PONTIFÍCIA UNIVERSIDADE CATÓLICA
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Matheus Lopes Peres

An integrated approach for the design of reinforced concrete buildings in a BIM environment

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-graduação em Engenharia Civil of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Engenharia Civil.

Advisor: Prof. Elisa Dominguez Sotelino

Rio de Janeiro
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*I dedicate this work to my family,
who has always supported me and makes my
journey happier.*

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To God for the health and for the gift of life.

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Abstract

Peres, Matheus Lopes; Sotelino, Elisa Dominguez (Advisor). **An integrated approach for the design of reinforced concrete buildings in a BIM environment**. Rio de Janeiro, 2019. 102p. Dissertação de Mestrado – Departamento de Engenharia Civil e Ambiental, Pontifícia Universidade Católica do Rio de Janeiro.

There is an increasing demand for lean solutions in the construction industry. To achieve this, not only the final solution must be efficient, but the whole process also needs to have its efficiency improved. The BIM methodology with the collaboration between engineers and architects in the design process is viewed as a way of generating more efficient and lean solutions. 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 design and the architectural design at the early stages of the process. The proposed philosophy can be extended to enable better integration between the architectural design and other design areas, such as mechanical and electrical systems. To help the implementation of the proposed process a plugin, named ConDA, was developed for the Software Autodesk Revit. The developed tool allows the architect to perform preliminary verifications of reinforced concrete structures. The use of ConDA anticipates this verification to an earlier stage in the design process, which avoids the conception of unfeasible structures and facilitates the communication between architects and structural engineers. The plugin was tested by twenty-four architects. They evaluated its usability and the benefits in reducing the time and effort spent in the architectural design. ConDA's main contributions, according to the architects interviewed, is the improvement of the communication between architect and structural engineer, and the reduction of the number of design reviews and, consequently, the reduction of time spent during the design. The comments given by the interviewees also indicate that the plugin can be a useful tool in education by helping architectural students improve their structural design skills. The results of the test ratified the hypothesis that the ConDA assisted design process can increase the quality and efficiency of the architectural design process.

Keywords

BIM; structural design; integrated design; parametric modeling; plugin; reinforced concrete.

Resumo

Peres, Matheus Lopes; Sotelino, Elisa (Orientadora). **Uma abordagem integrada para o projeto de edifícios de concreto armado em um ambiente BIM**. Rio de Janeiro, 2019. 102p. Dissertação de Mestrado - Departamento de Engenharia Civil e Ambiental, Pontifícia Universidade Católica do Rio de Janeiro.

Há uma crescente demanda por soluções enxutas na indústria da construção. Para atingir esse objetivo, não apenas a solução final deve ser eficiente, mas também todo o processo deve ter sua eficiencia melhorada. A metodologia BIM associada à colaboração entre engenheiros e arquitetos no processo de projeto é vista como uma forma the gerar soluções mais eficientes e enxutas. Contudo, as pesquisas têm focado no desenvolvimento e no uso de softwares de modelagem 3D e pouca atenção tem sido dada a interação entre as equipes de projeto. Neste trabalho, um processo de projeto é proposto para facilitar a integração entre o projeto estrutural e o projeto arquitetônico nas fases iniciais do desenvolvimento do projeto. A filosofia proposta pode ser estendida para melhorar a integração entre o projetos de arquitetura e os projetos de outras áreas como instalações hidráulicas e elétrica. Para auxiliar na implementação do processo proposto, um plugin, chamado ConDA, foi desenvolvido para o software Autodesk Revit. A ferramenta desenvolvida permite que o arquiteto verifique de forma preliminar estruturas de concreto armado. Ao se utilizar o ConDA, essa verificação é antecipada dentro do processo de projeto, evitando a concepção the estruturas inviáveis e facilitando a comunicação entre engenheiros estruturais e arquitetos. O plugin foi testado por vinte e quatro arquitetos que avaliaram a sua usabilidade e seus benefícios em reduzir tempo e esforço gastos nos projetos arquitetônicos. As principais contribuições do aplicativo apontadas pelos entrevistados foram a melhoria na comunicação entre engenheiros estruturais e arquitetos, e a redução no número de revisões de projeto, o que consequentemente reduzem o tempo gasto no projeto. A partir dos comentários dos entrevistados também foi possível concluir que o plugin é uma ferramenta útil no ensino de projeto de arquitetura, ajudando o aluno a desenvolver suas habilidades estruturais. Os resultados do teste ratificaram a hipótese de que o processo de projeto auxiliado pelo ConDA tem sua qualidade e eficiência aumentadas.

Palavras-chave

BIM; projeto estrutural; projeto integrado; modelagem paramétrica; plugin; concreto armado.

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List of Abbreviations

BIM	Building Information Modeling
BEM	Building Energy Modeling
SLR	Systematic Literature Review
S-BIM	Structural Building Information Modeling
IFC	Industry Foundation Class
CDB	Case-based Design
UPOEM	User Pre-Occupancy Evaluatuion Method
CIBIM	Costumer Interactive Building Information Modeling
LCA	Life Cycle Assessment
SPL	Spacy Layout Plan
BPS	Building Performance Simulation
AR	Augmented Reality
GIS	Geographical Information Systems
POE	Post-Occupancy Evaluation

List of Symbols

ε,   Cross Sectional Strain Field;

ε_{xo},   Strain in the origin of the cross sectional coordinate system;

ε_{c2},   Strain in the Peak of the Compression;

ε_{cu},   Ultimate Strain of the Cross Section;

κ_y,   Curvature in y direction;

κ_z,   Curvature in z direction;

σ_x,   Cross Section Longitudinal Stress;

f_{cp},   Peak Concrete Compressive Stress;

f_{ck},   Characteristic Compressive Strength of the Concrete;

f_{cd},   Design Compressive Strength of the Concrete;

f_{yk},   Characteristic Yield Tension of the Steel;

f_{yd},   Design Yield Tension of the Steel;

$F(\varepsilon)$,   Unbalanced forces;

N_{xe},   External Normal Force in x direction;

N_{xi},   Internal Normal Force in x direction;

M_{ye} External Bending Moment in the y direction;

M_{yi} Internal Bending Moment in the y direction;

M_{ze} External Bending Moment in the z direction;

M_{zi} Internal Bending Moment in the z direction;

N_{xc},   Concrete Contribution to Internal Normal Force in the x direction;

M_{yc}, Concrete Contribution to Internal Bending Moment in the y direction;

M_{zc}, Concrete Contribution to Internal Bending Moment in the z direction;

N_{xs}, Steel Contribution to Internal Normal Force in the x direction;

M_{ys}, Steel Contribution to Internal Bending Moment in the y direction;

M_{zs}, Steel Contribution to Internal Bending Moment in the z direction;

$S(\varepsilon)$, Tangent Stiffness Matrix;

E_s, Steel Elastic Modulus;

g, Gravity acceleration.

1
Introduction

1.1
Motivation and Problem formulation

In his attempt to adopt BIM design methodology, Coelho (2016) encountered three main types of barriers: Process, Technology and People. To illustrate how the adoption of BIM influences in the workflow of the design teams, Figure 1 shows the usually adopted workflow for building design in which there is the compartmentalization of the disciplines involved.

If the design process stays compartmentalized, the use of parametric tools during building modeling will not improve the information exchange amongst the design teams. This concentration of information characterizes a process barrier and generates a lot of rework for all design teams.

The improvement in software interoperability in the last two years reduced the technology barrier. However, this issue has not yet been resolved, which further hinders integration.

The people barrier is related to the miss understood of the procedures necessaries to design the building using the BIM methodology by the professionals involved in the design process. The client's non-understood of the necessity to the design teams work integrated also characterizes a people barrier. This can be seen when the client hires the structural engineers only after the architectural basic design phase to reduce the cost of the design.

In an attempt to help improve the much-needed integration, this research proposes an adapted project design workflow for the interaction between architects and structural engineers. The principles used for this integration can be easily extended to the relation between architects and the other design teams, such as MEP Engineers, as shown in Figure 2. The main idea of the proposed workflow is that the structural engineers, MEP engineers and architects start together conceiving the

building. Then a team of architects makes a preliminary design considering the space distribution and verifying the position and the characteristics of the structural, electrical, hydraulic and mechanical elements such as columns, beams, slabs, air conditioner equipment, electrical and hydraulic components. After that, each specialist team receives the preliminary design to develop the basic design, which is the phase when the first project compatibilization is performed.

The proposed workflow also covers the Executive Design, Construction and Maintenance phases. In the latter phase is when the model should be updated to represent the current state of the building. For each phase of the workflow, there is a specific recommended LOD (level of development) as can be seen in Figure 2. The LOD definition was developed by the AIA (The American Institute of Architects) and avoids over detailing of elements, by providing only the information necessary for a specific phase to the model. The suggested LOD are classified as follows:

- LOD 100 – Parameters like volume, area, height, location and orientation are modeled;

- LOD 200 – The model's elements have approximate size, shape, quantities and properties;

- LOD 300 – The information described for LOD 300 are set precisely;

- LOD 350 - The details that represents how elements interface with other elements;

- LOD 400 – The elements are modeled with complete fabrication, assembly and detailing information;

- LOD 500 – The elements are modeled as built for maintenance and operations.

This work focuses in the integration between the architectural design and the structural design at the preliminary design phase. It develops a mechanism to anticipate the compatibilization between these two designs areas by enabling the architect to perform a preliminary 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.
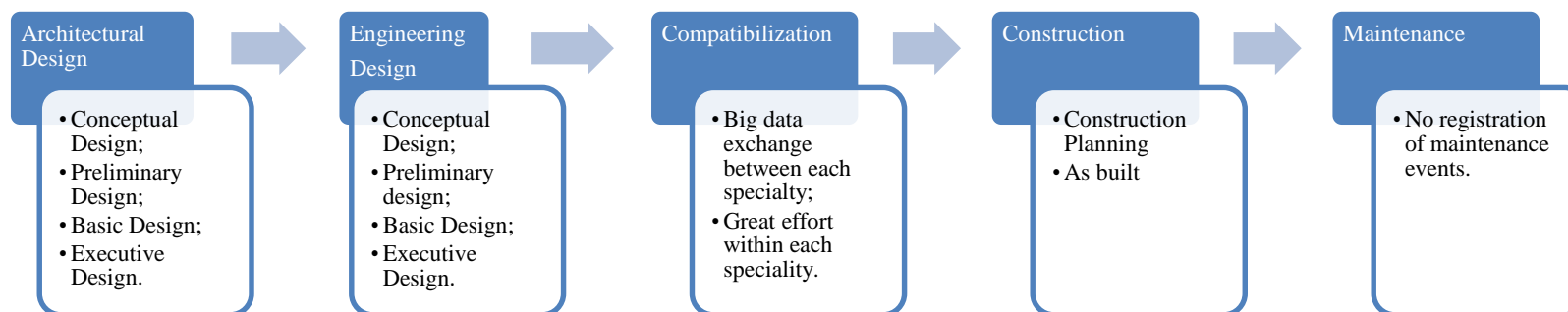
Figure 1: Traditional workflow for Building Lifecycle.
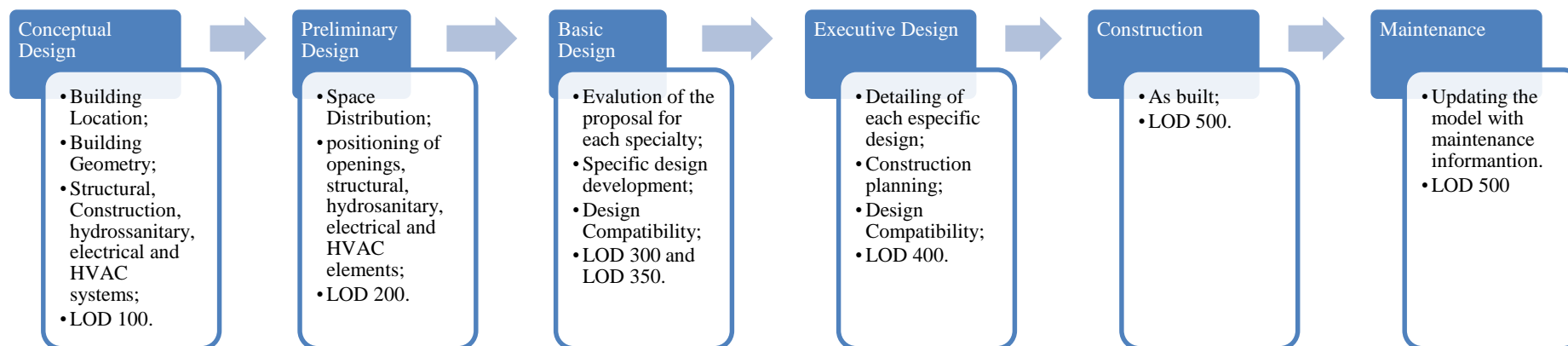
Figure 2: Adapted workflow for Building Lifecycle.

The implementation of the proposed design process demands a broader knowledge from the professional, what may be difficult to achieve, especially for unexperienced architects. To make it 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 as a step towards overcoming the technological barrier.

1.2
Objectives

This research aims to improve the BIM methodology implementation with respect to the process and technology. The improvements influence directly the workflow between structural engineers and architects in order to optimize the design process, and reduce rework produced by late integration and compatibilization.

1.3
Methodology

To reach the objectives, this study focused on correlating BIM Methodology, Structural Design and Architectural Design. A structure literature review was carried out to correlate these three main issues. So, it was necessary to search the topics in pairwise manner to collect more papers and to better structure a base to identify research gaps on these subjects. An identified gap was that the architects do not use BIM tools to improve the quality of the structure and the communication with the structural engineer at the early stage of the building design process. To fulfill this gap, a workflow for BIM implementation was proposed. To make it feasible, an Autodesk Revit plugin was developed, which performs a preliminary verification of reinforced concrete structures. To evaluate and validate the proposed approach, a survey with twenty-four architects was performed. Through this survey it was possible to validate the hypothesis that the ConDA assisted preliminary design process increases the quality of the architectural design and improves the efficiency of the process.

1.4
Research Structure

This document is organized in five chapters. Chapter 1 describes the problem formulation, the motivation, the objectives and the applied methodology for the research. Chapter 2 presents the structured literature review (SLR) process, its steps and its considerations. It also provides an analysis of the SLR and presents the main research works in the three areas of interest: structural engineering, architecture and BIM. It also presents the gap in knowledge that this research intends to contribute. Chapter 3 presents the developed tool ConDA, describing its capabilities, considerations and implementation. Chapter 4 describes ConDA´s evaluation and validation test, and presents the results from the survey as well as user´s comments during the survey. It also statistically analyzes the user's answers to a questionnaire relating them to the main contribution of the proposed design process. Chapter 5 gives the main conclusions of this research and provides some suggestions for future research in this area to further fill the gap found in the SLR and to improve ConDA´s functions.

2
Structured Literature Review and Analysis

2.1
Literature Research Methodology

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).

In order to do a SLR, first it was defined the evaluation criteria based on the research question that this work wants to answer. The precise definition of the evaluation criteria is fundamental because it makes the process transparent and shows the comprehensiveness of the review. It is essential to explain thoroughly the conduction of the review process, particularly regarding the section of the literature and the choices made in relation to the use of specific search terms and databases (Saunders; Lewis; Thornhill, 2008).

An effective review creates a solid foundation for advancing knowledge (Faria, 2017). According to Webster and Watson (2002), it occurs because of the solid and transparent way that review is structured, facilitating theory development, avoiding areas where there is a huge quantity of research, and uncovers areas where research is needed. Because all these benefits that SLR adds to the review, it has increasingly been used in literature management (Hallinger, 2013). However, compared to a traditional literature review, this methodology requires much more effort.

Faria (2017) suggests organizing the review in five different stages: question formulation, locating papers, paper selection and evaluation, analysis and synthesis, and reporting and using of results.

To overcome the additional effort of doing the SLR, some tools were used to support the SLR process, such as Microsoft Word, Microsoft Excel and VOSviewer. The databases researched for the review were Engineering Village,

Web of Science, Scopus and ScienceDirect. Figure 3 illustrates the phases of the research and their activities during the review.

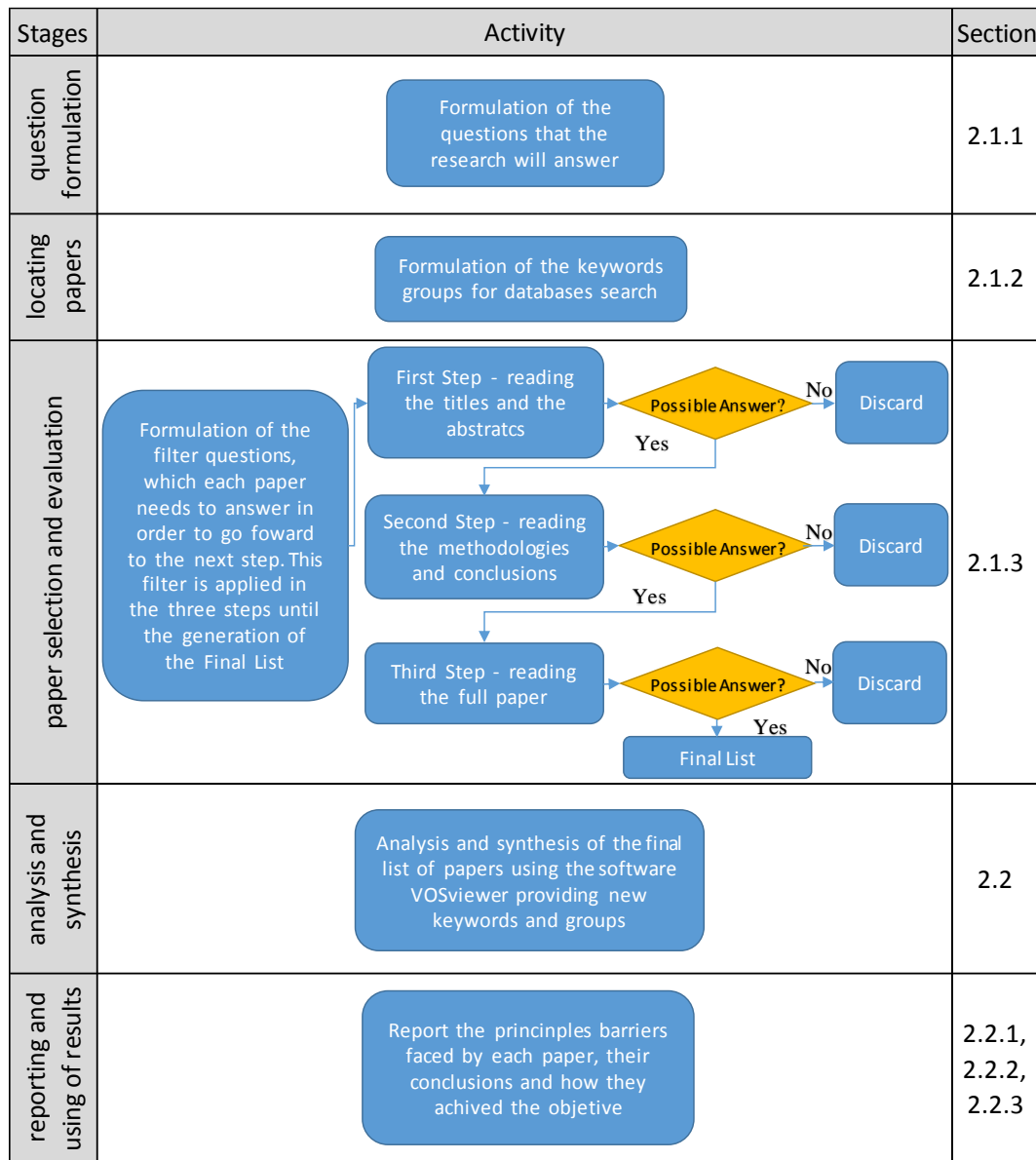| Stages	Activity	Section
question formulation	Formulation of the questions that the research will answer	2.1.1
locating papers	Formulation of the keywords groups for databases search	2.1.2
paper selection and evaluation	Formulation of the filter questions, which each paper needs to answer in order to go foward to the next step. This filter is applied in the three steps until the generation of the Final List — First Step - reading the titles and the abstratcs → Possible Answer? No → Discard / Yes → Second Step - reading the methodologies and conclusions → Possible Answer? No → Discard / Yes → Third Step - reading the full paper → Possible Answer? No → Discard / Yes → Final List	2.1.3
analysis and synthesis	Analysis and synthesis of the final list of papers using the software VOSviewer providing new keywords and groups	2.2
reporting and using of results	Report the princinples barriers faced by each paper, their conclusions and how they achived the objetive	2.2.1, 2.2.2, 2.2.3

Figure 3: SLR stages.

2.1.1
Question Formulation

To propose a workflow for BIM methodology implementation, it is necessary to understand how the involved areas relate to each other. Focusing in Structural Building Design, Architectural Building Design and their relation with BIM, the current research formulated and considered two questions.

(1) How do BIM Methodology, Architecture and Structural Engineering interact in design development to achieve better results?

(2) How can BIM functionalities and methodologies contribute to structural conception in an Architectural and Structural Engineering workflow?

2.1.2
Locating Studies

The first step to locate the studies was to formulate the keywords that drive the SLR. The keywords were divided into two groups, the first one is the main group and the second one is the derivative group composed of words derived from the word of the main group, as can be seen in Figure 4. Then using the Boolean Operators "AND" and "OR", these keywords were combined in a string, which was used to filter papers in the databases, as can be seen in Table 1.

The first attempted research filter was composed of the three main groups and their derivative words, characterizing papers that involve the three themes: 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. In order to do that it was necessary to combine the words into strings as can be seen in Table 1. The results showed that there are many studies relating Architecture and BIM (629 papers), and Architecture and Structural engineering (708 papers), but there are fewer relating BIM and Structural Engineering (109 papers).

At first sight, the gap looks like a shallow gap, but in BIM methodology, the integration between the areas is fundamental, so, in this context, the research's potential for contribution becomes clear.

Main Group	Derivative Group
Architecture	Design Process Sustainability Conceptual design Building Functionality Space Transformation
Structural Engineering	Structural Conception Reinforced Concrete Preliminary design Optimization Load Distribuiton Structural Analysis Code Checking
BIM	Principles Software Engineering Data Modeling Parametic Modeling Interoperability Information Management Plug-in workflow

Figure 4: Keywords.

Table 1: Strings of Keywords.

First Attempt	Second Attempt
Architecture AND (Design Process OR Architectural Conception OR …) AND Structural Engineering AND (Structural Conception OR Reinforced Concrete OR …) And BIM AND (Principles OR Software Engineering OR …)	Architecture AND (Design Process OR Architectural Conception OR …) AND Structural Engineering AND (Structural Conception OR Reinforced Concrete OR …)
	Architecture AND (Design Process OR Architectural Conception OR …) And BIM AND (Principles OR Software Engineering OR …)
	AND Structural Engineering AND (Structural Conception OR Reinforced Concrete OR …) And BIM AND (Principles OR Software Engineering OR …)

2.1.3
Study Selection and Evaluation

According to Saunders et al., (2008) conference proceedings and peer-reviewed articles are the most reliable sources of information and, thus, they were the only source considered in the present SLR.

Saieg et al., (2018) suggest that the study selection should be done in three steps:

- The first step is to read the titles and the abstracts of each study found and to evaluate them.

- The second one includes reading the methodology and the conclusion of the study that passed in the first evaluation.

- The last step is reading the full text of the remaining papers after the two steps are completed.

These three steps filtered the selected studies and the remaining papers compose the final list of papers relevant for this research.

During the evaluation, only the papers that answered or could answer one of these three question were considered for the next step:

- How BIM affects Architecture?

- How Architecture and Structural Engineering interact in design development?

- How BIM affects Structural Engineering?

2.2
Literature Research Results and Findings

This section presents the results for the various combinations of topics considered. The structural engineering and BIM combination provided smaller amount than the other two combinations with only 15 papers. The structural engineering and architecture combination produced 35 papers and the architecture and BIM combination resulted in 38 papers.

With data extracted from the SLR, it was possible to observe that since 1973 engineers and architects have been studying how they interact in design development. However, the developments were slow, i.e., only ten papers in 32 years. The interest in this subject became more frequent since 2005, just before BIM became an important research topic, which occurred from 2010 on as Figure 5 shows.

In Figure 5, it is possible to see that there is a tendency of increasing the quantity of papers produced despite the reduction in architecture and BIM papers in 2016. Differently from the papers of this combination produced in the years before, after 2016 the papers related to sustainability started to separate from those related to architecture, which caused this reduction. This separation is natural; as the interest in the sustainability issue is growing and more specific approaches in the research works become necessary.

Figure 5 also shows that the interest in the combined subject of architecture and BIM began before the interest in the combination of structural engineering and BIM subjects. Therefore, the increasing in the number of papers on structural engineering and architecture and the increasing in the number of papers on architecture and BIM motivated the increase in the number of papers on structural engineering and BIM. That is why the approach used in this research to investigate the integration of the three subjects is important.

Figure 5 also shows that research interest in structural engineering and BIM started in 2006 and has grown, stabilizing in three papers per year, since 2015. Based on these numbers, it is possible to infer that studies combining structural engineering and BIM is still a fairly open research topic.

Analyzing the distribution of the occurrence of the number of papers per country, it is possible to observe that only four countries have studied the three

subjects. They are United Kingdom, United States of America, Canada and Germany (Figure 6). UK is the country that has the most balanced distribution in number of papers amongst the three subjects. This is because the UK's government requires that all stakeholders involved in public construction (including the architectural and the structural designer) use BIM methodology for public contracts.

Despite the Brazilian government's decree that BIM must be implemented in the design stages by 2021, Brazil is one amongst 18 countries that has studied only one of the subjects. That is why studies that integrate BIM methodology and building design, like this research, are so relevant for Brazil's development.
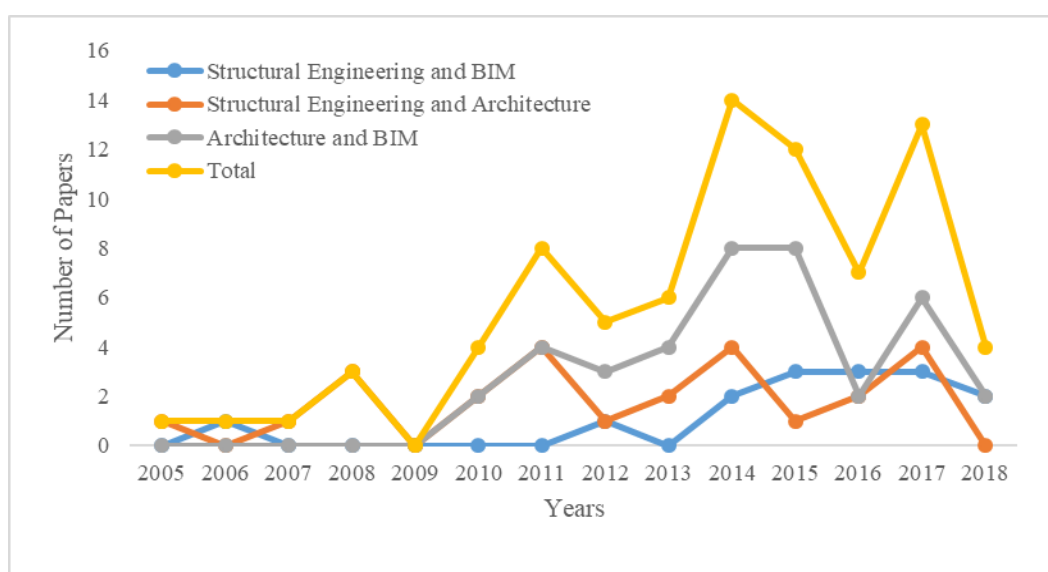
Figure 5: Number of papers per year since 2005.

Currently, the research works have given more attention to how BIM affects architecture than how architecture and structural engineering interact in the design process. Even though more popular, the first group has boosted research in the second one, because BIM methodology stimulates interdisciplinarity between the designing teams.

It is also possible to analyze the principal terms in the papers filtered during the SLR using the VOSviewer, a paper management software. Figure 7 and Figure 8 show the results extracted from the VOSViewer.

In Figure 7 it can be observed that the topics are grouped in two main groups: BIM and design. There are two points that with further development can connect these regions. One of the points is the sustainability topic, since there are many papers exploring and integrating it with the architectural design in a BIM design

process. However, there are few papers analyzing the sustainability during structural design.
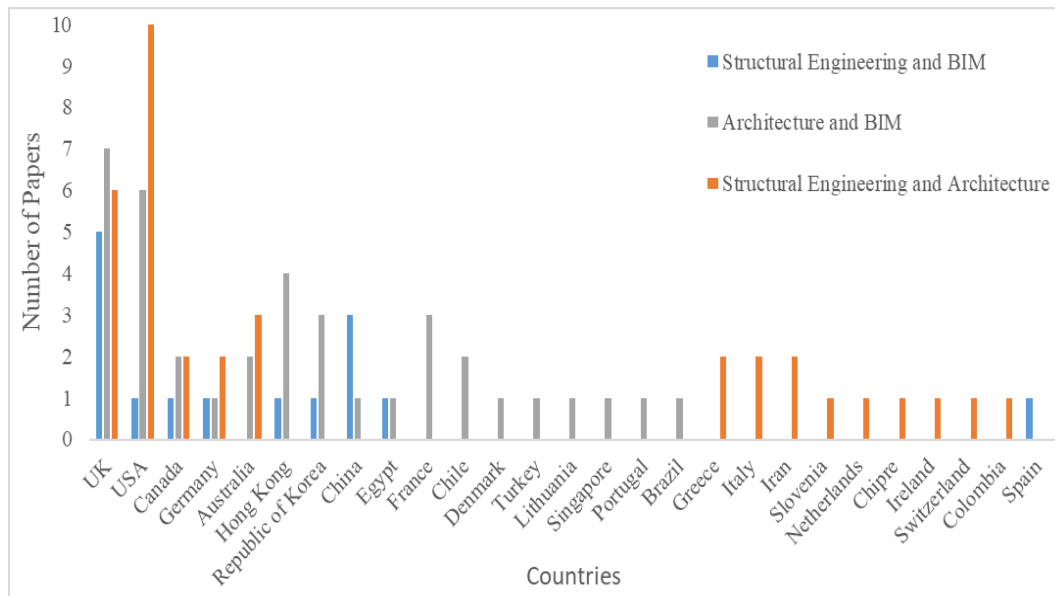
Figure 6: Number of papers per country.

The second point is tool development that can be developed 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).

Since 1973, discussions have occurred about the integration between architecture and structural designs, and these discussions usually conclude that the exchange of information between these areas in the early design stage is the most efficient way to achieve a better integration. That is why the term "early design stage" is the connection between the architectural design and the structural design in Figure 7. Therefore, the solution proposed by this research is in agreement with the best practices reported in the literature.

Figure 8 shows the reunion of the topics in three clusters: sustainability, design process and BIM. In spite of being different from the three initial main groups, this new division makes senses because of the current increase in interest on the sustainability topic.

Figure 7: Keywords Density Visualization.

Figure 8: Keywords Network Visualization.

The next three subsections (2.2.1, 2.2.2 and 2.2.3) report the objectives of each paper selected in the SLR for each of the pairwise searches. It also highlights the main obstacles faced by each of them. The final section (2.3) provides the conclusions and the strategies adopted to achieve this work's objective.
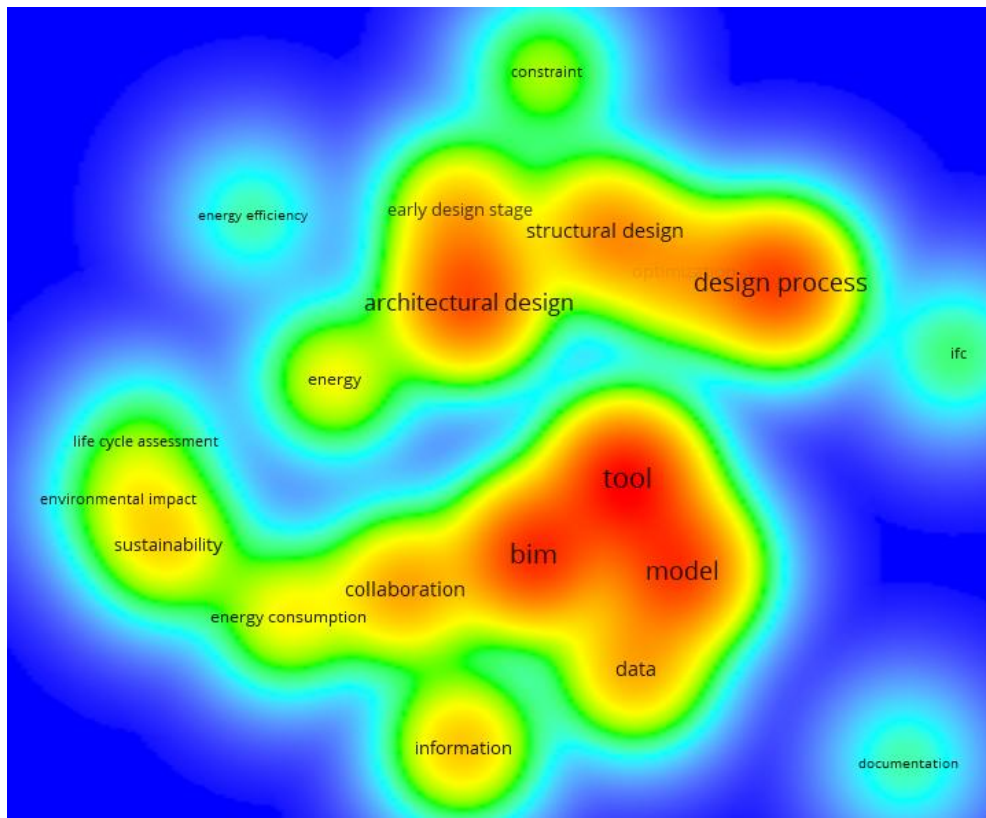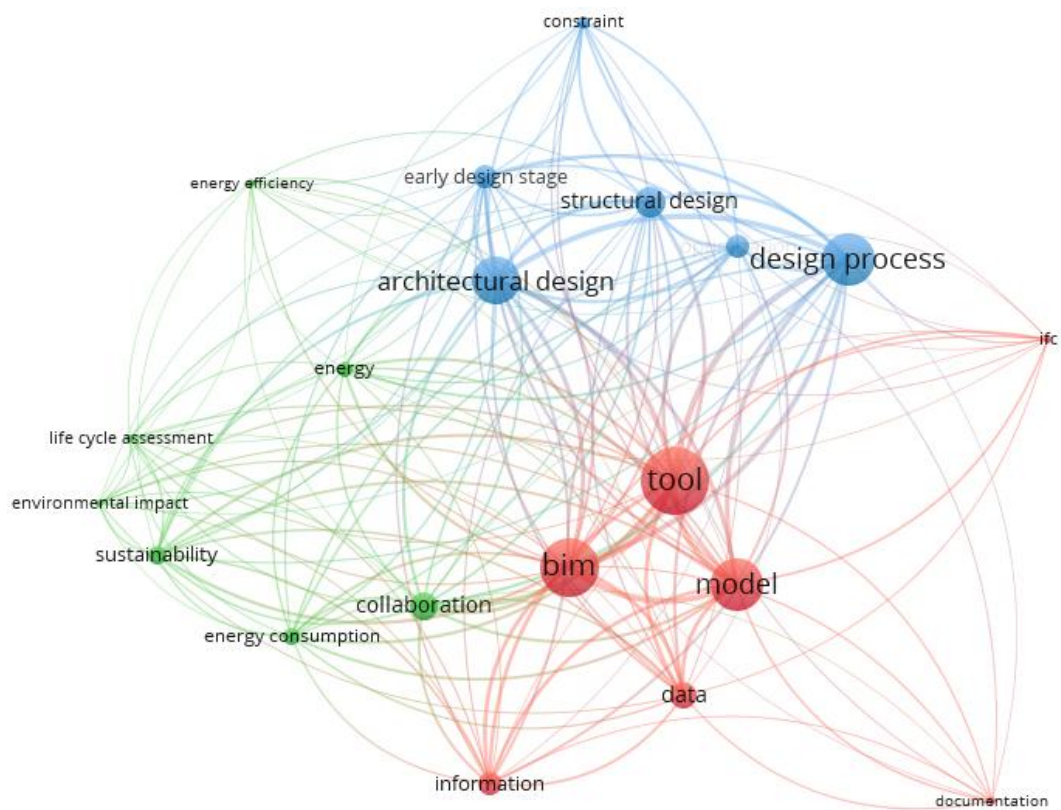
2.2.1
Structural Engineering and BIM

Schnellenbach-Held et al. (2006) 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, arguing that the latter were black boxes, which hinders improvements in the design process.

Lee et al. (2012) proposed a design procedure using Structural Building Information Modeling (S-BIM) to increase the efficiency in the structure selection and to obtain more optimal solutions in terms of constructability, structural safety, and economic feasibility of building. They observed that S-BIM enabled the flexible application of set-based design because it integrates various design alternatives.

Koch et al. (2014) summarized current achievements and open challenges in vision-based inspection of large concrete structures. They used the concept of BIM to present vision-based 3D reconstruction and as-built spatial modeling, concrete column recognition, concrete cracking and spalling detection and structural assessment procedures. However, they concluded fully automated structural integrity assessment is not possible to achieve yet.

Marzouk; Hisham (2014) also studied the use of the BIM methodology in cost and time management for infrastructure bridges. This paper developed a tool that integrates BIM with the Earned Value (EV) concept to determine the project status at a specific reporting date. The authors tested the developed application using as an example the Abo-Diab Bridge located in Egypt. They observed that the developed tool performed as expected, getting information from the BIM model and determining the Bridge's budget and schedule.

Oti; Tizani (2015) developed of a decision support tool for structural engineering using a BIM environment with sustainability indicators such as life cycle cost, ecological foot print and carbon footprint. Despite being a tool for structural engineering, this paper did not approach any aspects relevant to structural safety. Although the authors consider that the tool developed is a BIM tool, they did not discuss any other stakeholder in the process besides the structural engineer. Then in a follow up paper, Oti et al. (2016) examined the utilization of the tool and presented a case study.

Chi et al. (2015) performed a literature review focused on identifying the impacts and future development trends for structural design practice integrated with BIM technologies. The research emphasizes the benefits of BIM in facilitating current structural design, such as systematic modeling processes, powerful interactive visualization platform, and standardized exchanging data interfaces.

Costa; Madrazo (2015) developed a tool that integrates precast concrete components modeled in Autodesk Revit with web manufacturer catalogues, providing the structural designer with easy and efficient access to updated information, improving their workflow. The authors concluded that semantic web technologies combined with IFC standard is the most promising path to provide standard parametric description of products integrated with BIM software packages. However, they considered that this topic needs more research.

Zou et al. (2016) developed a tailored Risk Breakdown Structure (RBS), which is a management risk method, and formalized an active link with BIM. This approach has the limitation of being a qualitative evaluation, needing quantitative techniques to a complete analysis. Besides being a good method, it still needs implementation for validation in practice.

Yang et al. (2017) and Banfi et al. (2017) worked separately on similar tools to extract a cloud of points from existing construction, and then generate parametric Autodesk Revit elements that can be exported for Structural Design software to be analyzed. Yang et al. (2017) concluded that their tool is important in actual load bearing verification and in structural safety of historic timber roof structures. Banfi et al. (2017) suggested that the integration of NURBS algorithms in BIM applications would improve the management and generation of complex models from point clouds.

Eleftheriadis et al. (2017) organized the principal topics in which BIM and Life Cycle Assessment (LCA) theory can facilitate modifications in early stages of the design to improve structural design. Eleftheriadis et al. (2018) went forward with this topic and developed a multi-objective optimization tool that generates structural layout, and determinates the dimensions and the reinforcement of concrete columns and flat slabs, minimizing the cost and the embodied carbon. Despite the stimulation of structural engineering participation in conceptual design, these papers did not discussed how engineers and architects interact in the proposed approach. This interaction is one of the main requirements to go beyond just using information inside specific and isolated teams and to successfully apply the BIM methodology considering all stakeholders.

Mangal; Cheng (2018) also developed a tool to improve structural design. This tool uses an Autodesk Revit model integrated with Autodesk Robot Structural Analysis and an implemented genetic algorithm to optimize the amount of steel in the reinforced concrete of building frames. It achieves significant reduction in effort and error when dealing with frequent changes in architectural model, allowing designers to focus more on low cost solutions. As in the previous papers, it does not discuss the building design process involving other stakeholders, like architects, for example.

Hu et al. (2016) studied the interoperability between architectural and structural software packages; and between different structural software packages. They used an approach that combines an industry foundation classes (IFC)-based Unified Information Model with a number of algorithms to enhance the interoperability. Although Hu et al. (2016) 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.

Carrasco (2016) developed an Autodesk Revit plugin for steel structural elements. This tool uses structural analyses results stored in the model to do the structural verification, so it is implicit that it needs another tool responsible for the structural analysis, similar to the tool developed in this research. However, Carrasco (2016) also did not discuss the design process.

2.2.2
Structural Engineering and Architecture

Lavette; Stoker (1973) and Fenves (1979) 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; Stoker (1973) observed in their case study two areas for improvements assisted by computer, the first area is related with the selection of the building structural system, considering the architectural and mechanical constrains. The second area is related with the development of a framework for the entire design process instead of discrete design tasks. Fenves (1979) concluded that the interaction with architecture occurs when the design problems are first considered as a building problem instead of a structural problem. Thus, architects and engineers, assisted by computers, should make the decisions considering the two disciplines .

Sriram; et al. (1985) followed the principal ideas presented in Lavette; Stoker (1973) and Fenves (1979), but the used Knowledge-Based Expert System (KBES) to achieve an integrated structural design system. The authors described some KBES applications in conceptual architectural and structural integrated design. However, they concluded that for practical usage it is necessary to go forward in the development of advanced knowledge-based tools.

Luth et al. (1991), Syrmakezis; Mikroudis (1997) and Miles et al. (2001) developed different systems to enable a more accurate structural conception that considers architectural constrains. The main difference between the three systems is the user relation with the system. The first one considered only the structural engineer as the user, while the others two considered both. This is an important variation because all system interface and workflow depends on who is the user.

Luth et al. (1991) conceived a system in which the structural engineer can use architectural and mechanical constrains (such as elements dimensions) as input and then observe how the structure interacts with them. The structural engineer can then make changes until the desirable structure is reached.

Syrmakezis; Mikroudis (1997) used a knowledge base algorithm with expertise of structural engineering to help an architect to produce a design compatible with the requirements of the Greek seismic design code. However, the

author considers that the usage of expert system in usual building designs is still a long-range goal.

Miles et al. (2001) employed a Genetic Algorithm (GA) to search for a viable solution for the conceptual design. It is interesting to observe that in this work the GA was used more as a search engine rather than as an optimization tool.

Watson; Perera (1997) presented a review of Case-Based Design (CBD) and its application on conceptual design. CBD encourages the reuse of solutions instead of trying to solve problems in a totally different way. Thus, when using this methodology the architect can have a better idea of the structural behavior of the building.

Tiwari; Craig Howard (1994), Retik; Kumar (1996) and Lämmer et al. (2001) developed systems based on the object oriented paradigm to improve a collaborative building design among the stakeholders. The systems have the principal idea of a database in which all designers could insert information relevant for their discipline, so they are BIM tools precursors.

Lämmer et al. (2001) inserted an important feature to auto generate loads based on information of the architectural model and on the connectivity of the building elements in their system. The system developed in the present research uses this approach because of the facility that it gives for the design workflow. However, even today, BIM tools still do not use this approach.

Burry et al. (2005) analyzed a frame from Gaudi's Sagrada Família church Passion Facade using structural optimization and the result was close to the originally designed elements. This shows that is important to understand the system´s constraints and material properties rather than try to use pre-defined geometry.

Holzer et al. (2007) applied optimization for structures of a stadium roof. They concluded that in order for this approach to succeed, it requires the participation of structural engineers and architects at the conception to define the rules that guide the optimization to reach the expected performance goal.

Popovic-Larsen et al. (2012) used optimization as a design generator tool. The authors considers that the structural optimization may the link between technical and visual aspects. However, this was not confirmed by their research in building design. However, this technique provides the architect the possibility of designing geometries that have good structural performance.

Moreno-de-Luca; Carrillo (2013) studied how a multi-objective optimization can be used in the design of the structural system and of the facade. For that, the authors used constrains like life cycle cost, environmental impact and energy efficiency as an integrating agent between architecture and engineering. They consider that this approach expands the architect's creativity without penalizing the structural performance of the solution.

Beghini et al. (2014) discussed how topology optimization connects architecture and structural engineering, generating new integrated design ideas. The authors observed that even though structural engineers and architects have their own vocabulary and models, the integrated parametric model could be used as a common ground where the topology optimization is the common "language".

Byrne et al. (2015) combined grammar representation with real world constrains to explore optimal design solutions. The developed framework showed good results during the design of complex pylon structures. This approach still has the potential to allow the optimization design considering multiple loading conditions, as is the case of real structural design.

Tseranidis et al. (2016) explored the uses of data-driven algorithms, widely applied in aerospace engineering, as a tool to evaluate rapidly, at the early stages of the design process, the structural design considering operational energy consumption. The proposed method can also consider other aspects as aesthetic and constructability. The case study results show that this approach can be viable in the real building design, but it still needs more work for implementation in practical design software.

Zhang; Mueller (2017) developed an algorithm to minimize structural weight of shear wall of tall buildings with constrains on elements strength and accessibility. This algorithm can be applied at the beginning of the floor plan design (generating wall layout options) or after the generation of the floor plan design (removing the unnecessary structural walls). This way, the authors consider that this approach integrates engineers and architects, and reduce the trial-and-error design process.

Slack; Kilar (2008) studied how structural systems responsible for earthquake resistance can affect and contribute for architectural solutions. They used as an example the China Olympic Stadium, the Hancock Building in Chicago and Tod's Building in Tokyo. After they analyzed their examples, they concluded that

earthquake architecture represents a link between structural engineering and architecture.

Elnimeiri; Gupta (2008) and Foraboschi et al. (2014) showed that sustainability is an important link between architecture and structural engineering. Both papers discuss the necessary attention in the design of tall buildings in order to minimize their sustainability impact. Elnimeiri; Gupta (2008) highlighted a building design with a circular workflow instead of a linear workflow as a sustainable improvement. The results of Foraboschi et al. (2014) shown that the embodied energy depends mainly on the floor system than other structural elements.

Mora et al. (2008) developed a geometric modeling framework for conceptual structural design from early stages of architectural conception. The framework acts like an interactive guide for structural engineers to create a building structure based on constrains imposed by the architectural model. An important difference between this framework and the usual modeling software packages, like Autodesk Revit, is that it uses a top-down approach (i.e., the global model is developed first), while Autodesk Revit uses a bottom-up approach (i.e., element modeling is done first).

Yang; Bouchlaghem (2010) developed a system to reduce time and cost associated with the multidisciplinary (architecture, structural engineering, mechanical engineering and electrical engineering) design cycle. The framework applies a genetic multi-objective algorithm that considers the models information as constraints. The implementation of this system revealed its principal weakness: it requires a large processing capacity from the computer and that can hinder its usage in large-scale design.

Del Grosso; Basso (2010) studied the use of adaptive structures and optimization to propose a project of an acoustic envelop, for a better architectural performance. Adaptive structures can also be used to achieve high efficiency in other areas such as energy consumption. Their results demonstrate the versatility and the effectiveness of the proposed approach in the integrated design of structures with variable geometry.

Rolvink et al. (2011) and Shepherd et al. (2011) analyzed how parametric design could affect the interaction between architecture and engineering. The first work focused on analyzing many examples during the conceptual phase. The paper concluded that the parametric modeling gives agility and flexibility to the design

process. The second work focused on the modeling of the entire Aviva Stadium´s project in Dublin. This modeling required an extra time to create a link between the parametric model and the analysis. The authors considered this extra time a good investment, because it avoid the delay of the analysis in relation with the modeling.

Meyboom (2011) went further and proposed a parametric design approach named heavy design. Its concept consists of incorporating the structural behavior to an architectural model. By doing this, the architect is able to perform more realist studies especially during the initials phases of the design process. The author applied this approach using a simplified model that could inform the maximum displacements and the maximum moment of a beam and the buckling load of a column.

Cavieres et al. (2011) developed a parametric tool for architects so that they can model concrete masonry walls. With this tool, the user can verify if the modeled wall has enough strength to resist the forces in a simple way. This approach makes easier the exploration of different and unusual optimal building forms, without the preoccupation that the solution be unrealistic.

Arefi; Hadian (2013) made interviews with twelve renowned Iranian architects and engineers to identify the utility of structural engineering concepts in architectural thinking. The conclusions were that the architects should emphasize intuition, common sense, self-discovery and observation as the necessary knowledge to better interact with the structural engineer.

Reichert et al. (2014) presented an innovative design and fabrication process using fibrous material for ultra-lightweight buildings structures that facilitates the architect to explore more the tectonic of the form. This type of structure is very challenging due to the required deep integration amongst structural analysis, architecture, material science and fabrication industry.

Hurol (2014) discussed the ethical considerations during the collaborative design involving architects and structural engineers. He suggested the use of a value sensitive design approach, in which targets such as safety, economy and aesthetics receive weights, that the leader of the design team must consider during the decision making process. For the author, the collaboration should start immediately after the conceptual design, and before the end of the preliminary design.

Noorifard et al. (2016) investigated how to prevent undesirable seismic behavior of infill walls during the design. They concluded that even though these

elements do not have a structural function, they influence in the building's behavior during seismic events. They claim that this characteristic is more efficiently achieved when architects have this preoccupation in the architectural conception. This is because it becomes more expensive to achieve the same performance when only the structural engineering is concerned with seismic behavior.

Agustí-Juan; Habert (2017) highlighted the opportunities of integrating additional functions in structural material using digital fabrication to reduce the overall environmental impact of the building. For example, one case study was the digital fabricated brick that has structural function and good thermal performance. This way, the cost and time spent with thermal layer to the wall or with heating or cooling the rooms would be avoided. The results of this work also show that the environmental impacts for fabrication of the same material's volume are the same for digital fabrication and for usual manufacturing. Thus, as digital fabrication saves volume of material, this fabrication processes reduces the environmental impact.

Sharafi et al. (2017) presented a unified matrix method for automatic spatial design of modular buildings. This method consists of using a modular part of the building, such as an apartment or a group of rooms, to design the whole building following predefined rules relative to the position of the modular parts in the space. This technique assists designers to compare structural performance, environmental impacts and cost of the design solutions from the conceptual design stage.

2.2.3
BIM and Architecture

Sacks et al. (2010) compared two design and fabrication processes of precast concrete facade panels, one using traditional CAD tool and other using BIM tools. They observed a productivity gain of 57% over the CAD process. Despite that, the data exchange between the architects and the engineers were inconsistent and incomplete showing the need for improvements in the interoperability among the design tools.

Holzer (2010) presented the optioneering method as an alternative to assist designers solve design problems stating at the early stage of the process. He also affirmed that BIM methodology was not currently used at this stages yet. This

statement shows a gap in the implementation of BIM, and the present research aims to reduce this gap.

Arayici et al. (2011a) and Arayici et al. (2011b) explained the approach adopted by the John McCall Architecs in partnership whith the University of Salford for BIM implementation. They observed increases of efficiency due to the value generation and the elimination of wasted time and effort with the adoption of BIM. As for future research, they intended to extend this approach as a guideline of architectural operational practices for BIM implementation in other architectural companies.

Jeong; Ban (2011) developed an algorithm and implemented it in a program named J-SAP that extracts topological information stored as IFC format. J-SAP performs analysis to evaluate architetural alternatives using social issues and spaces acessibility information. The author expected to use the developed algorithm not only to evaluate existing buildings, but also to design new architetural solution using computacional systems.

Yan et al. (2011) implemented a game for buildings named BIM-Game that enhances architectural visualization and that could be used for education. Its implementation provides the integration of several areas like architecture, engineering, game development, computer science and visualization, improving architectural design process.

One of the biggest benefits of the adoption of the BIM methodology is the possibility of analyzing and evaluating many different types of solutions during the design phase. However, sometimes, it is necessary the creation of a different model for each kind of evaluation. So Sanguinetti et al. (2012) proposed a system to facilitate this type of analysis based on post-processing design-oriented building models that automatically adapts the model to the needs of the specific analysis. This enables the complete design in a single building model.

Cheung et al. (2012) proposed a multi-attribute based tool that enables the user to evaluate the cost of the building during the early stage of the design process. This tool makes possible to explore many solutions, knowing their cost with some accuracy, to achieve the best financial performance. This way, it reduces the time spent developing these options and anticipates the choice of the best solution at the early stage phase.

Schultz; Bhatt (2012) presented a multimodal spatial data access framework intended to provide support on spatial decisions during the architectural design. In order to improve the efficiency, the interoperability was achieved by using the IFC format. The use of IFC, however, was the bottleneck of the work, as it was not fully developed. In future research, the authors aimed to improve the IFC ontology to incorporate spatial artifacts and qualitative concepts.

Shen et al. (2013) developed a User Pre-Occupancy Evaluation Method (UPOEM) to facilitate the comunication with the client. This method helps the client to understand the design solution and to make suggestions during the architectural design process.

Wong; Fan (2013) studied how BIM can improve the consideration of sustainability in the solutions during the architectural design. They highlighted three benefits facilitated by the use of the BIM Methodology: the implementation of integrated project delivery, the design optimization and communication, and the improvement accuracy in coordination. On the other hand, they concluded that the lack of interoperability between tools limit BIM application.

Lee; Ha (2013) proposed a Costumer Interactive Building Information Modeling (CIBIM) method and compared with the conventional methods. The usage of CIBIM helped during the design of apartment houses, which can be very challenging due to its tailored units. They found that using CIBIM, the design generates a smaller number of drawings. The author also performed a survey to analyze the acceptance of the interactive method by the costumer (e.g., a fictitious apartment user). The survey's result showed that the costumers had the understanding of the apartment layout and the communication between the costumer and the designer improved.

The research works discussed next explore the integration between Architecture, BIM and Sustainability. In general, they have the major challenge to allow simulations using as input the architectural model. It should be noted that a similar challenge also needs to be faced to allow structural simulations, which is the topic of the present work. Thus, it is important to understand how the researchers are facing this challenge for sustainable simulations and to adapt their ideas for structural simulations.

Bahar et al. (2013) analyzed the importance and the barriers of integrating architecture design and thermal comfort simulation in a BIM environment. Some

of the barriers listed by the authors are: long analytical model preparation time, invalid or missing data in architectural models, and inconsistent conversion between architectural and thermal models.

Zanni et al. (2014) presented a coordinated collaborative design process model capable of identifing critical decisions actions, such as selection of solution, definition of priority related to structural and architectural concerns, etc. The design process model was based on interviews with British architects. They showed that in this process the project delivery planning significantly influences the sustainable approach.

He et al. (2014) combined architectural design and computer aided technology to develop a process capable of assisting the design of high quality living spaces with optimal energy conservation for new construction in China. They also compared features of traditional design methods and BIM design methodology applied since the early design stages. This study revealed that using simulation software without a well-defined process would not help the designer achieve the best results.

Gupta et al. (2014) presented a framework for developing IFC-compliant renewable energy simulation tools using a multi-model concept for architectural models. The proposed framework is the central data model to which simulation models and information repositories are linked. It is applicable to solar, energy, carbon emissions and financial simulations. The authors observed that IFC 2 x 3 (used in this research work) does not hold all the necessary data format to organize the information required for the simulation. Hence, it was necessary to create external data repositories and link them to the simulation model.

Jalaei; Jrade (2014) presented a methodology to integrate LCA (Life Cycle Assessment) tools, that use external databases, and a BIM environment. This methodology aims to simplify and accelerate the sustainable design process, by allowing the evaluation of environmental impacts at the conceptual stage. This methodology also allows the users to identify the earned points based on LEED-RS. The lack of automation is the main limitation of the proposed methodology.

Lobos; Trebilcock (2014) investigated the possibility of creating a unified workflow that links BIM, Space Layout Plan (SPL) and Building Performance Simulation (BPS) to support the creation of architectural solutions. The main

advantage of this framework is to allow the designers to use information from standards and norms in an integrated digital environment to make their choices.

Jeong et al. (2014) created a system to translate BIM data to Building Energy Modeling (BEM). This system facilitates the reuse of architectural models for energy simulation without an import/export process, reducing error-prone manual process. The authors only implemented this approach for thermal simulations, but it is possible to extend it for others domains like photovoltaic energy and daylighting.

Kota et al. (2014) discussed how to incorporate daylighting analysis into a BIM environment. As a case study, the authors validated a prototype that integrates Autodesk Revit with Radiance and DAYSIM software packages. They observed that some Autodesk Revit elements' representation were different from Radiance and DAYSIM representations. This made the usage of the IFC format difficult, so they used a direct link to connect the software packages.

Cemesova et al. (2015) described the implementation of a system that extends the IFC schema with energy concepts to calculate the annual heat demand of a building. This system improved the collaborative design among the design team members by inserting a BPS in the early stages of the architectural design process.

Negendahl (2015) critically reviewed how designers use BPS in a BIM environment at early stage. The author found that the methods and tools commonly used were insufficient to provide valid results. Also, they were not flexible to enable fast changes in the models, which occurs frequently in the early stages of design. He concluded that the most efficient way to integrate BPS and BIM tools for energy analysis in early design stage is using visual programming language.

Wong; Zhou (2015) performed an extensive literature review about green BIM and compared the different approaches used to implement sustainability concepts in architectural design. They emphasized that there is a lack of effort for managing environmental performance during building maintenance, retrofitting and demolition stages.

Salgueiro; Ferries (2015) investigated the integration of the environmental dimension of sustainability into schematic stage in an architectural design process supported by the BIM methodology. The authors developed a tool to link Autodesk Revit and ArchiWizard Esquisse. They observed that the plug-in saves time and

facilitates the iterative work. However, there were certain limitations in the plug-in's interoperability capabilities that demands the user intervention.

Khodeir; Nessim (2016) analyzed how architects integrates BIM and BEM in Egypt. They used a semi-structured questionnaire to evaluate this integration in two architectural offices. They found that the principal barrier for integration is the lack of interoperability amongst BIM and BEM tools.

Chardon et al. (2016) studied the cost and the energy performance during the building envelope design process in a BIM environment of single-family houses. This research work used a semantic system to automate this process. Then they applied a genetic algorithm to generate optimal solutions for the architect to choose. However, the main disadvantage of this approach is the weak interoperability between their system and architectural software packages. Thus, after this research work, the authors proposed the use of an IFC scheme to improve the tool´s interoperability.

Lapinskienė; Martinaitis (2017) proposed an approach to develop the architectural conception of low energy buildings in a BIM design process. In order to do that they used two methods, quality function deployment and axiomatic design. The authors presented and detailed the methods, but they did not exemplify them, so there is still no result to prove their effectiveness.

El-Diraby et al. (2017) developed a system called Green 2.0 to enable social-technical analysis and online collaboration during the early stage of architectural design in a BIM design process. The authors considered that the creation of a platform that integrates different technologies for social-technical analysis of buildings was the major challenge.

Saieg et al. (2018) studied the synergies between BIM, green construction and lean construction. The research work developed a plugin to assist the designer to choose the most sustainable design solution option. They showed that is possible to reduce economic and environmental impacts during the architectural conceptual design.

Wang et al. (2014) investigated how an approach that use Augmented Reality (AR) and BIM affects the architectural visualization in building lifecycle. They found that AR facilitates decision-making and communication with customers.

Son et al. (2015) empirically studied the factors that could facilitate architect's BIM adoption. The results showed that the four critical factors for BIM

adoption were top management support, compatibility, subjective norm, and computer processing capability.

Göçer et al. (2015) introduced a new Post-Occupancy Evaluation (POE) method, named spatial mapping method, to complete the design process using the BIM methodology and Geographical Information Systems (GIS). The authors implemented the method on a historical campus building. Its results showed that it is possible to link the building performance outcomes to spatial information in a BIM environment, which gives the designer more information to modify the existing building.

Abrishami et al. (2015) developed an interactive BIM environment that adopts generative design as a computational design method for early phases. This approach facilitates the automation and improves designers' cognition and collaboration during the architectural conception process. The validation of this framework is the next step of this research work, so there are no implementation results yet.

Lee et al.(2015) analyzed quantitatively the model's warning during a BIM process. Based on interviews with architects, it was realized that architects focus more on productivity than making warning-free models. Their study revealed that sometimes models are small so warnings do not slow down the processing time, but when models grow the warnings accumulation becomes a problem.

Li et al. (2017), Lu et al. (2017) and Santos; Costa; Grilo (2017) made an extensive literature review about BIM for architecture and its implementation. Li et al. (2017) collected and analyzed 1874 papers showing 60 key research areas. The most significant area was the architectural design studio area that covers parametric design, sustainable design, design for safety and constructability, and collaborative work. Lu et al. (2017) focused on green building research works in fields like energy performance, carbon emissions, natural ventilation, solar radiation and lighting, water usage, acoustic and thermal comfort. All these diretcly affetc architeture. Santos; Costa; Grilo (2017) collected 381 papers and observed that the most researched topics were related with the adoption of BIM worldwide, the development of BIM tools, the combination of energy simulation and BIM – based information, and the semantic interoperability and ontology.

Díaz et al. (2017) analyzed the use of multidisciplinary design optimization in architectural designs by a method named Process Integration and Design

Optimization. They concluded that this approach may integrate architectural, structural and budgeting disciplines. However, it requires better interoperability, which at the moment of the research and currently is not a reality.

2.3
Literature Research Conclusion

Based on the analysis of the SLR results, it is concluded that the more effective way to integrate the architectural and the structural designs is in the early stage. In order to facilitate this integration, this research developed a tool that allows architects to verify if their intended structure is feasible. The remaining chapters of this document present the strategy adopted to overcome the gap found in the SLR are discussed.

In Chapter 3 the developed tool is presented along with its functionalities and the implementation considerations. Then, Chapter 4 presents the results of the evaluation of the plugin by a group of architects. The two main points evaluated by the test were the plugin's usability and the improvements in the architectural design process enabled by the proposed workflow.

3
Proposed workflow for buildings design Development

The scope of the tool developed to fill the gap found in the results of the SLR is limited to the verification of the dimensions of reinforced concrete elements with a reasonable level of accuracy.

The verification tool, named ConDA (Concrete Design Assistant), is a plugin that uses the information from a model created in the Autodesk Revit software to perform the structural verification. The next sections present ConDA's user interface, its functionalities, and the implemented structural considerations.

3.1
ConDA Plug-in

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 9 provides a brief presentation of its toolbar. The toolbar has eight buttons organized in four tabs.

Tab Ⅰ is the one related to locating parameters and has only one button (①). This button opens a window for the user to input the aggressive environmental class and wind parameters (following the considerations of the Brazilian Code ABNT NBR 6123:1988.) as shown in Figure 10.

Tab Ⅱ is the one related to the room classification and has one drop down list (②). This drop down list has several room classifications like residential bathrooms, offices room, etc. When the user selects a room type from the drop down list and then selects a room in the model, the plugin creates an occupation load over

the room's area. The load intensity follows the considerations of the Brazilian Code ABNT NBR 6120:2018.

Tab Ⅲ is the verification tab and has the five buttons needed during the structural verification process (③ through ⑦). This process has three phases:

1. Information exchange between Autodesk Revit and Autodesk Robot;

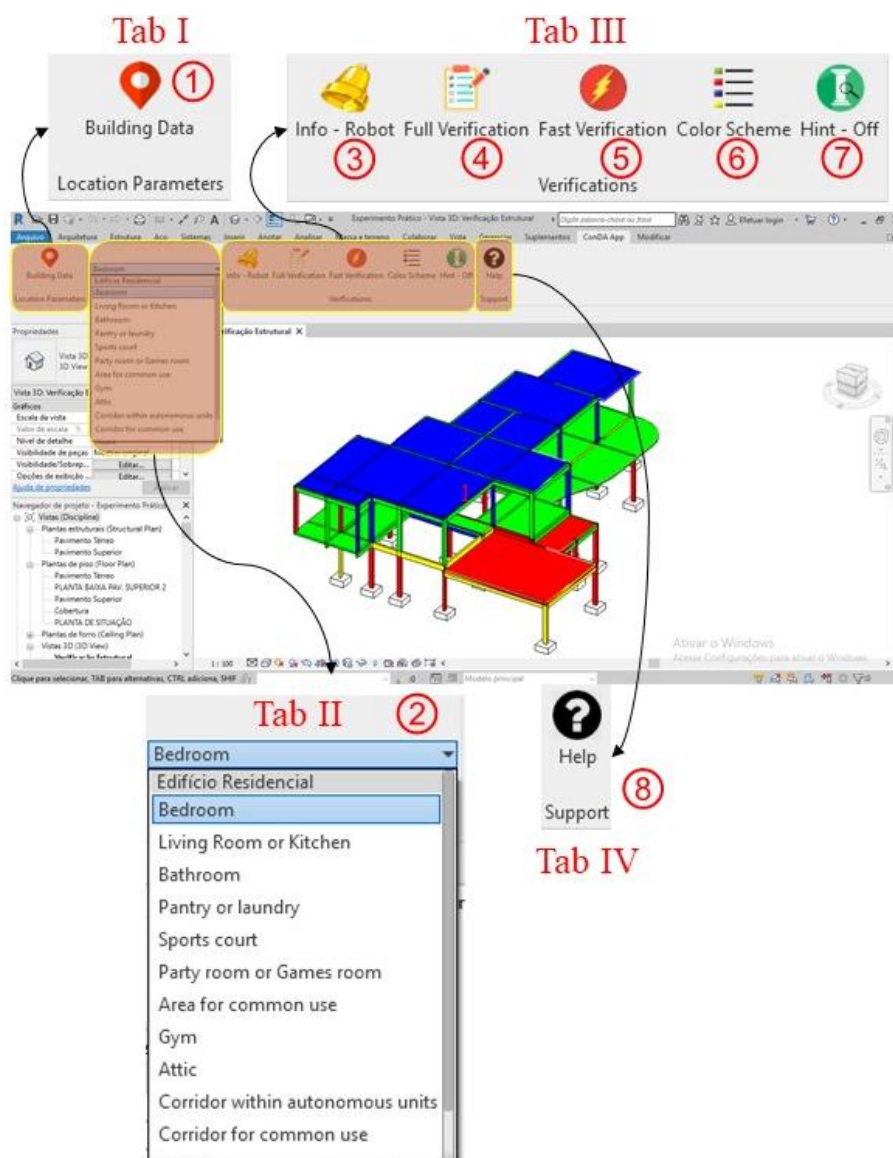2. Structural verification;

3. User intervention.

Figure 9: ConDA's toolbar.

During the first phase, the Autodesk Revit sends the structural model to Autodesk Robot that performs the structural analysis and sends back the analysis results to Autodesk Revit. The second phase is the verification itself, which is done by the developed plugin within Revit. The following sections describe this process in detail. The third phase is when the user, in general an architect, makes changes in the structural elements to achieve an economical and feasible structure, while still considering the architectural form. The five buttons in this tab have their functions detailed next.

Figure 10: Location parameters input window.

Figure 11 illustrates the window shown when the user selects button ③. This window shows the steps that the user needs to follow to perform the interoperability between Autodesk Revit and Autodesk Robot, which is necessary to perform the full verification, as is discussed next.

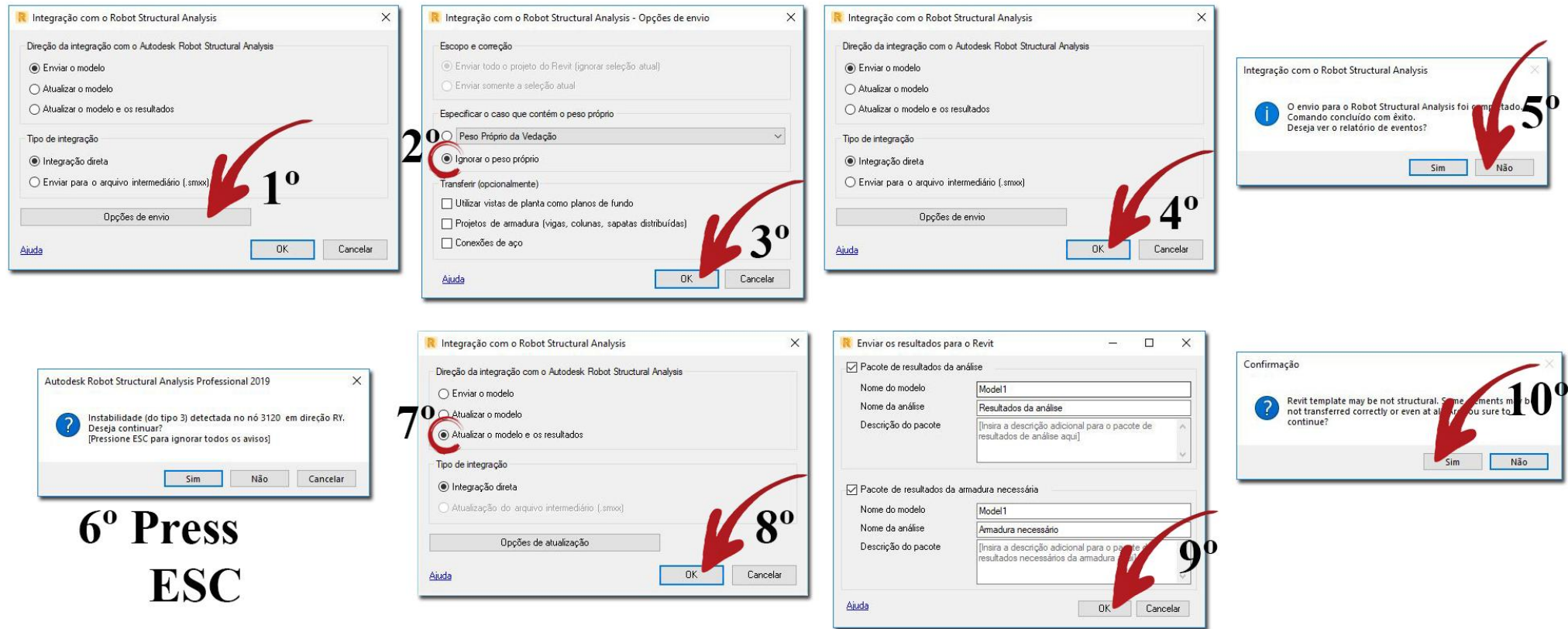**OBS: Following the sequence below has fundamental importance in the verification result.**

Figure 11: Window showing the summary of information exchange process.

Button ④ is used when the user desires to perform a full verification, i.e., it does the information exchange and does the structural verification, based on the updated structural analysis results.

Button ⑤ is used when the user prefers to do a fast verification, i.e., it does a structural verification based on existing structural analysis results without updating the analysis results (i.e., based on element´s dimensions that may not be current). Note that, the user can only use this button if a complete verification has already been done once.

The verification's results are displayed directly on the model using a color code scheme (ConDA's output will be better discussed in section 3.1.4). The colors are labeled according to the scheme described in Figure 12, which the user can access by clicking on button ⑥.

Button ⑦ displays suggestions for user´s consideration on how to change the structural elements in order to achieve a more feasible structure.

Tab IV is used to provide support to the user. It has the help button (⑧), which shows information about ConDA´s considerations and suggestions on how the user should model the structure.
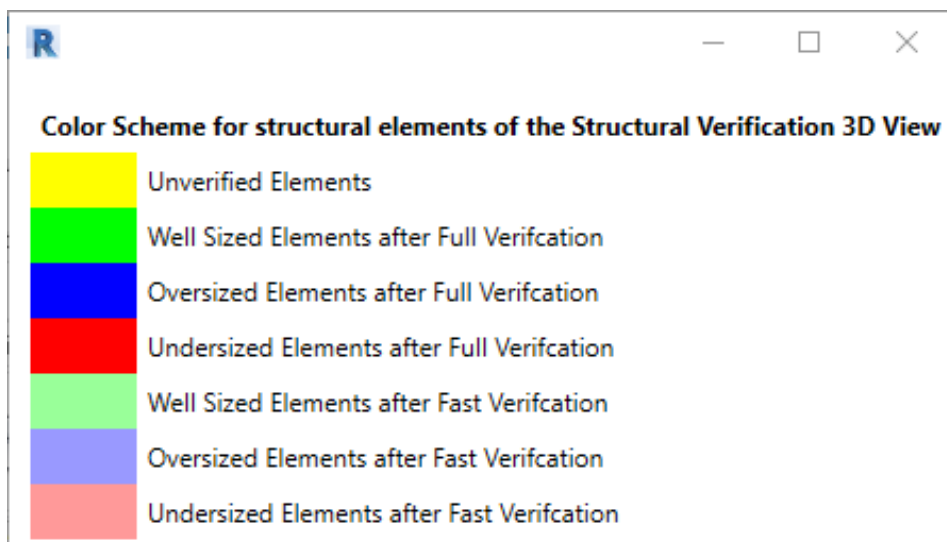

Figure 12: Window showing the meaning of elements colors.

3.1.1
Code Structure

The code of the developed plugin was written in C# programming language using the object-oriented paradigm. The code is divided into three parts as Figure 13 shows:
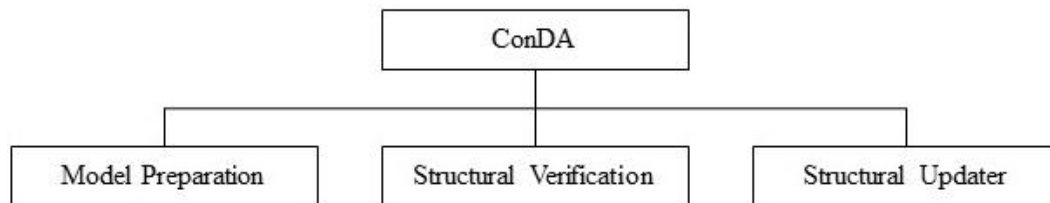

Figure 13: Structure of the ConDA´s code.

The Model Preparation part initializes the ConDA's toolbar in Autodesk Revit and creates ConDA's elements properties. The Structural Verification is the part of the code responsible for the exchange of information between Autodesk Revit and Autodesk Robot and for performing the cross sectional dimensions analysis. The Structural Updater is responsible for automatically updating de structural information necessary for the verification while the user modifies the model. This functionality is important because the user does not need to manage the loads´ application and, thus, avoiding mistakes. This part also updates the colors of the structural elements and creates and/or deletes loads when the user creates, modifies or deletes elements. There are four types of elements that can be modified by the Structural Updater (Figure 14). The flow charts in Figure 15 through Figure 18 detail these processes. The next sections provides additional details related to these flow charts.
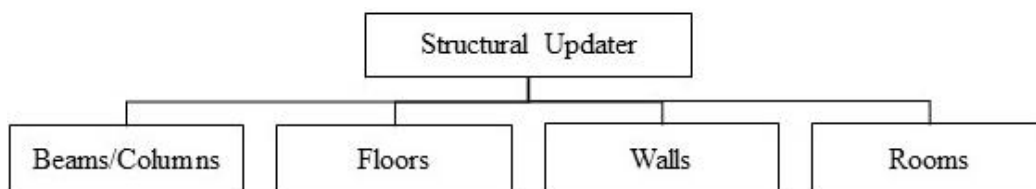

Figure 14: Structural Updater Types.
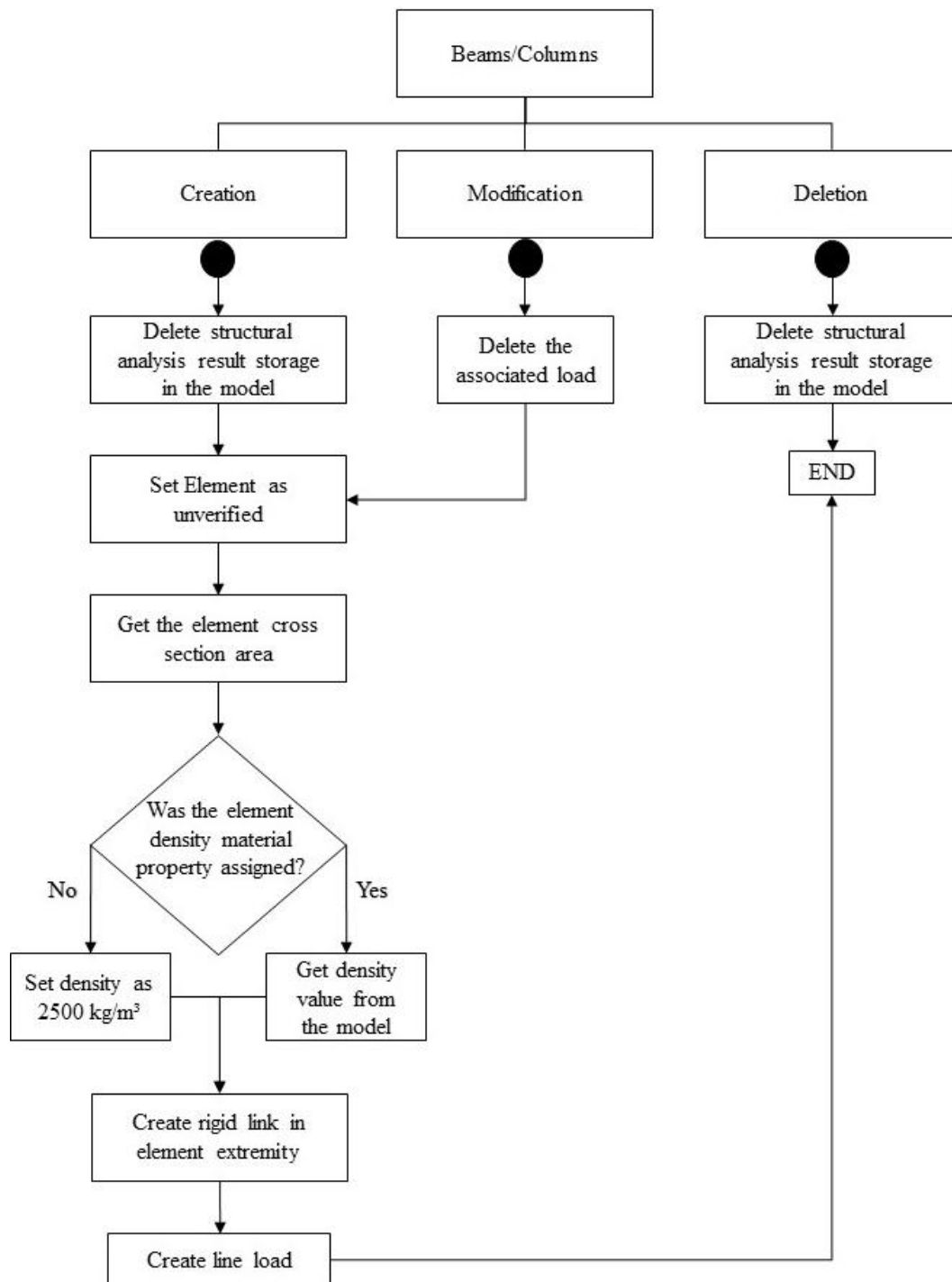
Figure 15: Beam/Column Updater.
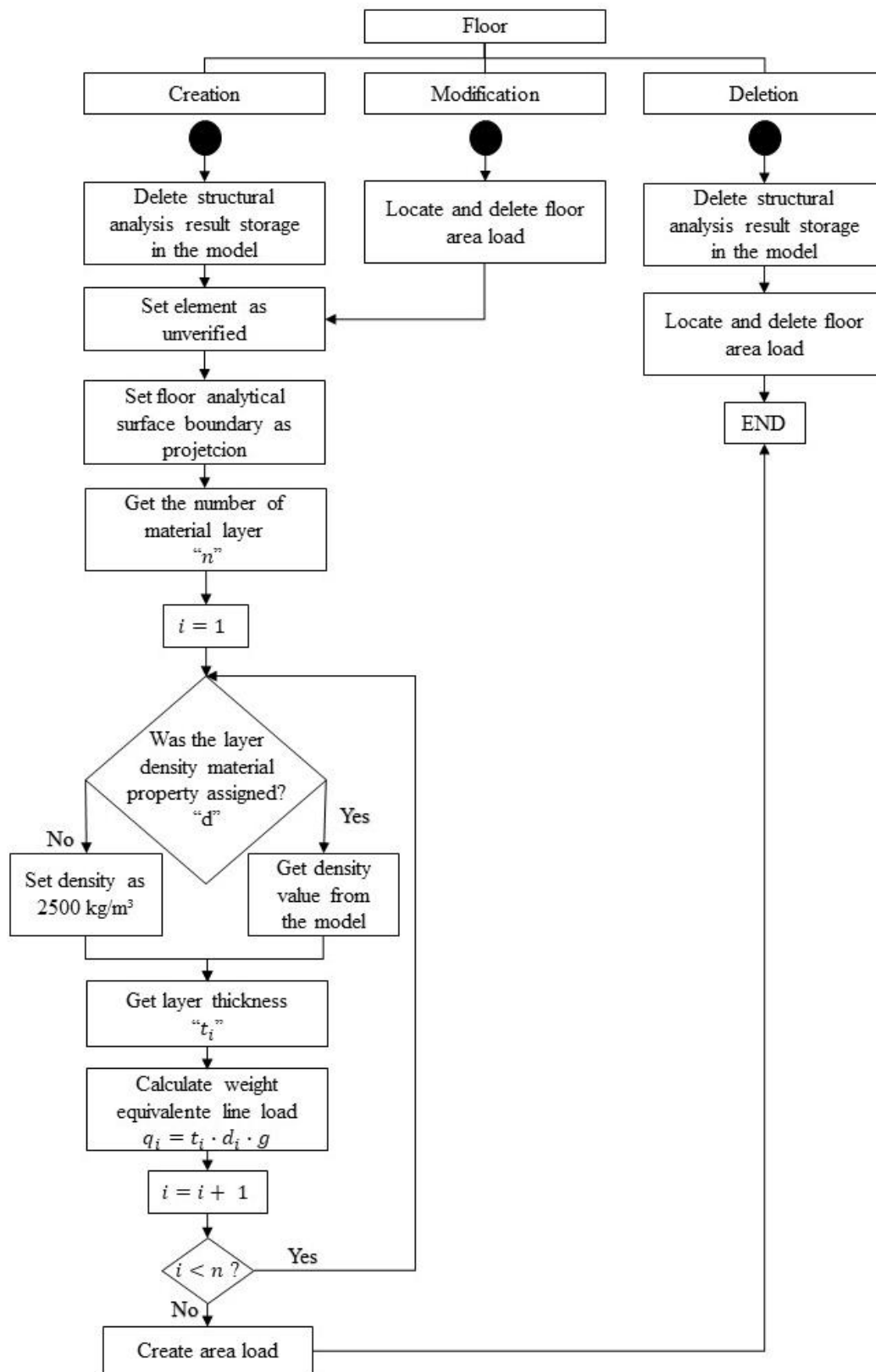
Figure 16: Floor Updater.
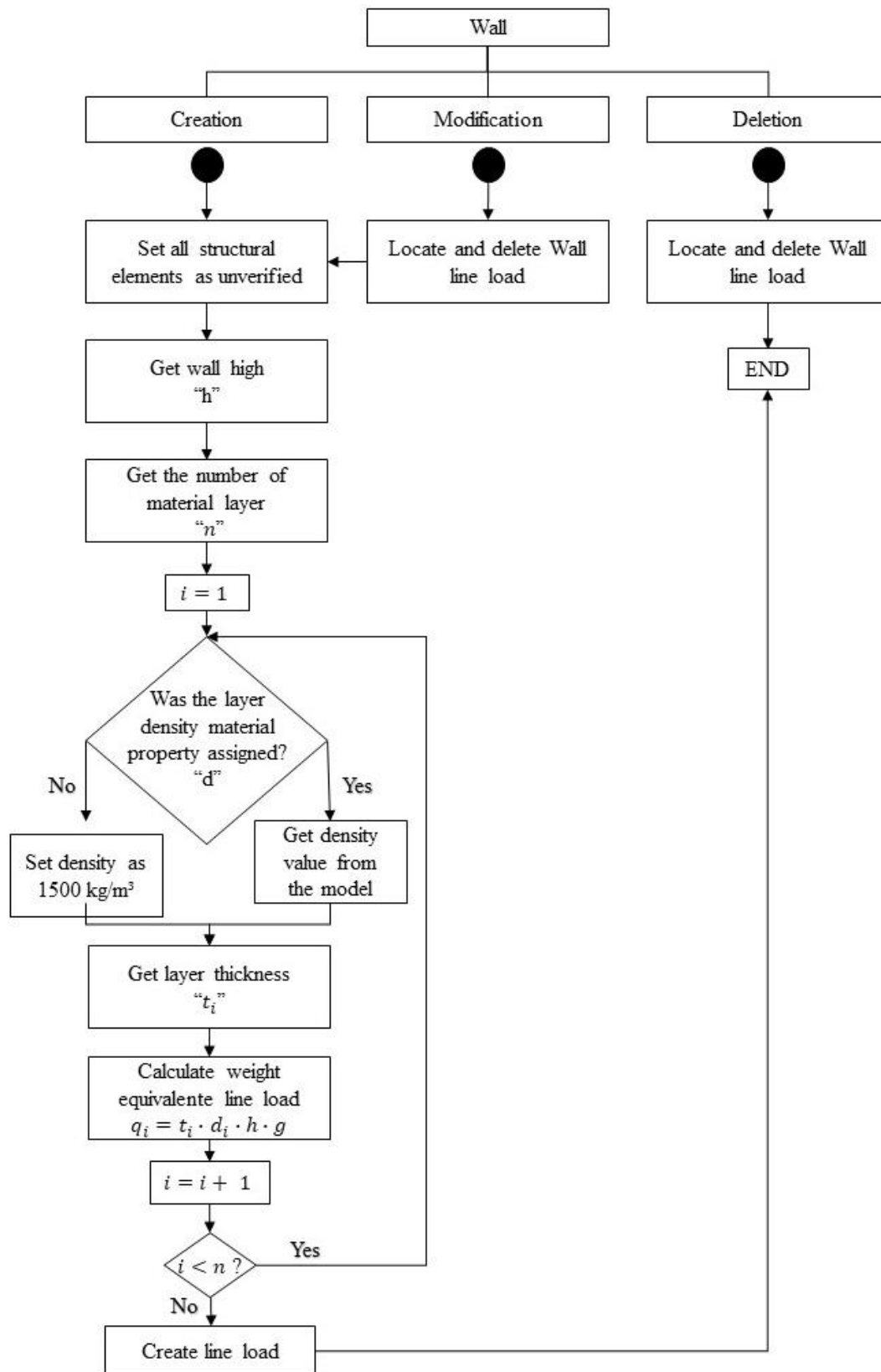
Figure 17: Wall Updater.
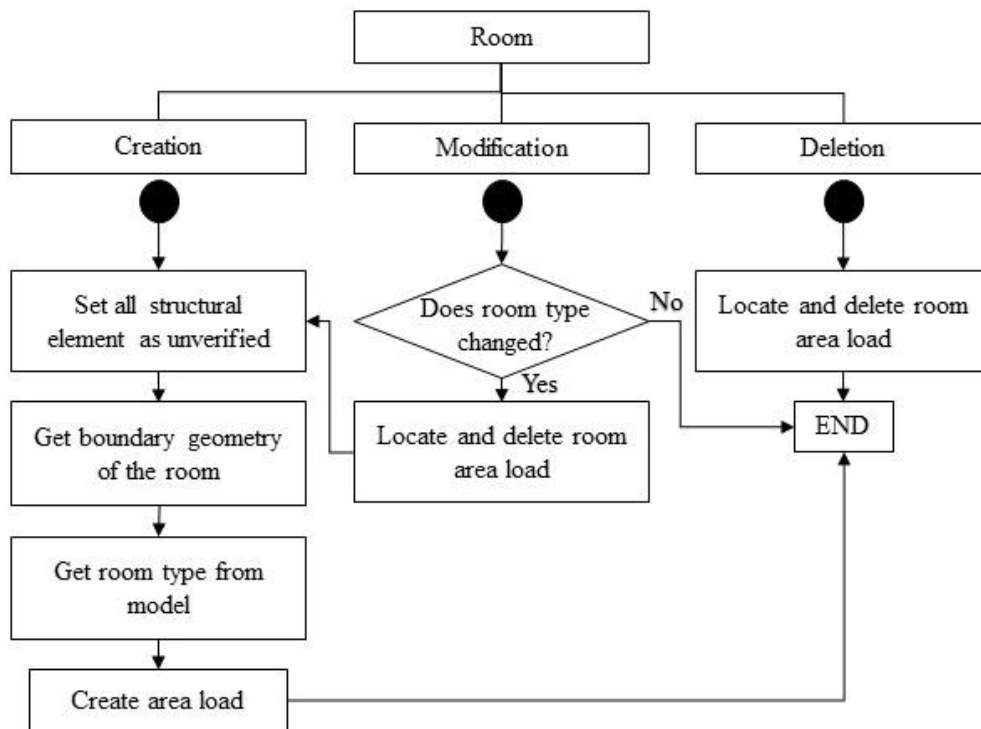
Figure 18: Room Updater.

3.1.2
ConDA's Scope

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. Using ConDA the user is able to perform structural verifications of reinforced concrete structures.

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 and set its use.

4 – Enter the information related to the location of the building.

This way the plugin is able to consider the effect of the gravity and the wind in the structure during the structural verification. The consideration of these two effects is described in the next sub-section.

3.1.2.1
Gravity Effect

ConDA considers the gravity effect in two ways. First, it considers the weight of columns and beams as a distributed linear loads acting on the element. 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 element. The NBR 6120:2018 classifies this type of load as dead load.

The density of the element's material defines the magnitude of these loads. In cases that there is no material specified by the user for the element or the material does not have any density specified, the plugin sets the value based on two criteria. If the element 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 on NBR 6120:2018 for masonry wall. If it is a concrete structural element it sets the density value as 2500 kg/m³, also in accord to the NBR 6120:2018. The flow charts of Figure 15 through Figure 18 show how the plugin manages these considerations.

When the users define the type of the room, the plugin also takes into account the gravity effect, by creating a distributed area load over the floor. The NBR 6120 classifies this type of load as live load which magnitude depends on the room's usage.

ConDA also considers a safety coefficient with the values established by the NBR 6120 code.

3.1.2.2
Wind effect

The plugin considers the effect of the wind over the building as a horizontal distributed area load over the slabs of each floor. Figure 19 shows how ConDA transforms the wind pressure over the walls' surface (p_i) in a horizontal area load acting in each floor slab of a building (q_i). The relation between p_i and q_i are shown in Equations 1 and 2, in which *n* is the number of floors. The magnitude of p_i are in accord to the prescriptions of the NBR 6123:1988 code. The plugin creates these loads after the user fills in the information about the location of the building as shown in Figure 19.
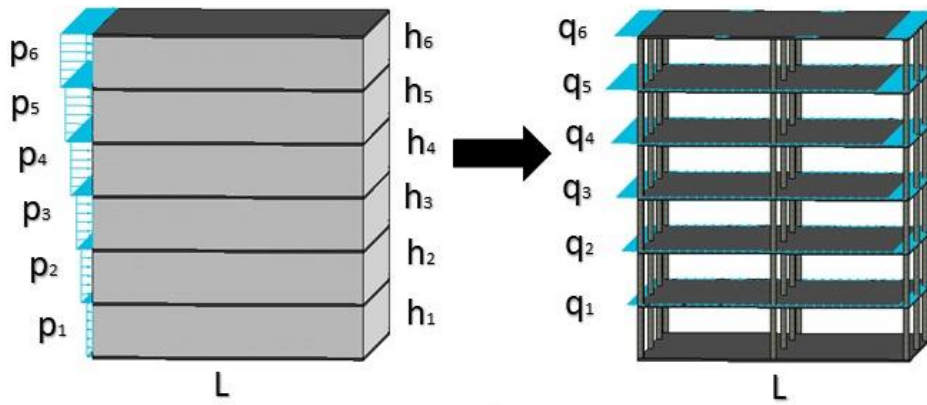
Figure 19: Wind effect.

$$p_i \cdot \frac{h_i}{2} = q_i \cdot L, \quad if \ i = 1 \ or \ i = n \tag{1}$$

$$p_i \cdot \frac{h_i + h_{i-1}}{2} = q_i \cdot L, \quad if \ 1 < i < n \tag{2}$$

3.1.3
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 responsible for that, the "Full Verification", which executes a structural analysis before the verification, and the "Fast Verification", which uses the previously obtained structural analysis results. The results of the Full Verification are more accurate, but its execution time is longer. Figure 20 shows a flow chart of the Structural Verification function.

To perform the verification, the system needs to read the information from the elements modeled in the Autodesk Revit to define the maximum and the minimum reinforcement configuration of each column and 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 does a local second order analysis according to the NBR 6118:2014 iterative method as shown in Figure 22. This is valid for columns with slenderness coefficient smaller than 140. For beams, the system does not analyze local second order effects, i.e., it only executes the cross sectional verification for

the maximum and the minimum configurations once. The flow chart of Figure 21 synthesizes this procedure.
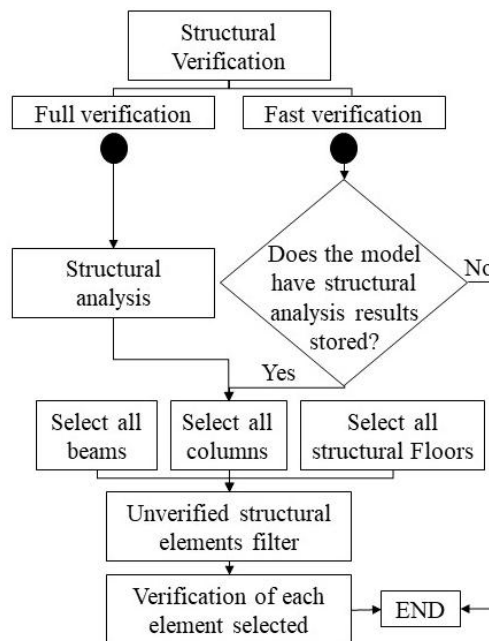
Figure 20: Structural Verification.
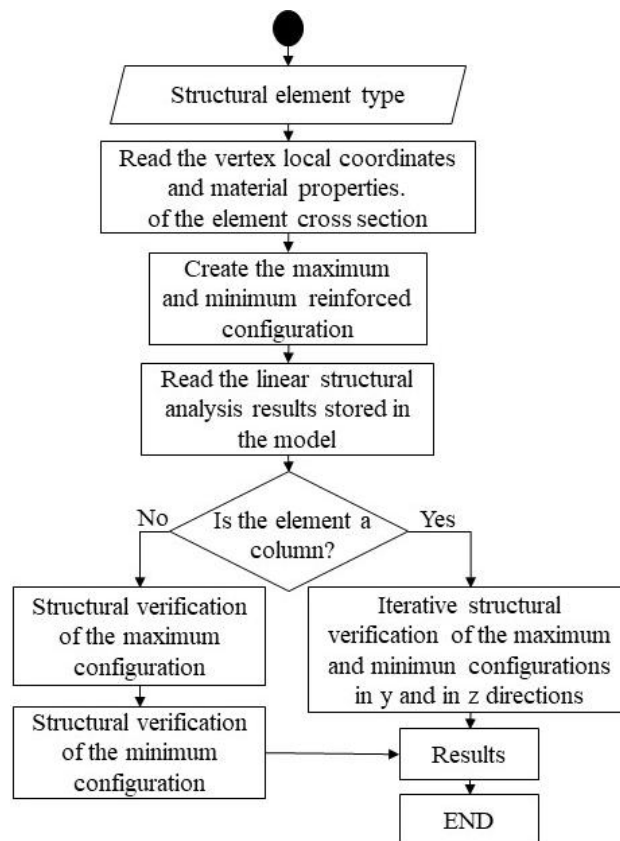
Figure 21: Verification of each structural element depending on its type.
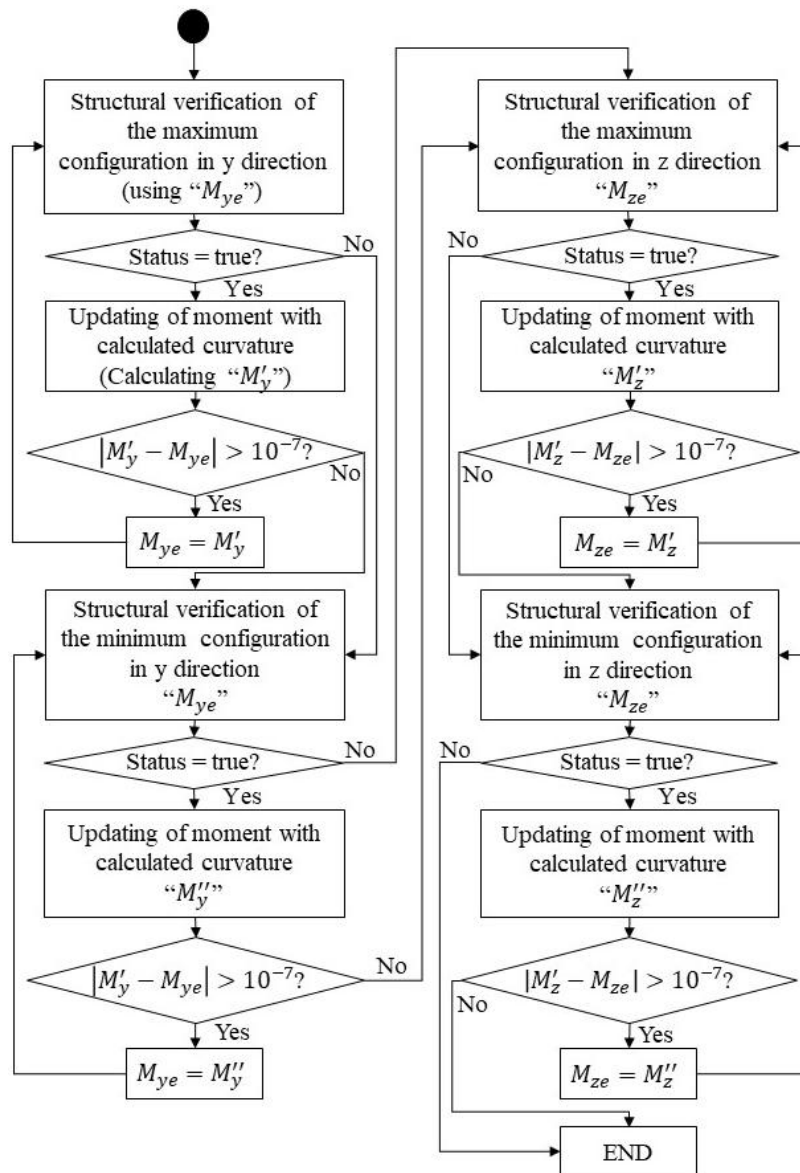
Figure 22: Iterative Method for the consideration of geometric second order effects.

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 configuration is also 4% of the cross sectional area, but the minimum configuration has the reinforcement rate (ρ_{min}) varying according to the Table 2 extracted from NBR 6118:2014. These two configurations are predefined so that ConDA is able to classify the structural response of the element.

Table 2: Minimum Reinforcement rate for beams and slabs according to NBR
6118:2014.

Minimum reinforcement rate for each concrete strength class														
fck (Mpa)	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
reinforcement rate (%)	0,150	0,150	0,150	0,164	0,179	0,194	0,208	0,211	0,219	0,226	0,233	0,239	0,245	0,251	0,256

The configuration of the reinforcement also depends on the element type. It has as restrictions the rebar cover (c), which is defined when the user set the environmental aggressiveness class, and the stirrup diameter (s), which is considered as 6,3mm as default, as Figure 23 shows.
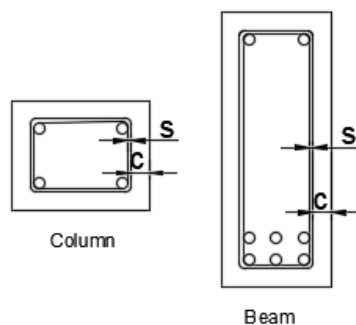
Figure 23: Reinforcement configuration.

Figure 24 and Figure 25 show the flow charts that define the reinforcement configuration.

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. If the compressive strain in the concrete is bigger than ε_{cu}, defined in Eq. 3, 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, which means that the cross section does not fail. Figure 26 shows the flow chart for this routine. If the verified element is a beam and its status is true, the plugin checks if the relation demanded by NBR 6118:2014 to

guarantee that the beam is ductile (Eq. 4) is valid. When Eq. 4 is not valid the status is set as false.

$$\varepsilon_{cu} = \begin{cases} 0,35\% & f_{ck} \leq 50MPa \\ 0,26\% + 3,5\% \cdot \left[\dfrac{(90-f_{ck})}{100}\right]^4 & 50MPa < f_{ck} \leq 90MPa \end{cases} \tag{3}$$

Where f_{ck} is the characteristic compressive strength of the concrete.
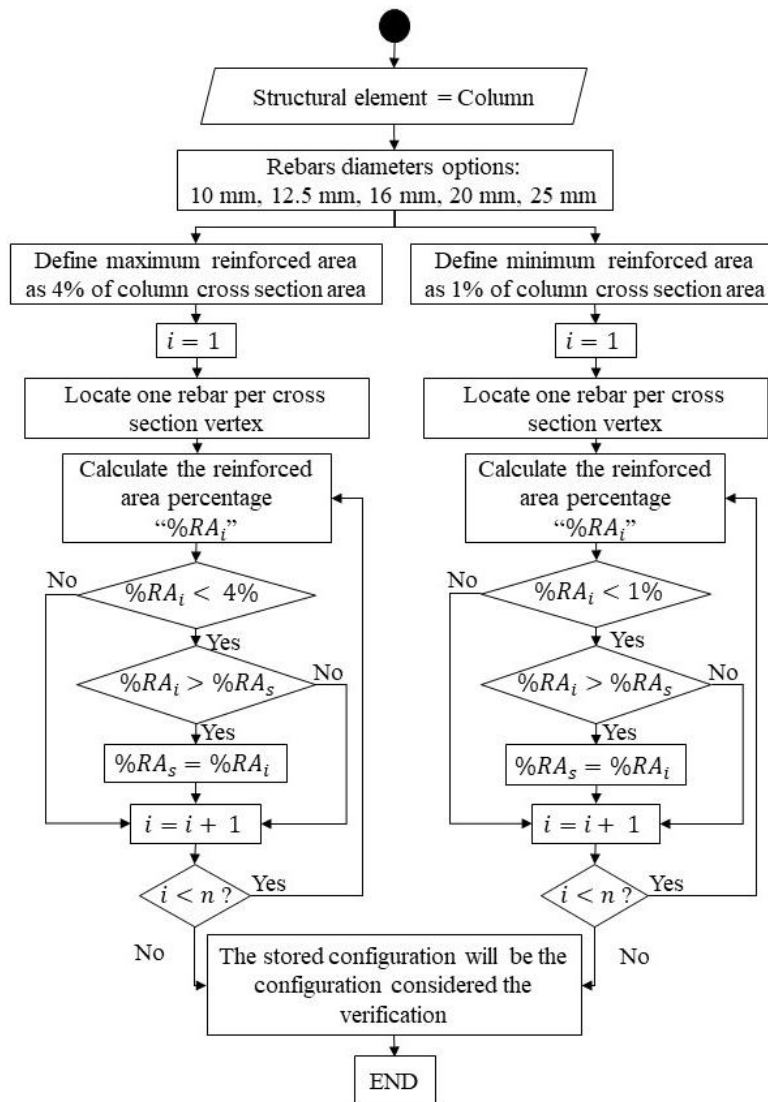
Figure 24: Definition of maximum and minimum reinforcement configuration for Columns.
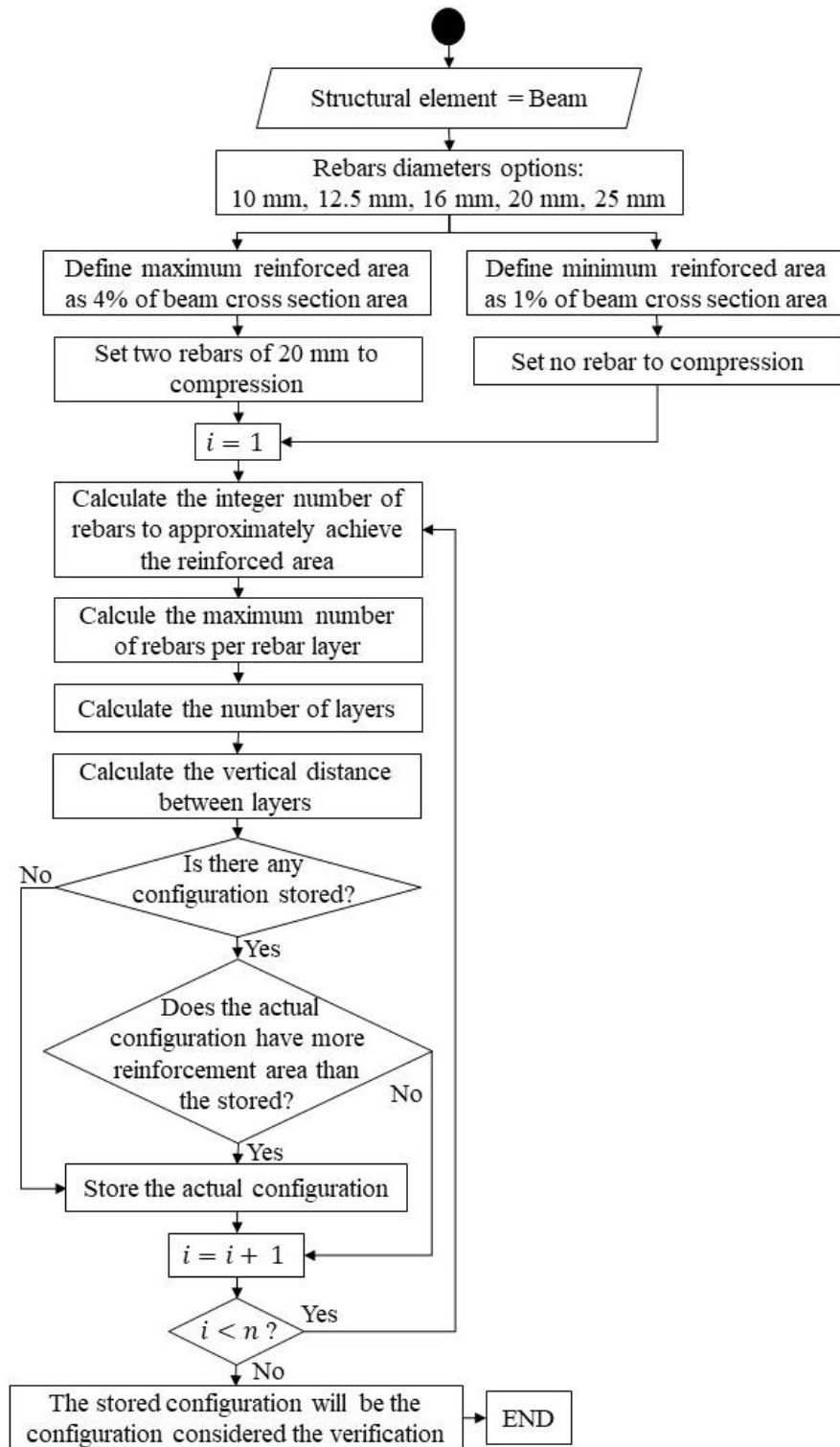
Figure 25: Definition of maximum and minimum reinforcement configuration for beams.

$$\frac{\varepsilon_{c_{\max}}}{\varepsilon_{c_{\max}} + \varepsilon_s} \leq 0,45 \tag{4}$$

Where $\varepsilon_{c_{\max}}$ is the maximum compressive strain in the cross section and ε_s is the strain at the center of gravity of the tensile reinforcement.
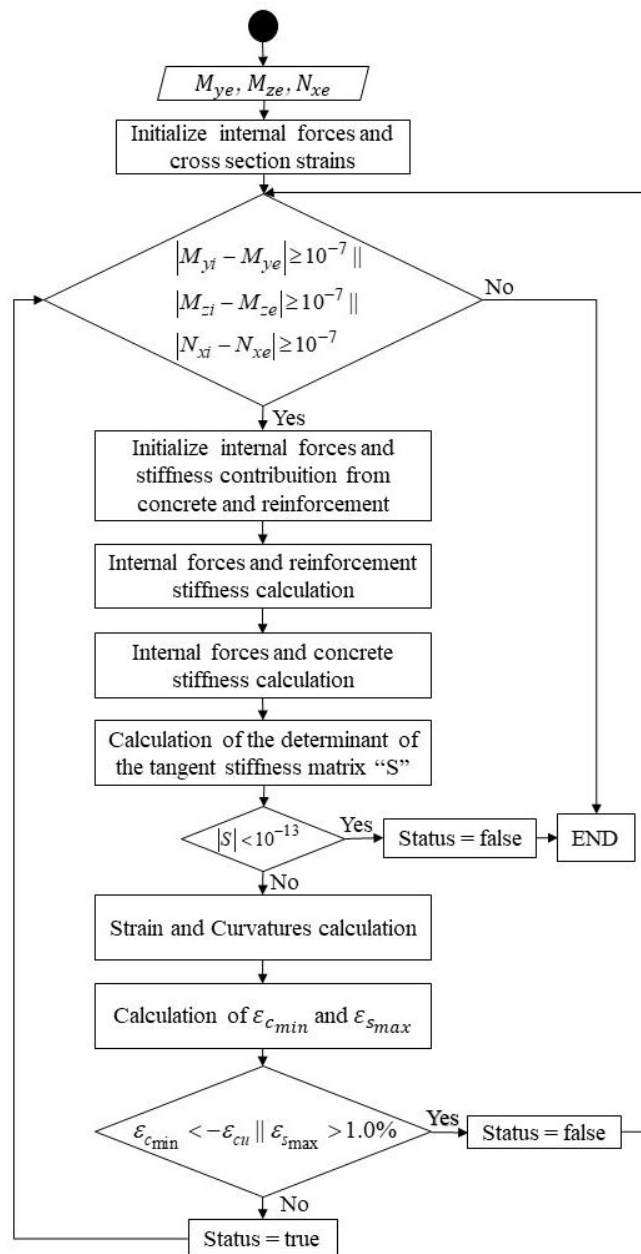
Figure 26: Procedure to calculate the strains' field for balanced forces.

To make the unbalanced force equal to zero, the plugin uses the Newton-Raphson Method to solve the nonlinear matrix expression defined by Eq. 5:

$$\{F(\varepsilon)\} = [S(\varepsilon)]\{\varepsilon\} = 0 \qquad (5)$$

Both, the concrete and the rebars of the cross section contribute to the unbalanced forces vector, $F(\varepsilon)$, and to the stiffness matrix, $S(\varepsilon)$. Their expressions were deducted based on the approach presented by Neto (2004) and detailed in Appendix A.

The verification of the slabs did not use the concept of reinforcement configuration. To perform this verification, ConDA calculates de minimum thickness (t_{min}) that the slab must have using Eq. 6. This parameter is established in NBR 6118:2014 in order to keep beams and slabs ductile. If the thickness of the slab (t) is smaller than t_{min} the element fails, otherwise ConDA calculates the necessary reinforcement rate using Eq 7. If the calculated reinforcement rate is bigger than the minimum reinforcement rate (Table 2) the thickness of the slab is well sized otherwise it is oversized. This procedure is synthetized in the flow-chart of Figure 27.

$$t_{min} = \sqrt{\frac{M_d}{f_{cd} \cdot 0,25092}} + c + \frac{\phi}{2} \qquad (6)$$

Where f_{cd} is the design compressive strength of the concrete, M_d is the design external moment and ϕ is the diameter of the rebar, set as 10 mm as default in ConDA.

$$\rho = \frac{M_d}{\left(d - 0,4 \cdot \frac{0,68 \cdot d - \sqrt{(0,68 \cdot d)^2 - 4 \cdot 0,272 \cdot \left(\frac{M_d}{f_{cd}}\right)}}{0,544} \right) \cdot f_{yd} \cdot t} \qquad (7)$$

Where f_{yd} is the design yield tension of the steel and $d = t - c - \frac{\phi}{2}$.
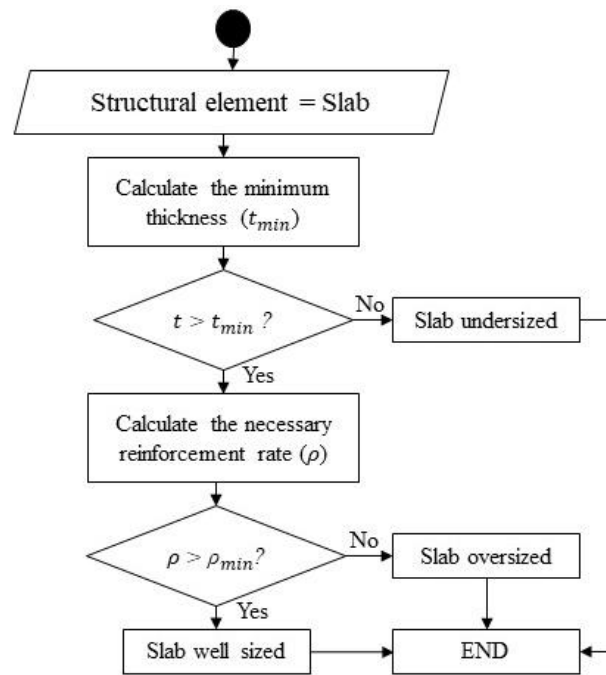
Figure 27: Slab Verification.

3.1.4
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:

- Yellow - means that the verification is outdated;

- Green - means that the cross section is well sized, i.e., the status of the maximum reinforcement configuration is true and the status of minimum reinforcement configuration is false;

- Blue - means that the cross section is oversized, i.e., the status of the minimum reinforcement configuration is true and, consequently, the status of maximum reinforcement configuration is also true;

- Red - means that the cross section is undersized, i.e., the status of the maximum reinforcement configuration is false and, consequently, the status of minimum reinforcement configuration is false.

ConDA also differentiates between the output of the full verification and of the fast verification. The latter is displayed using transparency in the colors, while the former uses solid colors with no transparency. The Figure 28 shows the difference between the two representations.

The user is able to also see the suggestion on how to achieve a more feasible and economical structural solution by clicking in the desirable structural element. The suggestions depends on the element's structural type and its structural verification result. Table 3 shows the possible suggestions for each case.

a)   b)
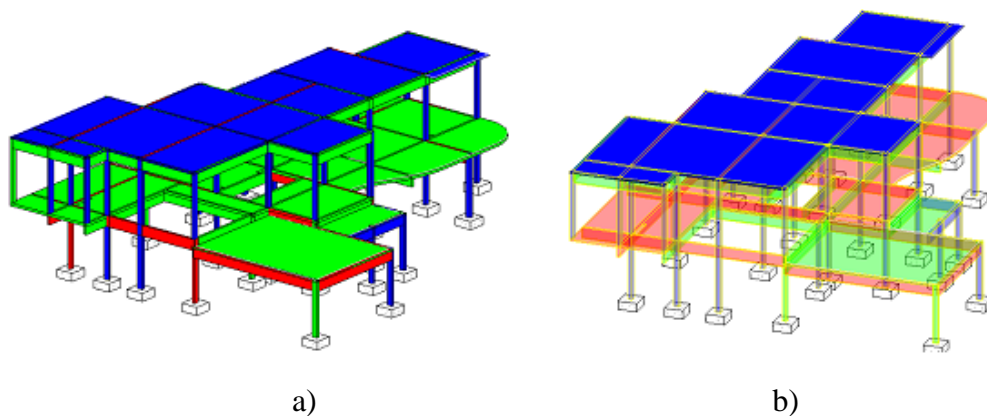
Figure 28: Structural Verification Output; (a) after a full verification; (b) after a fast verification.

Table 3: Structural Suggestions

		Structural Suggestions		
		Structural Type		
		Column	Beam	Floor
Structural verification result (Color)	Unverifided (Yellow)	This element has no verification result storage		
	Well Sized (Green)	This element is well sized, but the structural design did not end yet. Send your model to a structural engineer for a comprehensive analysis and design.		
	Oversized (Blue)	You can reduce the dimensions of this column. If the result persists you can remove it, if possible.	You can reduce the height of this beam. If the result persists you can remove it or remove a supporting column, if possible.	You can reduce the thickness of this floor. If the results persists you can remove a supporting beam, if possible.
	Undersized (Red)	You can increase the dimensions of this column, create another column close to this one, increase the strength of its material, reduces its high or insert a beam in its middle high.	You can increase the high of this beam, increase its width, if it is too thick or insert a column to reduce its span.	You can increase the thickness of this floor or add a one more beam to reduce its span.

4
Evaluation and validation of the proposed process

The proposed work process and plugin were evaluated and validated through a series of tests with architects in their work environment. This type of test is classified as User Experience (UX) evaluation. In total, 24 individuals were selected based on a snowball strategy to participate in the test. This strategy consists of the invitation of architects known by the authors to evaluate the developed tool, which suggested other architects to the interview. Then the suggested architects evaluated the plugin and indicated others colleagues to perform the test. This strategy was applied until 24 architects were selected. Only architects with some knowledge on how to use Autodesk Revit were chosen to participate. An existing Autodesk Revit model was used to expedite the process.

The main goal of the test was to extract information about the architects' understanding of the design process in a BIM context, about their current and usual workflow during the design process, and about the influence of the new application in the building design. This information is important to analyze the impact on the time spent during the architectural design when the designer adopts the proposed workflow and uses ConDA to pre-verify the structure of the building.

According to Hartson; Pyla (2012) the data obtained from the test can be objective or subjective and can be quantitative or qualitative. Objective data are data observed directly by the evaluator or the participant, subjective data represents opinions and judgments that usually relates the user's experience with the system tested. Quantitative data are the numerical data such as performance metrics or opinion rating and qualitative data are non-numerical data. In the present work, the qualitative information is the one extracted by the researcher's perception of the architect's comments during the test and the quantitative data is the one extracted from the answers to the questionnaire shown in Figure 29.

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Architect: _____

1 I found the plugin easy to use.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

2 I found that I do not need other knowledge beyond architecture to use the plugin.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

3 I found the plugin workflow intuitive.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

4 I found that the plugin behave as expected.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

5 After the test, I felt able to use the plugin without much dificulty.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

6 The hints suggested by the plugin are clear and usefull.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

7 I think that the use of the plugin reduces the number of reviews during the project.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

8 I think that the use of the plugin facilitates the communication with the structural engineer.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

9 I think that the use of the plugin adds value to the architectural design.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

10 I think that the use of the plugin antecipates conflicts, facilitating their solutions.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

11 I think that the use of the plugin reduces the design time.

Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
☐	☐	☐	☐	☐

Figure 29: Questionnare for ConDA's test.

The test consisted of the following steps:

(1) The researcher made a brief presentation (about 10 minutes) of the plugin, the model and the basic steps to be performed by the user.

(2) The Architect (user) performed the test (in average it took about 30 minutes).

(3) The Architect answers a paper questionnaire (Figure 29).

The model used in the test is that of a residential house with two floors and with approximately 400 square meters of constructed area. The first floor contains the social space of the house, with the living room, dining room, kitchen and garage. The second floor has four suites (bedroom with attached bathroom), an office and a balcony around the house.

The level of development of the model was low to simulate early design stage. Thereby, the only elements modeled were walls, beams, columns, floors and rooms with their dimensions and materials configured, as shown in Figure 30 and Figure 31. The materials used in the model already included the information about density and mechanical properties. It should be noted, that the structure provided in the model was not verified previously and purposely did not meet all structural requirements.
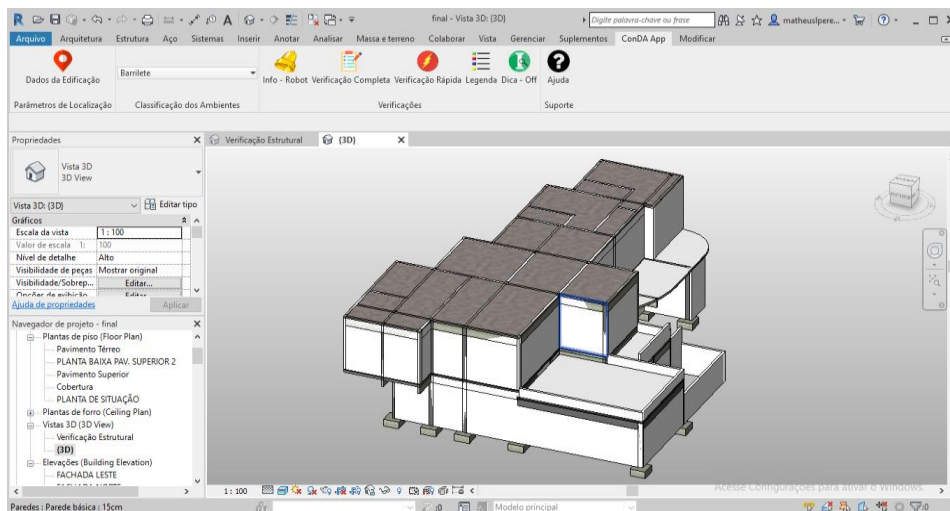
Figure 30: The modeled building for the experimentation.

The main issues that the architect was asked to observe during the test were:

(1) Information workflow between Autodesk Revit and Autodesk Robot;

(2) ConDA's verification output;

(3) Usability of the plugin.

The revision of the structural elements by the architect happened in a free form. Each architect modified the elements positions and dimensions using their judgment, but the main goal was always to achieve the safest and the most economical structure without violating the architectural objectives.

In average, the entire test (including the initial presentation) took about thirty to forty minutes. This amount of time was sufficient for all the architects to understand how to use the application as well as to answer the questionnaire.
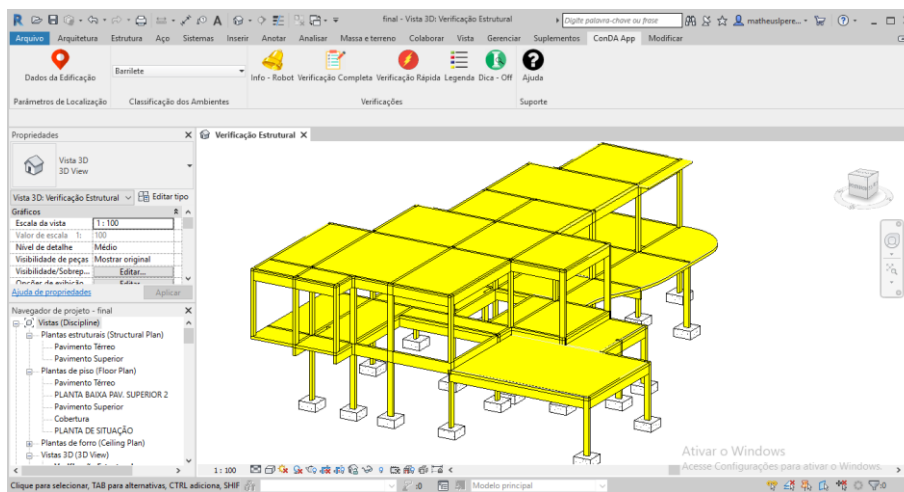
Figure 31: The initial reinforced concrete elements of the building for experimentation.

4.1
Results and Discussion

Since there are two types of data, the results are discussed in two separate subsections. Section 4.1.1 provides the qualitative findings and the discussion associated with them. On section 4.1.2, the quantitative results are presented along with their statistical analysis. These two classes of data have complementary information, which strengthens the results of the test. For example, the situations reported by the architects help to understand or ratify their quantitative answers.

4.1.1
Qualitative Data

During the validation, the interviewer inquired the architects about their design procedures and their information exchange process with the structural engineer. As their previous experience influences the test result, these questions are important to know their level of experience in integrated design, their knowledge on BIM methodology, and how the proposed process could affect their workflow.

Of the twenty-four architects interviewed, thirteen use Autodesk Revit during their usual workflow. Due to this previous experience, these users handled the application faster than the other eleven users did.

Another information obtained during the evaluation was that some users understand that just using three-dimensional modeling software packages, like Autodesk Revit, is already applying the BIM methodology. Two opposite comments by architects that work together in the same firm exemplify this misunderstanding about BIM definition. One architect said that their firm applies BIM and the other one denied, saying that they use Autodesk Revit, but not in an integrated way. This configures a people barrier.

Three BIM managers highlighted that they experienced the technological barrier, also experienced by Coelho (2016), during BIM design process. They reported that the integration of all models in a unique environment was the main challenge during BIM implementation. Thus, the architectural team needed to remodel the other disciplines' design solutions to perform clash detection analyses. The main reason for this rework, according to them, is the lack of interoperability amongst the architectural modeling software and the others design software packages. Due to this need for rework, theirs firms avoid the integrated design when it is not a client demand. Hence, the BIM managers end up working as an architecture design manager.

The majority of the interviewed architects informed that they usually exchange information with structural engineers only after the architectural predesign is completed. This practice characterizes a process barrier and is responsible for much of the rework. This is due the fact that the structural engineer may end up proposing a solution that can badly affect the architecture of the building. They related that the main reason for this is the fact that the client usually

does not hire the structural engineer until the project's approval by the city. A change in this culture is not trivial, thus ConDA application could be useful for architects, because it makes them able to create a more feasible structural system earlier at the design process. Thereby, the use of ConDA improves the workflow by providing the structural engineer with a more feasible design.

Some interviewees commented that using the plugin would help them in their discussions with the structural engineer. This is possible because the plugin makes it easier for the architects to defend their structural solution, or to accept that their structural solution is not feasible.

4.1.2
Quantitative Data

After testing the plugin, the users answered the questionnaire provided in Figure 29. The first six statements of the questionnaire are objective and the remaining are subjective. Table 4 shows the interviewees' profiles and Table 5 shows the statistical results of the answers. The possible answers follow the Likert scale from one to five to quantify the answers.

Nine answers had the median equal to five. This means that more than 50% of the architects totally agreed with these affirmative. Statement 2 is related to whether the architect needs to have knowledge beyond architecture to use the plugin had a median of three, which means the extra knowledge is not a prerequisite to use ConDA. The median for statement 3, which is related to how intuitive the plugin workflow is, had a median of four. This means that the workflow is intuitive, but it could become more intuitive with further improvements.

Statement 2 have the largest standard deviation and some factors may justify this. The fact that the sentence is written in the negative may have contributed to this. It also means that the interviewees did not reach a consensus about what knowledge beyond architecture is required. Even though there was not a consensus, the high agreement seen in statement 1, which is related to how simply to use the plugin is, indicates that the knowledge in areas like structural engineering are welcome, but not required for using ConDA.

The statement with the largest mean is statement 10, which indicates that facilitating solutions by anticipating conflicts is the main contribution of the plugin

in the design process. The lowest standard deviation of this statement reflects that the few architects that did not totally agreed with this, partially agreed with it.

According to the interviewee's answers, the second most advantageous use of the plugin was that the plugin facilitates the communication with the structural engineer (statement 8, mean = 4.79). The answers to this statement had a standard deviation (0.51), which is larger than those obtained for statements 5 and 6 (0.44). This is due the fact that the statement 8 had one answer that did not agree with it, while all architects interviewed, totally or partially, agreed with statements 5 and 6. Free comments about this issue during the test ratified this advantage. For example, two architects commented that with the verification results from the plugin, they could better argue with the structural engineer in order to achieve the integration between structural and architectural design.

The Hint Function, which gives some suggestions to the architects about how to proceed to achieve better structural results during their design process, was well accepted by all users. This can be seen by the fact that all answers related to this issue were "partially agree" or "totally agree".

The concept of application usability is related to statements 1, 3 and 5. The mean of 4.75 and the low standard deviation (0.44) of statement 5 indicates that the users felt prepared to use the plugin after the experimentation although five interviewees (21%) did not agree that ConDA is intuitive. This shows that the reason for the disagreement about how intuitive the plugin workflow (statement 3) is that the architects had their first user experience during the test.

Even though eighteen architects agreed that using ConDA might decrease the number of design revisions and the time spent in the project, as statements 7 and 11, respectively, suggest, five architects had a different opinion. These users commented that their projects involve many other disciplines beyond architecture and structure. This ratifies the need for the development of other tools similar to ConDA for other disciplines design. An interviewee also pointed out that that despite potentially decreasing the design time of all disciplines, the architectural design time could increase due to the new structural considerations during the architectural design process. In this situation, the interviewee disregarded that the time spent in the revision of the architectural design contributes to the increase of the architectural design time.

Table 4: Interviewees' profiles

Interviewee	Professional use of Revit	Design Experience
01	1	3
02	1	1
03	0	3
04	1	1
05	1	1
06	1	3
07	1	4
08	1	1
09	1	4
10	0	4
11	0	1
12	0	1
13	0	4
14	1	4
15	0	4
16	0	3
17	1	4
18	0	4
19	1	3
20	1	4
21	0	4
22	1	3
23	1	3
24	1	2

Notes

Design Experience	
< 2 years	1
2 - 5 years	2
5 - 10 years	3
> 10 years	4

Professional use of Revit	
Yes	1
No	0

Table 5: Interview results

Answers in likert scale											
Questions number	1	2	3	4	5	6	7	8	9	10	11
Median	5	3	4	5	5	5	5	5	5	5	5
Mean	4,54	3,21	4,04	4,58	4,75	4,75	4,54	4,79	4,63	4,88	4,33
Standard deviation	0,59	1,44	1,00	0,65	0,44	0,44	0,72	0,51	0,71	0,34	0,92

It is interesting to highlight that, in general, more experienced architects were more critical during the interview than the less experienced ones. This suggests ConDA may be useful in teaching architectural design, while the architects or students develop their structural sensibility.

5
Conclusion and Recommendations for Future Research

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 gravity and wind effects acting on the structure.

To validate ConDA's effectiveness, the research did a UX (User Experience) evaluation with twenty-four architects. During the evaluation, the architects answered a questionnaire evaluating the usability and utility of the developed tool. Statistical analyses of the data obtained from the responses to the questionnaire show that the interviewed group agreed with the benefits of the plugin and were

satisfied with its usability. Situations experienced by each architect and reported during the evaluation ratifies the statistical results.

ConDA's great contribution, according to the architects interviewed, is the improvement of the communication between architect and structural engineer. The other contributions are the reduction of the number of design reviews and, consequently, the reduction of time spent during the design. From the comments given by the interviewees, it could be concluded that the plugin can also be a useful tool for architectural design education and would help students improve their structural design skills.

Based on the results of the validation process it is possible to say that the proposed workflow, supported by ConDA, efficiently achieves the objective of increasing the integration between the architecture and structural design at the early stage of the design process. This is in line with the integration necessary for the successful implementation of BIM.

Some recommendations for future research in this area include:

- The creation of tools in order to enable this early integration between architecture and the other areas such as hydraulic, electrical and HVAC systems;

- The extension of the tool for other types of structures beyond reinforced concrete, such as: pre-stressed concrete, steel, composite and timber structures.

- The improvement of the structural verification considering other effects like fire safety;

- The integration of ConDA with GIS systems to automate the geographical coordinate dependent parameters.

- The creation of a structural analysis tool for the architectural software to avoid the spent of time due the exchange of information between the Autodesk Revit and the Autodesk Robot, which is ConDA's bottleneck.

6
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Appendix A – Internal Forces and Stiffness Formulation

An interactive process that converges when the external forces acting on the structure are equal to internal forces is the base of ConDA's structural verification. The cross sectional internal forces of a reinforced concrete element have two parts, one associated with the concrete and the other with the reinforcement. Figure shows the reference coordinate system and the forces applied at the cross section and their positive directions.
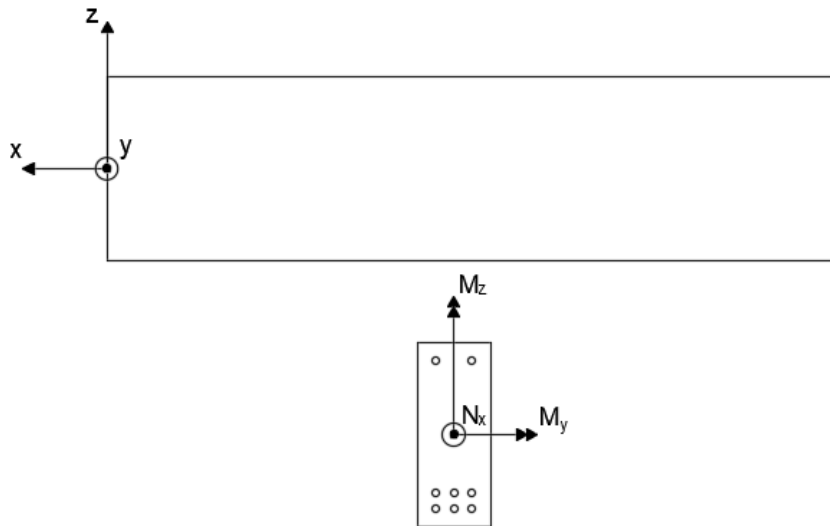
Figure A1: Coordinate system and forces applied in the cross section.

The structural verification problem consists in determining the cross section deformations for which the external and internal forces are in equilibrium. As this problem is nonlinear, an iterative procedure such as the Newton-Raphson method is necessary to solve it. Equation A1 gives the recurrence formula to this problem:

$$\varepsilon_{i+1} = \varepsilon_i + S\left(\varepsilon_i\right)^{-1} \cdot F\left(\varepsilon_i\right) \qquad (A.1)$$

Where i is the previous iteration, ε is the cross section deformation vector, $F(\varepsilon)$ is the unbalanced force vector and $S(\varepsilon)$ is the tangent stiffness matrix and their expressions are given in Equations A.1, A.2 and A.3, respectively.

$$\varepsilon_i = \begin{bmatrix} \varepsilon_{xo} \\ \kappa_y \\ \kappa_z \end{bmatrix} \tag{A.2}$$

Where ε_{xo} is the strain at x direction in the origin of the coordinate system, κ_y and κ_z are the curvature of the cross section related to the y and z axes, respectively.

$$F(\varepsilon_i) = \begin{bmatrix} N_{xe} - N_{xi} \\ M_{ye} - M_{yi} \\ M_{ze} - M_{zi} \end{bmatrix} \tag{A.3}$$

Where N_{xe} and N_{xi} are external and internal forces in x direction, respectively, M_{ye} and M_{yi} are external and internal moments in y direction and M_{ze} and M_{zi} are external and internal moments in z direction.

$$S(\varepsilon_i) = \begin{bmatrix} \dfrac{\partial N_{xi}}{\partial \varepsilon_{xo}} & \dfrac{\partial N_{xi}}{\partial \kappa_y} & \dfrac{\partial N_{xi}}{\partial \kappa_z} \\[3mm] \dfrac{\partial M_{yi}}{\partial \varepsilon_{xo}} & \dfrac{\partial M_{yi}}{\partial \kappa_y} & \dfrac{\partial M_{zi}}{\partial \kappa_z} \\[3mm] \dfrac{\partial M_{zi}}{\partial \varepsilon_{xo}} & \dfrac{\partial M_{zi}}{\partial \kappa_y} & \dfrac{\partial M_{zi}}{\partial \kappa_z} \end{bmatrix} \tag{A.4}$$

Equations A.5, A.6 and A.7 are used to calculate the concrete and reinforcement contributions to the internal forces.

$$N_{xi} = \iint_A \sigma_x(\varepsilon_x)\partial y \partial z, \tag{A.5}$$

$$M_{yi} = \iint_A \sigma_x(\varepsilon_x) \cdot z \partial y \partial z, \tag{A.6}$$

$$M_{zi} = -\iint_A \sigma_x(\varepsilon_x) \cdot y \partial y \partial z \tag{A.7}$$

Where σ_x and ε_x are the stress and strain, respectively, in the x direction, and A in the cross sectional area.

The next section provides the expressions implemented in ConDA for the concrete and reinforcement internal forces and their derivatives.

A.1
Concrete Contribution

In order to obtain the analytical expressions for the concrete contribution as function of the cross section boundary, the Green theorem was applied to rewrite the equations A.5, A.6 and A.7, which were function of the cross sectional area. This procedure reduces the problem to one dimension and allows the formulation of analytical expressions. The implementation of these expressions improves the processing time when calculating the cross sectional forces and stiffness. The deduction of these expressions can be found in Neto (2004).

To condense the analytical expressions generated by this approach, first, it is necessary to introduce the potential terms, defined in Eqs A.8 through A.13:

$$I_1(\varepsilon_x) = \int_0^{\varepsilon_x} \sigma_x(\zeta)\partial\zeta \tag{A.8}$$

$$I_2(\varepsilon_x) = \int_0^{\varepsilon_x} I_1(\zeta)\partial\zeta \tag{A.9}$$

$$I_3(\varepsilon_x) = \int_0^{\varepsilon_x} I_2(\zeta)\partial\zeta \tag{A.10}$$

$$J_1(\varepsilon_x) = \int_0^{\varepsilon_x} I_1(\zeta)\cdot\zeta\partial\zeta \tag{A.11}$$

$$K_1(\varepsilon_x) = \int_0^{\varepsilon_x} \sigma_x(\zeta) \cdot \zeta \partial \zeta \tag{A.12}$$

$$K_2(\varepsilon_x) = \int_0^{\varepsilon_x} \sigma_x(\zeta) \cdot \zeta^2 \partial \zeta \tag{A.13}$$

Where ζ is an auxiliary variable used to avoid the repetition of the strain ε_x in the integral, which would be mathematically incorrect.

Also to further condense the analytical expressions, it is import to define the gradients as shown in Eqs. A.14 through A.22.

$$\Delta y = y_{i+1} - y_i \tag{A.14}$$

$$\Delta z = z_{i+1} - z_i \tag{A.15}$$

$$\Delta \varepsilon = \varepsilon_{i+1} - \varepsilon_i \tag{A.16}$$

$$\Delta I_1 = I_{1_{i+1}} - I_{1_i} \tag{A.17}$$

$$\Delta I_2 = I_{2_{i+1}} - I_{2_i} \tag{A.18}$$

$$\Delta I_3 = I_{3_{i+1}} - I_{3_i} \tag{A.19}$$

$$\Delta J_1 = J_{1_{i+1}} - J_{1_i} \tag{A.20}$$

$$\Delta K_1 = K_{1_{i+1}} - K_{1_i} \tag{A.21}$$

$$\Delta K_2 = K_{2_{i+1}} - K_{2_i} \tag{A.22}$$

The following sections (A.1.1 through A.1.4) show the implemented expressions for the normal forces, bending moments in y and z directions and tangent stiffness matrix.

The numbering conventions for the vertex and the edge of the cross section are given in Figure 2. It is important to highlight that the first vertex to be numbered receives two numbers in order to mathematically define that the sectional edges form a closed region.
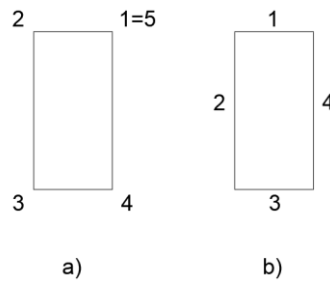
Figure A2: Convention to number a) the vertex and b) the edges of the cross section.

A.1.1
Internal Normal Force

The concrete contribution for the internal normal force, N_{xc}, is given by Eq. A23.

$$N_{xc} = \begin{cases} -\dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot n_{xci} & \kappa_y \neq 0 \\[2ex] -\dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot n_{xci} & \kappa_z \neq 0 \\[2ex] \sigma_x \cdot A & \kappa_y = \kappa_z = 0 \end{cases} \qquad (A.23)$$

Where i is the previous iteration, N is the total number of edges in the cross section, and n_{xc} is given by Eq. A24.

$$n_{xci} = \begin{cases} I_1 & \Delta\varepsilon_{x_i} = 0 \\ \dfrac{\Delta I_{2_i}}{\Delta\varepsilon_{x_i}} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \tag{A.24}$$

A.1.2
Internal Bending Moment in the y direction

The concrete contribution for the internal bending moment in the y direction, M_{yc}, is given by Eq. A25.

$$M_{yc} = \begin{cases} -\dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot m_{yci} & \kappa_y \neq 0 \\ -\dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot m_{yci} & \kappa_z \neq 0 \\ \sigma_x \cdot S_y & \kappa_y = \kappa_z = 0 \end{cases} \tag{A.25}$$

Where S_y is the static moment in relative to the y direction.

If $\kappa_z \neq 0$, the expression for m_{yc} is given by Eq. A26.

$$m_{yci} = \begin{cases} \dfrac{z_i + z_{i+1}}{2} \cdot I_{1_i} & \Delta\varepsilon_{x_i} = 0 \\ \dfrac{g_i \cdot \Delta I_{2_i} + \Delta z_i \cdot \Delta J_{1_i}}{\Delta\varepsilon_{x_i}^2} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \tag{A.26}$$

Where g is given by Eq. A.27.

$$g_i = z_i \cdot \varepsilon_{i+1} - z_{i+1} \cdot \varepsilon_i \tag{A.27}$$

.

If $\kappa_y \neq 0$, the expression for m_{yc} is given by Eq. A28.

$$m_{yci} = \begin{cases} \dfrac{z_i + z_{i+1}}{2} \cdot I_{1_i} - \dfrac{1}{\kappa_y} \cdot I_{2_i} & \Delta\varepsilon_{x_i} = 0 \\[4mm] \dfrac{g_i \cdot \Delta I_{2_i} + \Delta z_i \cdot \Delta J_{1_i}}{\Delta\varepsilon_{x_i}^{2}} - \dfrac{1}{\kappa_y} \cdot \dfrac{\Delta I_{3_i}}{\Delta\varepsilon_{x_i}} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \qquad (A.28)$$

A.1.3
Internal Bending Moment in the z direction

The concrete contribution for the internal Bending moment in the z direction, M_{zc}, is given by Eq. A29.

$$M_{zc} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \displaystyle\sum_{i=1}^{N} \Delta y_i \cdot m_{zci} & \kappa_y \neq 0 \\[4mm] \dfrac{1}{\kappa_z} \cdot \displaystyle\sum_{i=1}^{N} \Delta z_i \cdot m_{zci} & \kappa_z \neq 0 \\[4mm] \sigma_x \cdot S_z & \kappa_y = \kappa_z = 0 \end{cases} \qquad (A.29)$$

Where S_z is the static moment in relative to the z direction.

If $\kappa_y \neq 0$, the expression m_{zci} is given by Eq. A30.

$$M_{zc} = \begin{cases} \dfrac{y_i + y_{i+1}}{2} \cdot I_{1_i} & \Delta\varepsilon_{x_i} = 0 \\[4mm] \dfrac{h_i \cdot \Delta I_{2_i} + \Delta y_i \cdot \Delta J_{1_i}}{\Delta\varepsilon_{x_i}^{2}} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \qquad (A.30)$$

Where h_i is given by the Eq. A.31.

$$h_i = y_i \cdot \varepsilon_{i+1} - y_{i+1} \cdot \varepsilon_i \qquad (A.31)$$

If $\kappa_z \neq 0$, the expression for m_{zci} is given by Eq. A32.

$$M_{zc} = \begin{cases} \dfrac{y_i + y_{i+1}}{2} \cdot I_{1_i} + \dfrac{1}{\kappa_z} \cdot I_{2_i} & \Delta\varepsilon_{x_i} = 0 \\[4mm] \dfrac{h_i \cdot \Delta I_{2_i} + \Delta y_i \cdot \Delta J_{1_i}}{\Delta\varepsilon_{x_i}^{\;2}} + \dfrac{1}{\kappa_z} \cdot \dfrac{\Delta I_{3_i}}{\Delta\varepsilon_{x_i}} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \tag{A.32}$$

A.1.4
Tangent Stiffness

If $\kappa_y = 0$ and $\kappa_z = 0$, the stress in the cross section is constant. In this case the tangent stiffness matrix is given by Eq. A.33:

$$S(\varepsilon_i) = \sigma_x(\varepsilon_x)' \cdot \begin{bmatrix} A & S_y & S_z \\ S_y & I_y & -I_{yz} \\ S_z & -I_{yz} & I_z \end{bmatrix} \tag{A.33}$$

If $\kappa_z \neq 0$, the expressions for the members of the tangent stiffness defined by Eq. 4 are given by Equations A.34 through A.39.

$$\frac{\partial N_{xc}}{\partial \varepsilon_{xo}} = \begin{cases} \dfrac{1}{\kappa_z} \cdot \displaystyle\sum_{i=1}^{N} \Delta z_i \cdot \sigma_{x_i} & \Delta\varepsilon_{x_i} = 0 \\[4mm] \dfrac{1}{\kappa_z} \cdot \displaystyle\sum_{i=1}^{N} \Delta z_i \cdot \dfrac{\Delta I_{1_i}}{\Delta\varepsilon_{x_i}} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \tag{A.34}$$

$$\frac{\partial N_{xc}}{\partial \kappa_y} = \frac{\partial M_{yc}}{\partial \varepsilon_{xo}} = \begin{cases} -\dfrac{1}{\kappa_z} \cdot \displaystyle\sum_{i=1}^{N} \Delta z_i \cdot \sigma_{x_i} \cdot \dfrac{z_{i+1} + z_i}{2} & \Delta\varepsilon_{x_i} = 0 \\[4mm] -\dfrac{1}{\kappa_z} \cdot \displaystyle\sum_{i=1}^{N} \Delta z_i \cdot \dfrac{g_i \cdot \Delta I_{1_i} + \Delta z_i \cdot \Delta K_{1_i}}{\Delta\varepsilon_{x_i}^{\;2}} & \Delta\varepsilon_{x_i} \neq 0 \end{cases} \tag{A.35}$$

$$\frac{\partial N_{xc}}{\partial \kappa_z} = \frac{\partial M_{zc}}{\partial \varepsilon_{xo}} = \begin{cases} \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \left(\dfrac{n_{xci}}{\kappa_z} + \dfrac{y_i + y_{i+1}}{2} \cdot \sigma_{x_i} \right) & \Delta \varepsilon_{x_i} = 0 \\[3ex] \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \left(\dfrac{n_{xci}}{\kappa_z} + \dfrac{h_i \cdot \Delta I_{1_i} + \Delta y_i \cdot \Delta K_{1_i}}{\Delta \varepsilon_{x_i}^2} \right) & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \quad \text{(A.36)}$$

$$\frac{\partial M_{yc}}{\partial \kappa_y} = \begin{cases} \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \dfrac{z_i^2 + z_i \cdot z_{i+1} + z_{i+1}^2}{3} \cdot \sigma_{x_i} & \Delta \varepsilon_{x_i} = 0 \\[3ex] \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \dfrac{g_i^2 \cdot \Delta I_{1_i} + 2 g_i \cdot \Delta z_i \cdot \Delta K_{1_i} + \Delta z_i^2 \cdot \Delta K_{2_i}}{\Delta \varepsilon_i^3} & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \quad \text{(A.37)}$$

$$\frac{\partial M_{yc}}{\partial \kappa_z} = \frac{\partial M_{zc}}{\partial \kappa_y} = \begin{cases} \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \left[\dfrac{m_{yci}}{\kappa_z} - \dfrac{y_i \cdot z_{i+1} + 2\left(y_i \cdot z_i + y_{i+1} \cdot z_{i+1} \right) + y_{i+1} \cdot z_i}{6} \cdot \sigma_{x_i} \right] & \Delta \varepsilon_{x_i} = 0 \\[3ex] \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \left[\dfrac{m_{yci}}{\kappa_z} - \dfrac{h_i \cdot g_i \cdot \Delta I_{1_i} + \left(g_i \cdot \Delta y_i + h_i \cdot \Delta z_i \right) \Delta K_{1_i} + \Delta y_i \cdot \Delta z_i \cdot K_{2_i}}{\Delta \varepsilon_i^3} \right] & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \quad \text{(A.38)}$$

$$\frac{\partial M_{zc}}{\partial \kappa_z} = \begin{cases} \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \left(-\dfrac{2 \cdot m_{zci}}{\kappa_z} + \dfrac{y_i^2 + y_i \cdot y_{i+1} + y_{i+1}^2}{3} \cdot \sigma_{x_i} \right) & \Delta \varepsilon_{x_i} = 0 \\[3ex] \dfrac{1}{\kappa_z} \cdot \sum_{i=1}^{N} \Delta z_i \cdot \left(-\dfrac{2 \cdot m_{zci}}{\kappa_z} + \dfrac{h_i^2 \cdot \Delta I_{1_i} + 2 h_i \cdot \Delta y_i \cdot \Delta K_{1_i} + \Delta y_i^2 \cdot \Delta K_{2_i}}{\Delta \varepsilon_i^3} \right) & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \quad \text{(A.39)}$$

If $\kappa_y \neq 0$, the expressions for the tangent stiffness defined by Eq. 4 are given by Equations A.40 through A.45.

$$\frac{\partial N_{xc}}{\partial \varepsilon_{xo}} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \sigma_{x_i} & \Delta \varepsilon_{x_i} = 0 \\[3ex] \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \dfrac{\Delta I_{1_i}}{\Delta \varepsilon_{x_i}} & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \quad \text{(A.40)}$$

$$\frac{\partial N_{xc}}{\partial \kappa_y} = \frac{\partial M_{yc}}{\partial \varepsilon_{xo}} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \left(\dfrac{n_{xci}}{\kappa_y} - \sigma_{x_i} \cdot \dfrac{z_{i+1} + z_i}{2} \right) & \Delta \varepsilon_{x_i} = 0 \\[4mm] \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \left(\dfrac{n_{xci}}{\kappa_y} - \dfrac{g_i \cdot \Delta I_{1_i} + \Delta z_i \cdot \Delta K_{1_i}}{\Delta \varepsilon_{x_i}^{\ 2}} \right) & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \tag{A.41}$$

$$\frac{\partial N_{xc}}{\partial \kappa_z} = \frac{\partial M_{zc}}{\partial \varepsilon_{xo}} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \dfrac{y_i + y_{i+1}}{2} \cdot \sigma_{x_i} & \Delta \varepsilon_{x_i} = 0 \\[4mm] \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \dfrac{h_i \cdot \Delta I_{1_i} + \Delta y_i \cdot \Delta K_{1_i}}{\Delta \varepsilon_{x_i}^{\ 2}} & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \tag{A.42}$$

$$\frac{\partial M_{yc}}{\partial \kappa_y} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \left(-2 \dfrac{m_{yci}}{\kappa_y} + \dfrac{z_i^2 + z_i \cdot z_{i+1} + z_{i+1}^2}{3} \cdot \sigma_{x_i} \right) & \Delta \varepsilon_{x_i} = 0 \\[4mm] \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \left(-2 \dfrac{m_{yci}}{\kappa_y} + \dfrac{g_i^2 \cdot \Delta I_{1_i} + 2 g_i \cdot \Delta z_i \cdot \Delta K_{1_i} + \Delta z_i^2 \cdot \Delta K_{2_i}}{\Delta \varepsilon_i^{\ 3}} \right) & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \tag{A.43}$$

$$\frac{\partial M_{yc}}{\partial \kappa_z} = \frac{\partial M_{zc}}{\partial \kappa_y} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \left[\dfrac{m_{zci}}{\kappa_y} - \dfrac{y_i \cdot z_{i+1} + 2 \left(y_i \cdot z_i + y_{i+1} \cdot z_{i+1} \right) + y_{i+1} \cdot z_i}{6} \cdot \sigma_{x_i} \right] & \Delta \varepsilon_{x_i} = 0 \\[4mm] \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \left[\dfrac{m_{zci}}{\kappa_y} - \dfrac{h_i \cdot g_i \cdot \Delta I_{1_i} + \left(g_i \cdot \Delta y_i + h_i \cdot \Delta z_i \right) \Delta K_{1_i} + \Delta y_i \cdot \Delta z_i \cdot K_{2_i}}{\Delta \varepsilon_i^{\ 3}} \right] & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \tag{A.44}$$

$$\frac{\partial M_{zc}}{\partial \kappa_z} = \begin{cases} \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \dfrac{y_i^2 + y_i \cdot y_{i+1} + y_{i+1}^2}{3} \cdot \sigma_{x_i} & \Delta \varepsilon_{x_i} = 0 \\[4mm] \dfrac{1}{\kappa_y} \cdot \sum_{i=1}^{N} \Delta y_i \cdot \dfrac{h_i^2 \cdot \Delta I_{1_i} + 2 h_i \cdot \Delta y_i \cdot \Delta K_{1_i} + \Delta y_i^2 \cdot \Delta K_{2_i}}{\Delta \varepsilon_i^{\ 3}} & \Delta \varepsilon_{x_i} \neq 0 \end{cases} \tag{A.45}$$

A.1.5
Uniaxial concrete constitutive model

The developed expressions for internal forces depend on integrals that are dependent on the stress-strain relation. As this research work followed the

prescriptions of ABNT NBR – 6118 code, it considered the uniaxial constitutive model for the concrete suggested by this code and given by Eq. A.46.

$$\sigma\left(\varepsilon_x\right)=\begin{cases}0 & \varepsilon_x>0\\[2mm] f_{cp}\cdot\left\{\varepsilon_x+\left[\left(1-\dfrac{\varepsilon_x}{\varepsilon_{c2}}\right)^n-1\right]\right\} & \varepsilon_{c2}\le\varepsilon_x\le 0\\[2mm] f_{cp} & \varepsilon_x<\varepsilon_{c2}\end{cases} \tag{A.46}$$

The analytical expressions given by Eq. A.47 through A.52 were formulated by solving the integrals of the potential terms, and considering the constitutive model for the concrete given by Eq. 46.

$$I_1\left(\varepsilon_x\right)=\begin{cases}0 & \varepsilon_x>0\\[2mm] f_{cp}\cdot\left\{\varepsilon_x+\dfrac{\varepsilon_{c2}{}^2\cdot\left[\left(1-\dfrac{\varepsilon_x}{\varepsilon_{c2}}\right)^{n+1}-1\right]}{n+1}\right\} & \varepsilon_{c2}\le\varepsilon_x\le 0\\[2mm] f_{cp}\cdot\varepsilon_x-\dfrac{f_{cp}\cdot\varepsilon_{c2}}{n+1} & \varepsilon_x<\varepsilon_{c2}\end{cases} \tag{A.47}$$

$$I_2\left(\varepsilon_x\right)=\begin{cases}0 & \varepsilon_x>0\\[2mm] f_{cp}\cdot\left\{\dfrac{1}{2}\cdot\varepsilon_x{}^2-\dfrac{\varepsilon_{c2}{}^2\cdot\left[\left(1-\dfrac{\varepsilon_x}{\varepsilon_{c2}}\right)^{n+2}-1\right]}{(n+1)\cdot(n+2)}-\dfrac{\varepsilon_{c2}\cdot\varepsilon_x}{n+1}\right\} & \varepsilon_{c2}\le\varepsilon_x\le 0\\[2mm] \dfrac{1}{2}\cdot f_{cp}\cdot\varepsilon_x{}^2-\dfrac{f_{cp}\cdot\varepsilon_{c2}}{n+1}\cdot\varepsilon_x+\dfrac{f_{cp}\cdot\varepsilon_{c2}{}^2}{(n+1)\cdot(n+2)} & \varepsilon_x<\varepsilon_{c2}\end{cases} \tag{A.48}$$

$$I_3(\varepsilon_x) = \begin{cases} 0 & \varepsilon_x > 0 \\[4pt] \dfrac{1}{2} \cdot f_{cp} \cdot \left\{ \dfrac{1}{3} \cdot \varepsilon_x^3 + \dfrac{2 \cdot \varepsilon_{c2}^3 \cdot \left[\left(1 - \dfrac{\varepsilon_x}{\varepsilon_{c2}}\right)^{n+3} - 1 \right]}{(n+1)\cdot(n+2)\cdot(n+3)} - \dfrac{\varepsilon_{c2} \cdot \varepsilon_x^2}{n+1} + \dfrac{2 \cdot \varepsilon_{c2}^2 \cdot \varepsilon_x}{(n+1)\cdot(n+2)} \right\} & \varepsilon_{c2} \le \varepsilon_x \le 0 \\[4pt] \dfrac{1}{6} \cdot f_{cp} \cdot \varepsilon_x^3 - \dfrac{f_{cp} \cdot \varepsilon_{c2}}{2\cdot(n+1)} \cdot \varepsilon_x^2 + \dfrac{f_{cp} \cdot \varepsilon_{c2}^2}{(n+1)\cdot(n+2)} \cdot \varepsilon_x - \dfrac{f_{cp} \cdot \varepsilon_{c2}^3}{(n+1)\cdot(n+2)\cdot(n+3)} & \varepsilon_x < \varepsilon_{c2} \end{cases}$$ (A.49)

$$J_1(\varepsilon_x) = \begin{cases} 0 & \varepsilon_x > 0 \\[4pt] f_{cp} \left[\varepsilon_{c2} \dfrac{r(\varepsilon_x)^{n+1} - \dfrac{n+3}{2}}{(n+1)(n+3)} \varepsilon_x^2 + \dfrac{\varepsilon_x^3}{3} - \dfrac{\varepsilon_{c2}^2 \cdot r(\varepsilon_x)^{n+1}}{(n+2)(n+3)} \varepsilon_x - \varepsilon_{c2}^3 \dfrac{r(\varepsilon_x)^{n+1} - 1}{(n+1)(n+2)(n+3)} \right] & \varepsilon_{c2} \le \varepsilon_x \le 0 \\[4pt] \dfrac{1}{3} \cdot f_{cp} \cdot \varepsilon_x^3 - \dfrac{f_{cp} \cdot \varepsilon_{c2}}{2\cdot(n+1)} \cdot \varepsilon_x^2 + \dfrac{f_{cp} \cdot \varepsilon_{c2}^3}{(n+1)(n+2)(n+3)} & \varepsilon_x < \varepsilon_{c2} \end{cases}$$ (A.50)

$$K_1(\varepsilon_x) = \begin{cases} 0 & \varepsilon_x > 0 \\[4pt] f_{cp} \left[\varepsilon_{c2} \dfrac{\varepsilon_{c2} \cdot r(\varepsilon_x)^n + n \cdot \varepsilon_x \cdot r(\varepsilon_x)^n - \varepsilon_{c2}}{(n+1)(n+2)} + \dfrac{\varepsilon_x^2}{2} - \dfrac{r(\varepsilon_x)}{n+2} \varepsilon_x^2 \right] & \varepsilon_{c2} \le \varepsilon_x \le 0 \\[4pt] f_{cp} \left[\dfrac{\varepsilon_x^2}{2} - \dfrac{\varepsilon_{c2}^2}{(n+1)(n+2)} \right] & \varepsilon_x < \varepsilon_{c2} \end{cases}$$ (A.51)

$$K_2(\varepsilon_x) = \begin{cases} 0 & \varepsilon_x > 0 \\[4pt] f_{cp} \left[\dfrac{n \cdot \varepsilon_{c2} \cdot r(\varepsilon_x)^n}{(n+2)(n+3)} \varepsilon_x^2 + \dfrac{\varepsilon_x^3}{3} - \dfrac{r(\varepsilon_x)^n}{n+3} \varepsilon_x^3 + 2 \cdot \varepsilon_{c2}^2 \dfrac{\varepsilon_{c2} \cdot r(\varepsilon_x)^n + n \cdot \varepsilon_x \cdot r(\varepsilon_x)^n - \varepsilon_{c2}}{(n+1)(n+2)(n+2)} \right] & \varepsilon_{c2} \le \varepsilon_x \le 0 \\[4pt] f_{cp} \left[\dfrac{\varepsilon_x^3}{3} + - \dfrac{2 \cdot \varepsilon_{c2}^3}{(n+1)(n+2)(n+2)} \right] & \varepsilon_x < \varepsilon_{c2} \end{cases}$$ (A.52)

Where f_{cp} is the peak of concrete compressive stress, ε_{c2} in the peak of the compressive strain, which is defined by Eq. A.53 and n is a variable defined by Eq. A.54. The term $r(\varepsilon_x)$ is given by Eq. A.55.

$$\varepsilon_{c2} = \begin{cases} 0,2\% & f_{ck} \leq 50 MPa \\ 0,2\% + 0,085\% \cdot \left(fck - 50 \right)^{0,53} & 50 MPa < f_{ck} \leq 90 MPa \end{cases} \tag{A.53}$$

$$n = \begin{cases} 2 & f_{ck} \leq 50 MPa \\ 1,4 + 23,4 \cdot \left[\dfrac{\left(90 - f_{ck} \right)}{100} \right]^{4} & 50 MPa < f_{ck} \leq 90 MPa \end{cases} \tag{A.54}$$

$$r\left(\varepsilon_x \right) = \left(1 - \frac{\varepsilon_x}{\varepsilon_{c2}} \right) \tag{A.55}$$

A.2
Reinforcements Contributions

Assuming that the steel reinforcement can be represented as a single point in the concrete cross section and that there is perfect bond between concrete and reinforcement, it is possible to use the Eq. A56 to calculate the reinforcement strain.

$$\varepsilon_{xs_i} = \varepsilon_{xos_i} + z_{s_i} \cdot \kappa_y - y_{s_i} \cdot \kappa_z \tag{A.56}$$

Where s indicates that the variables are related to the steel reinforcement. Eqs A.57, A.58, A.59 give the expression for internal forces considering all the n rebars.

$$N_{xs} = \sum_{i}^{n} \sigma_x \left(\varepsilon_{xs_i} \right) \cdot A_i \tag{A.57}$$

$$M_{ys} = \sum_{i}^{n} \sigma_x \left(\varepsilon_x \right) \cdot z_i \cdot A_i \tag{A.58}$$

$$M_{zs} = -\sum_{i}^{n} \sigma_x \left(\varepsilon_x \right) \cdot y_i \cdot A_i \tag{A.59}$$

`

Using Eqs. A.57, A.58, A.59 in Eq. A.4, The tangent stiffness matrix is obtained and the result is given by Eq. A.60.

$$S\left(\varepsilon_{x_i}\right) = \begin{bmatrix} \sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot A_i & -\sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot z_i \cdot A_i & \sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot y_i \cdot A_i \\ -\sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot z_i \cdot A_i & \sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot z_i^2 \cdot A_i & -\sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot y_i \cdot z_i \cdot A_i \\ \sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot y_i \cdot A_i & -\sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot y_i \cdot z_i \cdot A_i & \sum\limits_{i}^{n} \sigma_x\left(\varepsilon_{xs_i}\right)' \cdot y_i^2 \cdot A_i \end{bmatrix} \quad \text{(A.60)}$$

Where $\sigma_x\left(\varepsilon_{xs_i}\right)'$ is the first derivative of the stress.

Considering the perfect elastoplastic constitutive model suggest by the NBR-6118 code for the passive reinforcement, $\sigma_x\left(\varepsilon_{xs_i}\right)'$ can assume two values as shown in Eq. A61.

$$\sigma_x\left(\varepsilon_{xs_i}\right)' = \begin{cases} E & |\sigma_x| \le f_{yd} \\ 0 & |\sigma_x| > f_{yd} \end{cases} \quad \text{(A.61)}$$

Where f_{yd} is the characteristic yield stress of the rebar and E is the elastic modulus of steel.