also according to NBR 6120 (2018).

When the user defines the room type, the plugin also takes into account the dead load by creating a distributed area load over the floor. The Brazilian Standard Code NBR 6120 (2018) classifies this type of load as live load and its magnitude depends on the room's usage. ConDA also considers a safety coefficient with the values established by NBR 6120 (2018).

The plugin considers the effect of the wind over the building as a horizontal distributed area load over the slabs of each floor. Figure 3 shows how ConDA transforms the wind pressure over the walls' surface (p_i) into a horizontal area load acting in each floor slab of a building (q_i). The magnitude of the pressure p_i follows the prescriptions of the NBR 6123 (1988) code. The plugin creates these loads after the user enters the information related to the location of the building as shown in Figure 3.

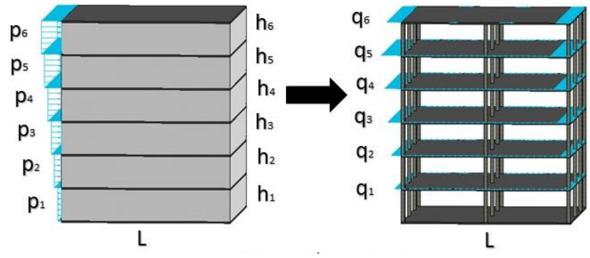


Figure 3: Wind effect.

3.2 Structural Elements Verification

The Structural Verification is the main function of the plugin. It evaluates if the elements have the necessary size (cross section for beams and columns, and thickness for slabs) to provide enough strength to safely resist the loads acting on the structure. There are two buttons to perform this evaluation, the "Full Verification" and the "Fast Verification". The verification procedure is the same for both types of evaluation, the only difference is the external forces input. For every "Full Verification" one structural analysis is performed before the verification is done, while for the "Fast Verification" the structural analysis is not performed. In this case, the plugin uses external forces calculated from the previous structural analysis. It is important to highlight that every change in instance's properties (geometry, position or material) changes the structure's stiffness distribution, and hence, changes the external forces in each element of the structure. Therefore, the results from the "Full Verification" are more accurate. However, the "Fast Verification" is a good estimate at the conceptual design stage, even though the number of times it can be performed in a row is limited. The disadvantage of the "Full Verification" is its longer execution time. It is highly recommended that the structural verification starts and ends with a "Full Verification".

To perform the verification, the system needs to read the information from the elements modeled in Autodesk Revit to define the maximum and the minimum reinforcement configuration for each column and each beam, i.e., the number of reinforcement bars and their positions in the cross section.

For columns, ConDA considers that the element could have a local imperfection and it performs a second order analysis locally according to what is prescribed in the NBR 6118 (2014) iterative method. This is valid for columns with slenderness coefficient smaller than 140. For beams, the system does not analyze second order local effects, i.e., it executes only once the cross-sectional verification for the maximum and the minimum reinforcement configurations.

The adopted maximum and minimum reinforcement configurations are a cross sectional configuration that has the rebar area approximately equal to 4% and 1% of the cross-sectional area for columns, respectively. For beams the maximum reinforcement configuration is also 4% of the cross sectional area, but the minimum configuration has the reinforcement rate varying according to NBR 6118:2014. These two configurations are predefined so that ConDA is able to classify the structural response of the element. The reinforcement configuration also depends on the element type, the rebar cover, which is defined when the user set the environmental aggressiveness class, and the stirrup diameter, which is considered as 6,3mm as default.

The main routine in the structural element verification process is responsible for calculating the strain field in the cross section that makes the internal forces equal to the external forces, i.e., that makes the unbalanced forces vanish. This leads to a nonlinear system and the plugin uses the Newton-Raphson Method to solve it. If the compressive strain in the concrete is bigger than 0,35%, or the maximum rebar tensile strain is bigger than 1%, the cross section fails and the plugin sets the status of the reinforcement configuration as false, otherwise the plugin sets the status as true.

If the verified element is a beam and its status is true, the plugin checks if the relation demanded by neutral line depth is smaller than 0,45 of the beam's height. When satisfied, this relation ensures that the beam is ductile, otherwise the status is set as false.

To perform the verification of the slab, ConDA calculates de minimum thickness. This parameter is established by NBR 6118:2014, in order to keep beams and slabs ductile. If the thickness of the slab is smaller than the element fails, otherwise ConDA calculates the necessary reinforcement rate. If the calculated reinforcement rate is bigger than the minimum reinforcement rate defined by NBR 6118:2014 the thickness of the slab is well sized otherwise it is oversized.

3.3 Output

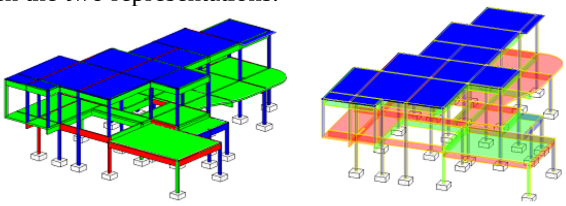
ConDA's output is completely graphical to facilitate the architect's understanding and to improve its usability. Depending on the verification results, the structural elements may have one of the four colors described in Table 3, which also provides the plugin's suggestions to the user.

Table 3: Structural Suggestions.

Color	Min*	Max**	Column	Beam	Floor
Yellow	-	-	This element has no verification results storage		
Green	F	T	This element is well sized, but the structural design is not concluded yet. Send your model to a structural engineer for a more refined structural analysis and design.		
Blue	T	T	Reduce the dimensions of this column. If the result persists, you can remove it.	Reduce the height of this beam. If the result persists, you can remove it or remove a supporting column.	Reduce the thickness of this floor. If the result persists, you can remove a supporting beam.
Red	F	F	Increase the dimensions of this column, create another column close to this one, increase the concrete fck.	Increase the height of this beam, increase its width if it is too thick or insert a column to reduce its span.	Increase the thickness of this floor or add one more beam to reduce its span.

*Status of minimum reinforcement configuration / ** Status of maximum reinforcement configuration

ConDA also differentiates between the outputs of the full verification and those of the fast verification. The latter is displayed using transparency in the colors, while the former uses solid colors with no transparency. Figure 4 shows the difference between the two representations.



a) b)

Figure 4: Structural Verification Output; (a) after a full verification; (b) after a fast verification.

4 Conclusion

The Structured Literature Review findings guided this research. It showed that the integration of the architectural design with the structural design should happen since the early stages of the process, and the BIM methodology has a great potential to allow this integration. However, for this to occur some barriers need to be overcome. The SLR also showed that the use of tools might be the bridge between the design areas and the BIM methodology. With this in mind, this research proposed a workflow in which the building design starts with one professional, which would typically be the architect, defining the shape of the building and its rooms. Added to this traditional task, the proposed workflow also attributes to this individual the task of preliminarily verifying the other systems related to the other disciplines involved in the project. This way the architect conceives an architecture that is inherently compatible with the other systems, avoiding unfeasible architectural decisions and, thus, overcoming a process barrier.

The proposed pre-verification task demands a broader knowledge from the professional what may be difficult to achieve, especially for unexperienced architects. It also needs to be done as soon as possible to avoid delays during the design process. To help enable this new workflow, tools are necessary to aid the architect during the process without loss of efficiency. In this work, a plugin for Autodesk Revit for the pre-verification of reinforced concrete structures is developed as a step towards overcoming part of the technological barrier.

The developed tool named ConDA (Concrete Design Assistant) is capable of verifying the feasibility of reinforced concrete columns, beams and slabs considering the environmental aggressiveness, the gravity and the wind effects acting on the structure. Furthermore, All ConDA capabilities are accessed by a friendly user interface implement in the Autodesk Revit in order to facilitate the results interpretation. The next step of this research is to verify the real impacts of the proposed workflow assisted by ConDA through a User experience analysis in which the interviewees will be architects.

Acknowledgements. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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