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Augmented BIM workflow for structural design through data visualization

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RESUMO

O impacto da tecnologia da informação (TI) na engenharia estrutural começou a ser discutido há décadas. Os primeiros protótipos de software para documentação e análise datam dos anos 1950 e 1960. Na década de 90, uma pesquisa indicou que um grande número de engenheiros estruturais já concordava que a TI estava acelerando a engenharia. Essa relação se estreitou com o barateamento do poder de computação ao longo dos anos. Atualmente, é possível que engenheiros explorem um espaço de projeto ampliado antes de chegar a uma solução final, principalmente por meio de modelagem paramétrica combinada com análise estrutural. Isso culminou na geração de grandes e complexos conjuntos de dados durante o projeto. Paralelamente, a popularização do Building Information Modeling (BIM), apresenta uma oportunidade para uso dos modelos BIM como um banco de dados para avançar o desempenho em projetos. Para se fazer um uso eficiente desses dados, é fundamental condensá-los em visualizações claras e interativas. Neste contexto, esta pesquisa se propõe a investigar e testar um fluxo de trabalho denominado "fluxo de trabalho ampliado pela visualização de dados para o design estrutural em BIM". O objetivo geral é a melhoria da colaboração interna em um time de projeto. Uma ferramenta computacional para viabilizar este fluxo é proposta, e sua prova de conceito (PoC) é implementada, combinando dados de modelos BIM e FEA (análise de elementos finitos). Para isso, foram realizados processos de extração, transformação e carregamento desses dados em um "armazém", via software de visualização de dados. A proposta foi apresentada a engenheiros estruturais e especialistas em BIM, cujos comentários foram coletados para basear a construção de painéis de controle padrão para visualização de dados. Os painéis finais tiveram a sua utilidade validada pelos profissionais. Limitações técnicas na implementação atual e barreiras subjacentes para adoção futura são discutidas.

Palavras-chave: BIM, Engenharia de estruturas, Visualização de dados, Fluxo de trabalho.

ABSTRACT

It has been decades since the impact of information technology (IT) on structural engineering started to be discussed. The first documentation and analysis software prototypes date from the 1950s and 1960s. In the 90s, a survey indicated that a great number of structural engineers already agreed that IT was accelerating engineering. This close relationship evolved with the increasing power of computation. Nowadays, it is possible that engineers explore an amplified design space before reaching a final solution, mainly through parametric modeling combined with analysis. This culminated in large and complex data being generated during design. At the same time, the popularization of Building Information Modeling (BIM) and its focus on information present an opportunity for engineers to use BIM models as databases for enhancing design and collaboration. To fully leverage this data, it is imperative to condense it into meaningful and actionable visualizations. In this context, this research investigates and tests a workflow for structural design in BIM, named an “augmented BIM workflow for structural engineering through data visualization". The general objective is the enhancement of collaboration within a design team. A computational tool for enabling this workflow is proposed and implemented at a proof of concept (PoC) level, combining data from FEA (Finite Element Analysis) and BIM models. Extraction, transformation, and load processes from these data sources into a data warehouse in a visualization software solution are executed. The proposal was presented to engineers and BIM specialists. Feedback was collected to base the construction of a set of standard dashboards for data visualization. The final dashboards had their utility validated by the professionals. Technical limitations on the current implementation and underlying barriers to adoption are discussed.

Keywords: BIM, structural engineering, data visualization, workflow.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ACAD	AutoCAD
AEC	Architecture, Engineering, and Construction
AIA	American Institute of Architects
API	Application Programming Interface
ASCE	American Society of Civil Engineers
A&D	Analysis and design
BIM	Building Information Modeling
BCF	BIM Collaboration Format
BoQ	Bill of quantities

CAD	Computer-aided Design
CAE	Computer-aided Engineering
CAM	Computer-aided Manufacturing
CHS	Circular Hollow Sections
CIM	City Information Modeling
COO	Coordination dashboard
COM	Comparison dashboard
D&C	Data and Control
DSR	Design Science Research
ETL	Extract, transform and load
FEA	Finite Element Analysis
FEM	Finite Element Method
IABSE	International Association for Bridge and Structural Engineering
IFC	Industry Foundation Classes
IoT	Internet of Things
Istructe	The Institution of Structural Engineers
IT	Information Technology
KPI	Key Project Indicators
MIPS	Million instructions per second
MNG	Management dashboard
PoC	Proof of concept
REC	Rectangular Sections
ROU	Round Sections
RHS	Rectangular Hollow Sections
SE	Structural engineers
SEI	Structural Engineers Institution
SHS	Square Hollow Sections
US	United States
UK	United Kingdom

CONTENTS

1. INTRODUCTION

1.1. Context and justification

The impact of information technology on structural engineering started to be discussed decades ago. In the 1990s, 68% of the respondent engineers in a survey carried out by Istructe[1] agreed that information technology was accelerating engineering (Gardner, 1995).

At that time, almost all structural engineers claimed to have access to a computer as a work tool, either for exclusive (47%) or shared (51%) use. This usage was coined as CAE (computer-aided engineering). More specifically, respondents reported significant use of the computer in aspects related to the design and calculation of structures, as shown in Figure 1.

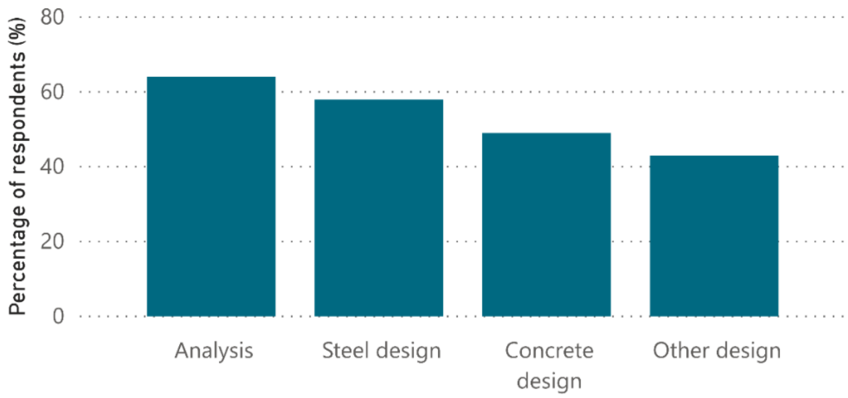

Figure 1: Respondents who reported significant use of CAE, by purpose, in 1995
Source: Adapted from Gardner (1995)

From the point of view of project documentation, the same survey reported an expansion in the use of CAD (computer-aided design). At that time, around 55% of large companies and 40% of medium companies declared to have one "screen" of CAD for each draftsperson, as shown in Figure 2.

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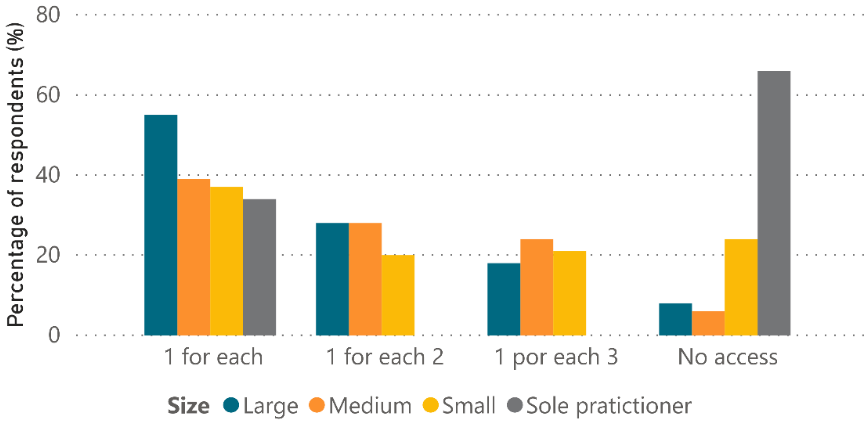
[1] The Institution of Structural Engineers, a professional body for structural engineering based in the United Kingdom



*large = 500+ employees, medium = 50-499 employees, small = 2-49 employees

Figure 2: CAD availability per draftsperson in structural design offices by size* in 1995

Source: Adapted from Gardner (1995)

With the computer starting to become a present tool in design offices, several studies on the automation of structural projects emerged in the literature.

Luth et al. (1991) proposed, from a theoretical point of view, the integration of computational technologies such as artificial intelligence, database management software, CAD, CAE, and CAM (computer-aided manufacturing) for the development of an intelligent automation system for structural building projects. This system should be able to capture the design intent, in addition to its results. Although it has been three decades since this publication, it gives some requirements for automation that are still research topics nowadays. Firstly, it advocated that data needs to be properly stored throughout the design process. Secondly, it suggested that the structural database should be directly linked to the CAD platform, avoiding bureaucratic steps that add workload to the engineer.

Sacks et al. (2000) presented a parametric template for the automation of the structural design of a building. The study pointed out that “structural design of buildings has proven to be particularly difficult to automate” and delimits the solution presented to buildings of rectangular plan views only (SACKS et al., 2000, p. 1).

The automation approaches proposed at that period were based on artificial intelligence methods, such as expert systems consisting of rules, neural networks, and genetic algorithms. Since then, the use of computational tools in design has been intensified. This has a lot to do with the fact that research progress in the Finite Element Method (FEM) and computer graphics coincided with the rapid growth of computer power (FISH; BELYTSCHKO, 2007).

This is corroborated by the data gathered in the graph in Figure 3. From the release of the first FEM paper and CAD software to the present time, the cost of processing power has declined several orders of magnitude (BOECHAT; CORRÊA, 2021).

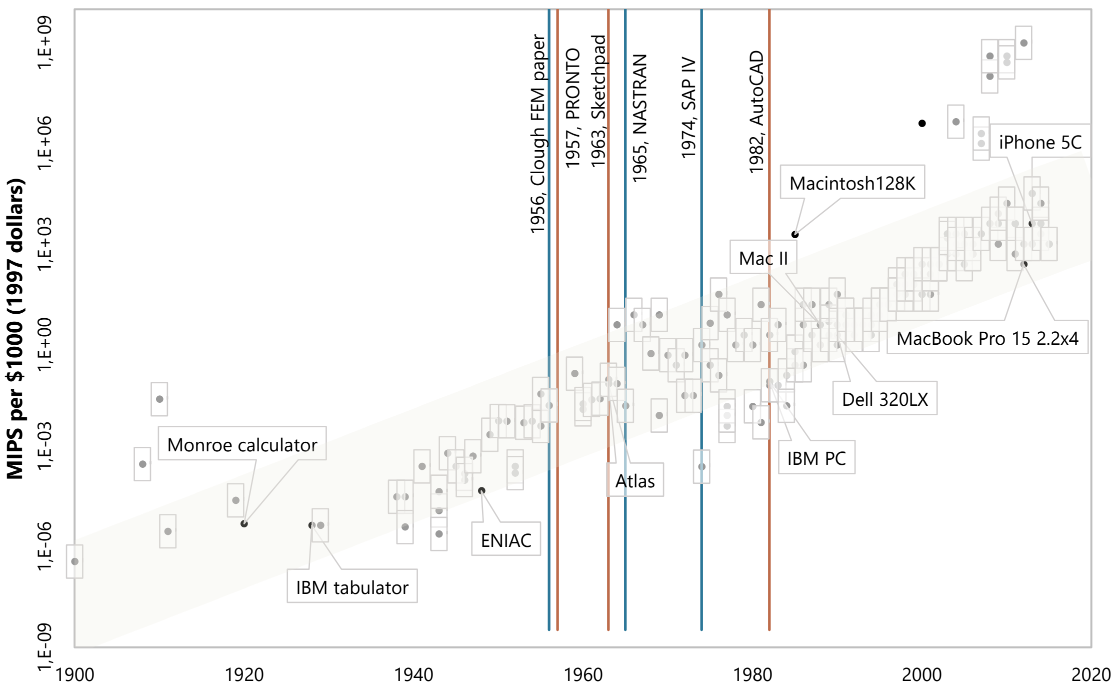


Figure 3. Evolution of MIPS (million instructions per second) per cost of computers, and milestones in the initial development of CAD and FEA

Source: Adapted from Boechat and Corrêa (2021)

The increasing availability of digital tools contributed to enabling complex engineering at a much faster pace. Nowadays, most structural engineering offices use FEA and 2D CAD, 3D CAD, or BIM software to develop projects.

Regarding structural analysis, this culminated in the possibility of investigating various load combinations and geometries for a given project, frequently using parametric design. Thus, engineers have access to large amounts of data, generated during the design and analysis of options. Joyce et al. (2019) named this as "big-design-data". In general, this data does not have the same collecting speed as conventional big data. Furthermore, it is not passively collected. Nevertheless, it presents the same issues of complex relationships and high volumes. Structural engineers interviewed during the development of this thesis reported that depending on geometry, load combinations, and model assumptions, the databases reach from 1GB to 10GB per model version.

Regarding design documentation, the advent and popularization of BIM have expanded the opportunities for improving performance in the entire construction industry. BIM is defined by the AIA (American Institute of Architects) as a representation of a building and everything about it, from initial studies and conceptual projects to design, documentation, and maintenance decision-making (AIA, *apud* SANTOS, 2017). According to the institution's definition, with the use of software from multiple platforms, the BIM database could be accessed at any time by project stakeholders, including the structural engineer. In fact, BIM is not merely a software evolution - but a procedural advance with a focus on design information and data consistency.

Vilutiene et al. (2019) report a growing academic interest in the use of BIM for structural engineering, which was found through a bibliometric study combining both themes and realized employing searches in the Scopus database (Figure 4).

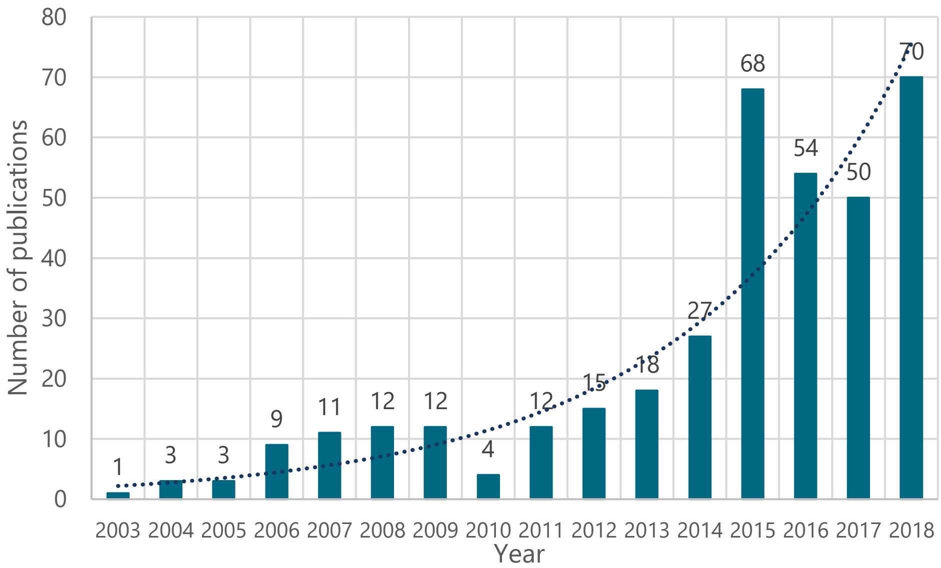


Figure 4 – Variation in the number of publications relating to structural engineering and BIM between 2003-2018

Source: Adapted from Vilutiene et al. (2019)

Studies about the future of the construction industry point to the integration of technologies in BIM platforms as the centerpiece of an imminent digital transformation in the sector, which would tackle the issue of its historic low productivity (GERBERT et al., 2016). In the context of structural projects, it is suggested that the adoption of BIM can significantly increase the productivity of design teams.

Indeed, according to Sacks and Barak (2008), a decrease of 15% to 41% in the total time required for the design of a regular reinforced concrete building project is expected with the use of BIM only thanks to the improvement in documentation.

The advantages when using BIM methodology are not limited to documentation. Specialists point out that the "potential for BIM in the structural profession has not reached its pinnacle" (SOLNOSKY, 2016, p. 4). In fact, it is repeatedly mentioned in the literature that the main component of the acronym "BIM" is information. It is exactly a paradigm shift towards information-based design that is required to enhance collaboration in structural engineering and adapt the teams to design at an unparalleled velocity (CHOK; DONOFRIO, 2010).

BIM could be the catalyst of this paradigm shift. It is also important to consider the opportunities that it offers for information management in design and construction. BIM models apply object-oriented programming principles, promoting the combination of construction data in an information model in a way that could be very useful for data science.

In this context, as presented in Boechat and Corrêa (2021), BIM models are suggested as an input source to a data warehouse, "which would be the basis for applying data science to the construction industry – comprising data visualization, statistics, machine learning, and data mining". Similar approaches are also suggested in Delatorre and Santos (2017) and Siddiqui (2018).

The idea is that an extract-transform-load (ETL) process be performed to use BIM data in a target data warehouse. The stored data could be used for generating insights and improving collaboration and productivity in engineering. The process is illustrated in Figure 5. It can initially be applied to a single project, but the target should be to apply it to all projects of a given company and constitute an intelligence database.

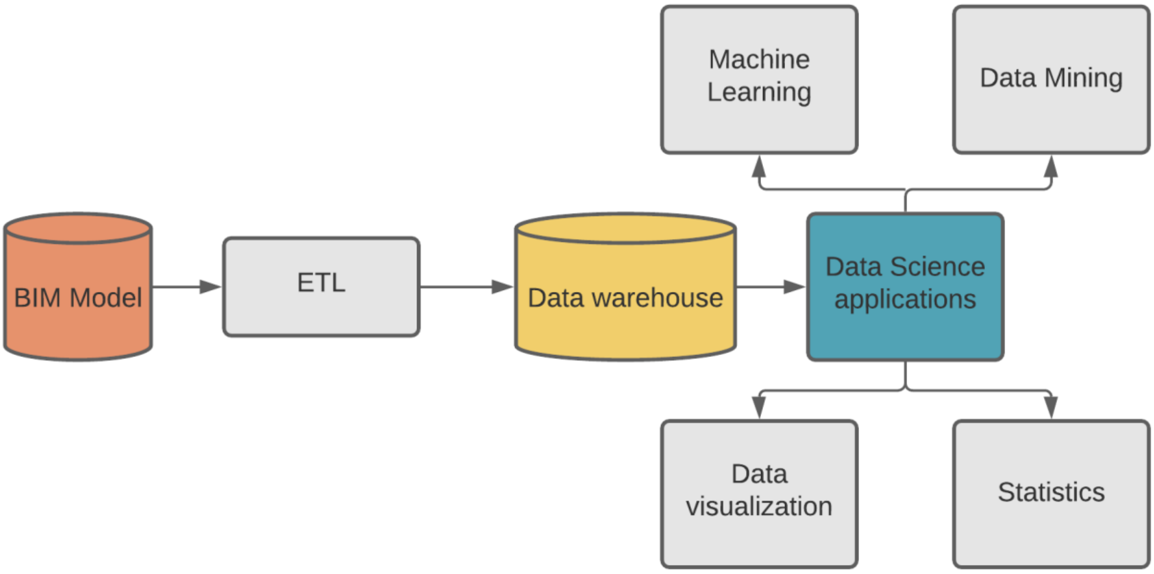


Figure 5 – Use of BIM database for data science applications

Source: Adapted from Siddiqui (2018)

1.2. Objective

The previous section suggests an opportunity to explore BIM for information management in the area of structural engineering. In this context, this research investigates how data visualization can be used to enhance workflows for structural design in BIM, i.e. proposing what is named an “augmented BIM workflow for structural engineering through data visualization". The focus of the enhancement in this thesis is on the structural design team's internal collaboration.

A tool that enables this augmented workflow, combining data from BIM and FEA models, is proposed, aiming to assist the design and collaboration between the actors of each project. The decisions taken for the proposal of a useful tool are derived from a literature review and qualitative interviews with potential users.

This tool is implemented at a proof of concept level, to demonstrate its feasibility and collect feedback about its possible contributions to the collaboration process in structural engineering.

A summary of these research objectives is described in Table 1.

Objective	Type	Description
1	General	Improve collaboration within the structural design team by strengthening the use of BIM model data, via an augmented BIM workflow
2	Specific	Propose a tool that enables the augmented BIM workflow through data visualization for structural engineering
3	Specific	Implement this tool at a PoC level and validate its usefulness with potential users

Table 1: Summary of the research objectives

1.3. Methodology

The research will adopt the Design Science Research (DSR) methodology, which, according to the description in Dresch et al. (2015), has a perspective aimed at prescribing, and consequently, generating practical design knowledge. The adoption of this method is particularly suitable since the research aims to test a proposal within an existing context of structural engineering; it has a high prescriptive character and seeks to change the current situation of the design and collaboration workflow in structural engineering to achieve better results.

The focus is on the construction of an artifact, in this case, an instantiation, defined as the execution of a method (or set of logical steps necessary for the realization of a given activity) in its real environment, showing its feasibility and effectiveness. In this case, the artifact is exactly the tool at a PoC level listed among the objectives in Section 1.2.

In this way, the DSR is consistent with the suggested research theme and goals. This methodological framework allows the research to be supported as scientifically valid with a rigorous and suitable methodological approach. The standard steps for conducting the DSR are listed in Figure 6, with arrows representing common iterations between the steps, which sometimes feed back each other.

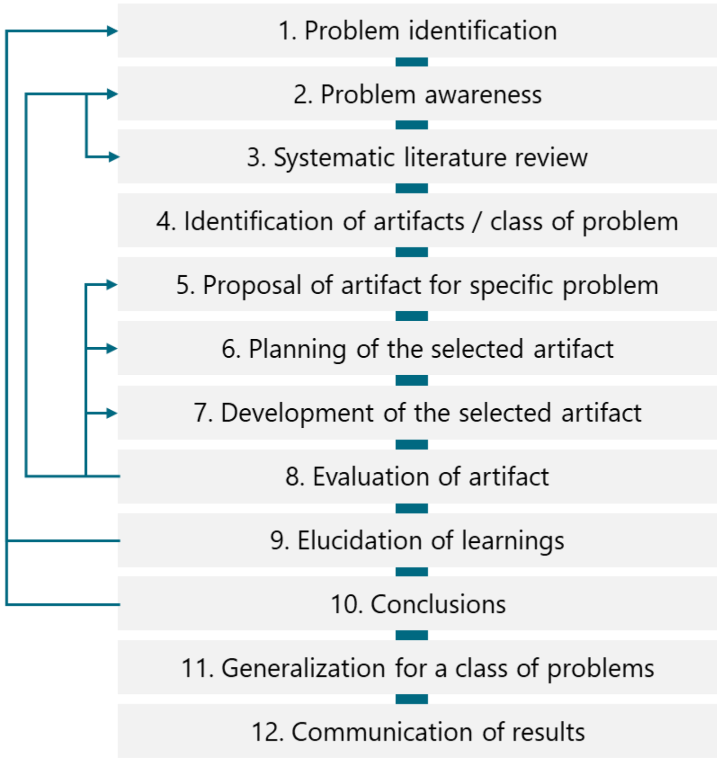


Figure 6 – Steps of the Design Science Research

Source: Adapted from Dresch et al. (2015 apud Dresch et al., 2019)

In this research, these steps were conducted based on the reality of a medium-sized structural engineering office. This was captured through qualitative interviews with the design team. The interviewees chosen were professionals of different specialties and hierarchy levels in this office. The author of this thesis is also an engineer, with a total professional experience in structural engineering of 5.5 years, including experience in this office, in similar structural engineering contexts, and some BIM projects.

The steps of the DSR in this case involved specifically the following actions:

- Steps 1 and 2: Four other structural engineers who have worked in BIM projects and BIM experts were consulted. Their inputs were collected through semi-structured interviews. The "Problem awareness" step also included participation in academic and technical events, such as the SBTIC (*Simpósio Brasileiro de Tecnologia de Informação e Comunicação na Construção*) 2019 and the Festival of BIM and Digital Construction 2020;

- Step 3: The systematic review of the literature was performed by searching the main topics of this thesis – “BIM”, “data visualization” and “structural engineering” – in the Web of Science and Scopus databases, as described in the Literature Review chapter;
- Steps 4 and 5: Further interviews with those BIM experts and structural engineers who have worked in BIM projects were used for the identification of artifacts for this class of problems and proposition of artifacts for the specific problem. Beyond that, the mapping of a typical structural design workflow in BIM in a medium-sized structural engineering office was executed. At last, one proposal of an augmented BIM workflow for a specific project was implemented and presented in the ICCCBE/W78 Virtual Joint Conference (BOECHAT; CORRÊA, 2021);
- Steps 6 and 7: For the planning and development of the artifact, this test workflow was generalized, aiming to suit a larger number of projects. This generalization resulted in a tool implemented at a proof of concept level. For that, tests with models from five different projects at different implementation phases were done;
- Step 8: The evaluation of the proposed workflow was done through tests in projects and presentation of intermediate and final results to ten professionals, including project engineers, project managers, and BIM specialists. Among those, three had been consulted in the first phases of interviews;
- Steps 9-12: These steps are done mostly via this document, with possibly more specific articles being produced in the near future and shared with the academic community.

In the description of some of the previously cited steps in the following chapters, consideration is given about execution times of codes. For reference, the computer used for the PoC implementation has the following capabilities:

- Processor: Intel® Core™ i5-6300U CPU @ 2.40GHz 2.50GHz;
- Installed Memory (RAM): 16.0 GB;
- System type: 64-bit Operating system, x64-based processor.

1.4. Considerations about the specific structural engineering perspective

As with most industries, the reality of the design and construction industry differs between locations, niches, and types of projects.

One important aspect of the context of this thesis regards the state of BIM implementation. In Brazil, a survey reported that in 2018, only 9.2% of contractors adopted BIM, and almost double of that, 17.6% could not even confirm whether they adopted or not, which shows a relevant lack of awareness about the BIM methodology in general (CASTELO; BEZERRA, 2018). In the same year, the UK National BIM Report informed that 74% of respondents were aware of and using BIM, while only 1% of them were unaware of BIM (NBS, 2018).

There are some sampling differences between these surveys (the latter includes contractors and design firms, while the first is limited to contractors). However, this would unlikely explain entirely such a relevant difference in the adoption rates. In fact, the UK has had a BIM mandate for all public projects since 2016. From the time when this was announced, in 2011, the British have seen rapidly increasing adoption rates. In Brazil, a gradual mandate started to be implemented in 2021, but only for some public agencies and with a rollout extending until 2028 (BRASIL, 2020).

The augmented BIM workflow proposed in this thesis was based on the context of an international office, which has around 200 employees divided in different locations across the globe. In this way, its work reality is closer to the UK market than to the Brazilian one. The BIM implementation at the office in question started in 2014. Currently, a considerable part of its engineers has worked on projects that use BIM methodology, and the major projects that the office works on are typically BIM projects.

In terms of niche, the focus of work of this office is on innovative structures, such as large span roofs, lightweight bridges, and gridshells. These projects often involve the use of parametric design, especially in the first project phases. Occasionally, more standard building projects are also done. In this context, it is also worth considering some specificities about how the collaboration between architects and structural engineers is handled at the office.

There is a dominant perception (and practice) in the construction industry that the division of labor between these disciplines is an architect-led process with engineers and other experts providing punctual disciplinary expertise along the way. However, as compiled in the book "Collaboration in Architecture and Engineering" by Olsen and Mac Namara (2014), some companies approach the architect-engineer relationship differently, with particularly well-integrated and successful collaborations, leading to greater innovation and boundary-pushing proposals. Those are called by the authors "symbiotic collaborations", and are exemplified in the book by a variety of cases of world-class projects, such as iconic museums, airports, and stadiums.

The interviews that Olsen and Mac Namara conducted with design teams of those projects highlight that symbiotic collaborations often rely on the fact that the engineer works with the architect from the concept phase, actually giving input on the typology of the solution to be designed. This symbiotic collaboration is the dominant project approach in the office whose workflows based the work in this thesis.

In terms of type, concluded BIM projects of this office may be divided into stadiums, buildings, special projects (such as gridshells), and bridges. The tool implemented in this thesis was conceived mostly for the three first types of projects, in which a larger team in the office is involved. Furthermore, most of those projects are in steel, and concrete design has not been specifically investigated in the context of this work.

Further considerations on the specificities of the structural engineering context explored and how it may have steered the development of the present PoC for an "Augmented BIM workflow for structural design through data visualization" are given in the chapter of Discussions.

To keep the confidentiality of the projects, all project data showed in dashboards and figures has been modified to not be identifiable. They are only shown for illustration of the workflow steps. No specific company knowledge is shared in this thesis and comments made and described processes are only the typical ones that are common among offices that work with this same kind of project.

1.5. Structure of the text

This work is structured in seven chapters following a logical development of reasoning.

The first chapter, "Introduction", contextualizes and justifies the importance of the work, highlighting the objectives and describing the problem to be analyzed. It explains the methodology adopted, namely the Design Science Research, and details the reasons why this method was chosen.

The second chapter, "Literature review", is dedicated to the assessment of related academic research. It is divided into two parts: "Main concepts", which defines the three main topics of this work, and "Systematic literature review", which groups by theme the main findings in the scientific databases.

The third chapter, "Typical BIM workflow in a medium-sized structural engineering office", presents the typical workflow based on interviews with the design team.

The fourth chapter, "Proposed data visualization workflow and tool", describes the augmented workflow. It is divided into three parts: workflow proposal, specific objectives of the implementation, and the description of the proposal and PoC as executed.

The fifth chapter, "Results", compiles feedback from team members based on initial dashboards and shows the final refined dashboards.

The sixth chapter, “Discussion”, is dedicated to the analysis of the results in practice. It lists the strengths, problems, and challenges found during the implementation process and discusses possible origins.

The seventh and last chapter, “Conclusion”, outlines a commented summary of the research and proposes future work that expands it.

In Appendix A, B, and C, detailed information on the PoC implementation is given.

2. LITERATURE REVIEW

This chapter reviews the synergy between the main topics of this thesis – "BIM", "structural engineering" and "data visualization" – as documented in the scientific and professional literature. As specialists with different specific backgrounds may read this research, the definition of each of these topics is given in a brief introduction. After the introduction, a systematic review of the literature is presented. This part is subdivided according to the selected relevant themes.

2.1. Main concepts

2.1.1. Building Information Modeling (BIM)

There are many accepted definitions of the acronym BIM. It is common to find definitions giving more emphasis in BIM as "Building Information Model", a product. Others define it as "Building Information Modeling", a methodology. Some examples of definitions from relevant institutions and research groups are given below.

According to the BIM Dictionary (2019)

> Building Information Modeling (BIM) is a set of technologies, processes, and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in a virtual space. As a term, BIM has grown tremendously over the years and is now the "current expression of digital innovation" across the construction industry.

According to the National BIM Standard-United States® (NBIMS-US, 2015, p. 1)

> a BIM is a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward.

According to the National Building Specification (NBS, 2016), from the United Kingdom (UK)

> BIM or Building Information Modeling is a process for creating and managing information on a construction project across the project lifecycle. One of the key outputs of this process is the Building Information Model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project. Creating a digital Building Information Model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset.

In this thesis, the term "BIM" is used when emphasizing the methodology – based on three main aspects common to all definitions: technology, processes, and people. To avoid confusion, when referencing the "BIM" product the term "BIM model" is used. This is used similarly to the term "BIModel", defined in the BIM Dictionary (2019), to describe more explicitly the object-based, data-rich, 3D digital model. In this thesis, the BIM model references mostly to the structural BIM model, as this is the object of study of the proposed tool.

2.1.2. Structural engineering and Finite Element Analysis (FEA)

Structural engineering is defined as an engineering discipline whose professionals, the structural engineers, design, assess, and inspect structures to ensure they are efficient and stable, as per the Design Buildings Wiki (2021), a dictionary maintained by several UK institutions. The term structure, by its turn, refers to any body of connected parts that is designed to bear loads, even if it is not intended to be occupied by people.

The main worldwide institution that congregates structural engineers is the IABSE - International Association for Bridge and Structural Engineering. It has over 10,000 associates. According to their website, "IABSE is a scientific/technical Association established in 1929 in Zurich, with members in 90 countries and 56 National Groups worldwide dealing with all aspects of structural engineering". They state that their mission is to “exchange knowledge to advance the practice of structural engineering in the service of the profession and society” (IABSE, 2021).

Additionally, there are some country-specific institutions with international relevance - such as the SEI (Structural Engineers Institution) and the ASCE (American Society of Civil Engineers), from the United States (US); and the Istructe, from the UK - whose publications are used as a source of information for many topics covered in this thesis.

For accomplishing their work, structural engineers may use many different calculation methods, but one of the most common is the FEM. Fish and Belytschko (2007) define FEM as a numerical approach for solving partial differential equations that describe many physical phenomena in engineering and science. In structural engineering, FEM is applied through FEA, generally via commercial software. In this thesis, the term “FEM” will be used when referring to the numerical method for calculation structures and “FEA” will refer to the software and models in which FEM is applied.

2.1.3. Data visualization

The definition of “data visualization” used in this thesis is the graphic representation of quantitative information.

Although data visualization is frequently associated with computation, its roots go back to the earliest map-making, as described in the historical review in Friendly (2006). The development of technologies such as printing and later digital communication simply enabled wider use of graphics, as well as advances in form and content.

One of the areas in which data visualization is commonly used nowadays is business intelligence. Gartner, a world-class consulting firm, releases yearly a report known as the “Magic quadrant”, in which it analyzes market trends, and classifies analytics and business intelligence platforms as “leaders”, “challengers”, “niche players” and “visionaries”. Those platforms support a full analytic workflow, from data preparation to visual exploration and insight generation. Data visualization is one of the 15 capability areas analyzed for this classification. According to the 2020 report, it is no longer a differential capability among the platforms, at least for most common business intelligence use, with visualization options that go beyond the most traditional ones (pie, bar, and line charts), such as heat and tree maps, geographic maps, and other special visuals being generally available (GARTNER, 2020). Figure 7 shows that for 2020, according to this analysis, the most relevant leaders are Microsoft (with Power BI) and Tableau.

Figure 7: Magic Quadrant for analytics and business intelligence platforms

Source: Gartner (2020)

The definition of "data visualization" in the website of those two main platforms is similar to the one used in this thesis, as specified at the beginning of this section.

According to the Power BI website (MICROSOFT, 2021), "data visualization helps you turn all that granular data into easily understood, visually compelling—and useful—business information".

According to the Tableau website (TABLEAU, 2021), "data visualization is the graphical representation of information and data. By using visual elements like charts, graphs, and maps, data visualization tools provide an accessible way to see and understand trends, outliers, and patterns in data."

Beyond understanding the definition of data visualization, it is also important to recognize the type of visualization compatible with the data available. There are many examples in the professional and academic literature to base the choice of visuals.

Holtz and Healy (2018), propose a set of decision trees, organized according to the following data types: numeric, categoric, numeric and categoric combined, maps, networks, and time series. Graphs possibilities are specified depending on the number of variables and the relation between them (whether they are independent, nested, a subgroup of the other, adjacent, etc.). The possible graphs suggested via this map are:

- Distribution graphs: violin plots, density plots, histograms, box plots, and ridgelines;
- Correlation graphs: scatter, heat maps, correlogram, bubble charts, connected scatted, 2D density plot;
- Ranking graphs: bar plots, spider/radar; word cloud; parallel; lollipop; circular bar plot;
- Part of a whole graph: tree map, Venn diagram, doughnut, pie chart, dendrogram, circular packing, sunburst;
- Evolution graphs: line plot, area, stacked are, stream chart;
- Map graphs: general map, choropleth, hexbin map, cartogram, connection map, bubble map.
- Flow graphs: chord diagram, network, Sankey diagram, arc diagram, and edge bundling.

An illustrative icon of some of those graphs is presented in Figure 8.

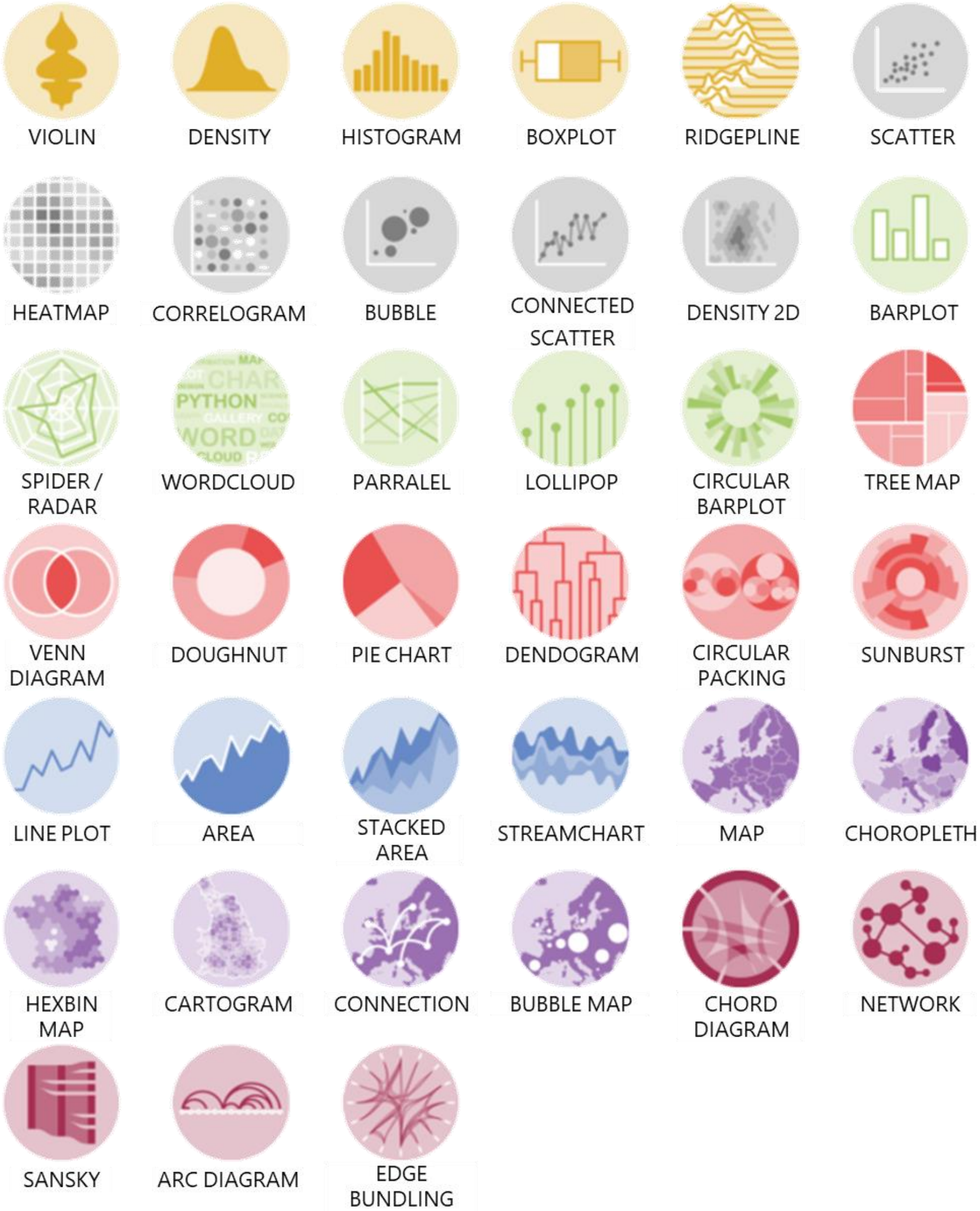


Figure 8: Examples of charts (non-exhaustive)

Source: Adapted from Holtz and Healy (2018)

2.2. Systematic literature review

A systematic review of the literature has been carried out by consulting the Web of Science and Scopus databases. The exact search strings adopted were:

- ("structural engineering" OR "structural engineer") AND "BIM"

- ("data visualization" OR "data-visualization" OR "data visualisation" OR "data-visualisation") AND "BIM"
- ("data visualization" OR "data-visualization" OR "data visualisation" OR "data-visualisation") AND ("structural engineer" OR "structural engineering")

The topics were searched in this arrangement since there is not yet a relevant number of articles on the three themes together. Additionally, professional sources such as websites of well-known companies that work in the structural engineering / BIM fields have been consulted.

This query returned 405 articles. They were filtered to avoid repetition and the articles that were not in English were removed. This resulted in 363 articles.

Then, via content analysis of abstracts and of the text itself, six relevant themes, presented in a total of 37 articles, were selected to compose this literature review:

1. Presentation of bibliometric analyses relating at least two of the three main topics of this thesis;
2. Overview of the relationship between information technology and structural engineering over the past decades;
3. Overview of BIM implementation for structural engineering, comprising advantages and disadvantages;
4. Diagnosis or proposals for BIM workflows for structural engineering;
5. Proposals or applications of data visualization for structural engineering;
6. Proposals or applications of the use of BIM models as a database.

The theme and article selection were iterative processes. The final themes were chosen since they provide relevant context information (topics 1, 2, and 3) and practical ideas (topics 4, 5, and 6) for the PoC of the augmented BIM workflow. The whole process is illustrated in Figure 9.

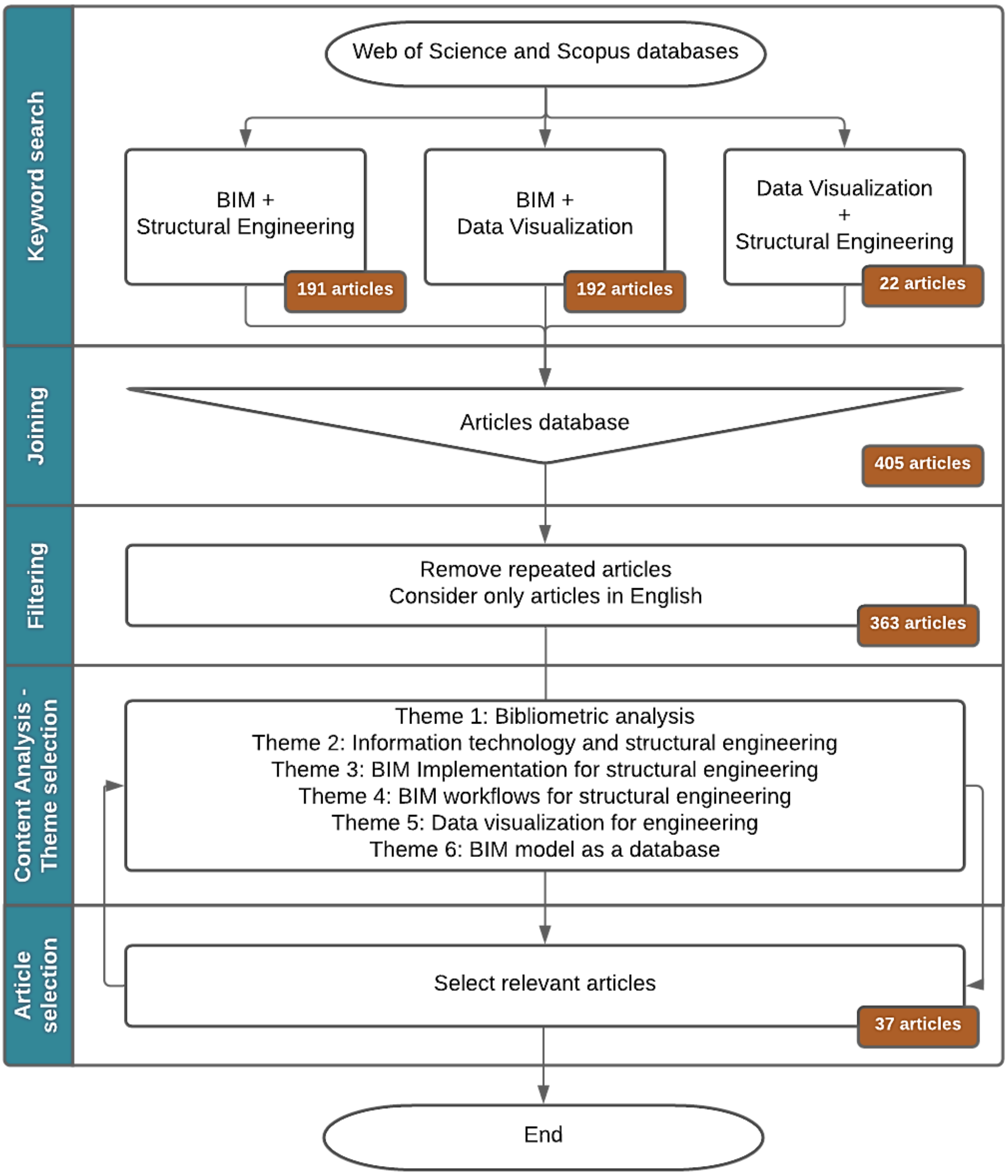


Figure 9: Systematic literature review

2.2.1. Bibliometric analyses

Although several bibliometric reviews of BIM are available since 2015, the first one relating BIM and structural engineering retrieved in this literature review was published only in 2019. This first review, by Vilutiene et al. (2019), covers 369 papers published between 2003 and 2018. The search was done in the Scopus database and the full filtering procedure is described in the referenced paper. The result shows a significant increase in the number of publications on BIM for structural engineering from 2014 onwards, which was shown in Figure 4, in the Introduction of this thesis.

This sudden increase has two years of delay compared to general BIM research, as argued by Santos et al. (2017). However, the number of studies on structural engineering and BIM is considered still low. According to Hosseini et al. (2018), less than 20% of studies on BIM referred to structural engineering applications. This reinforces other claims about the lack of attention paid to structural engineering in the BIM literature (SHOU et al. 2015; FANNING et al. 2015).

The work by Hamidavi et al. (2020) corroborates this claim. It presents a bibliometric study connecting “BIM”, “structural design” and “automation”, through a Scopus database search. The authors highlighted that automation in structural design is a fairly researched topic, with 2165 articles. However, only 787 resulted when “BIM” was included in the search topic list. By applying the filtering criteria specified in their publication, Hamidavi et al. (2020) selected 93 relevant articles. When analyzing those results over the years, the study also reveals a recent increase in the number of publications, as per Figure 10.

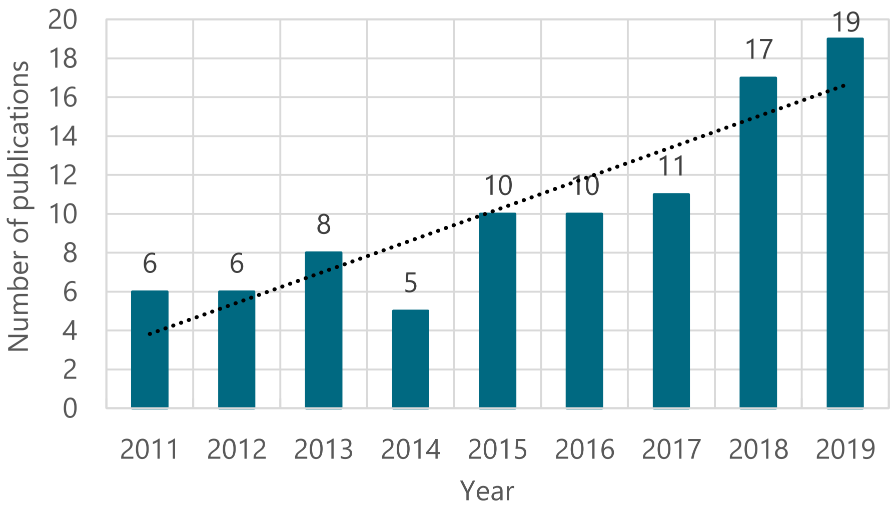


Figure 10: Number of publications associating BIM, structural engineering, and automation

Source: Adapted from Hamidavi et al. (2020)

Both Hamidavi et al. (2020) and Vilutiene et al. (2019) analyzed the themes of their selected publications. The first found more traditional generic themes, such as "structural design" and "information theory", using a keyword frequency study with VOSViewer, as shown in Figure 11.

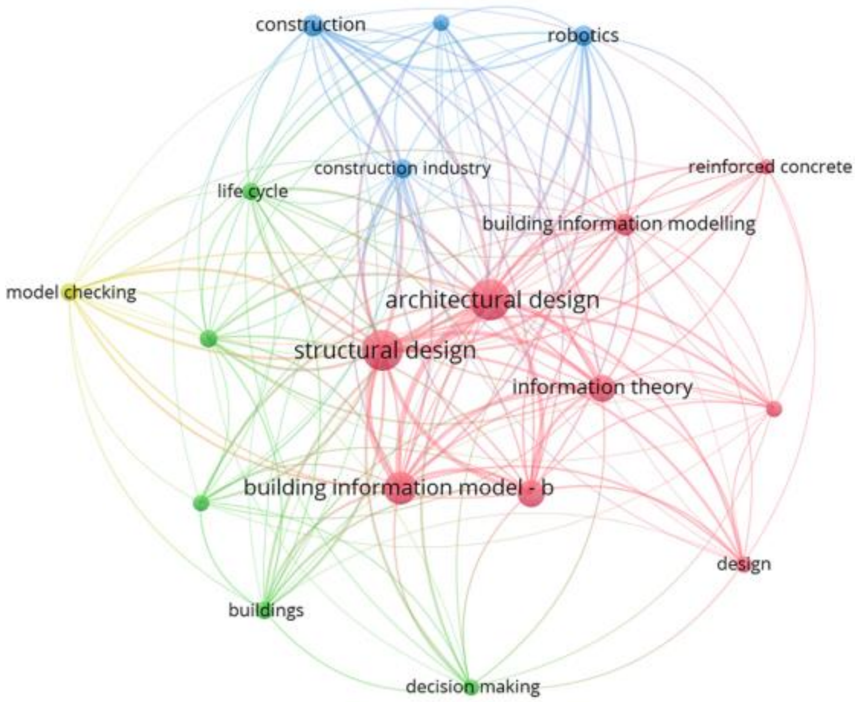


Figure 11: Keyword clustering

Source: Hamidavi et al. (2020)

Vilutiene et al. (2019) examined the evolution of the themes from their selected articles. According to the authors, research has started with fundamental concepts like parametric design, computer simulations, and analysis of data structures, followed by a focus on information management, interoperability, and collaboration in construction projects. More recently, topics such as automation, big data analyses, decision-making, and the development of knowledge management systems have been more in vogue (OLAWUMI, CHAN 2019). Figure 12 illustrates the resultant keyword map using various colors to show the chronological order of items. The yellow bubbles display these more recent topics (e.g. "automation", "data handling" and "decision making").

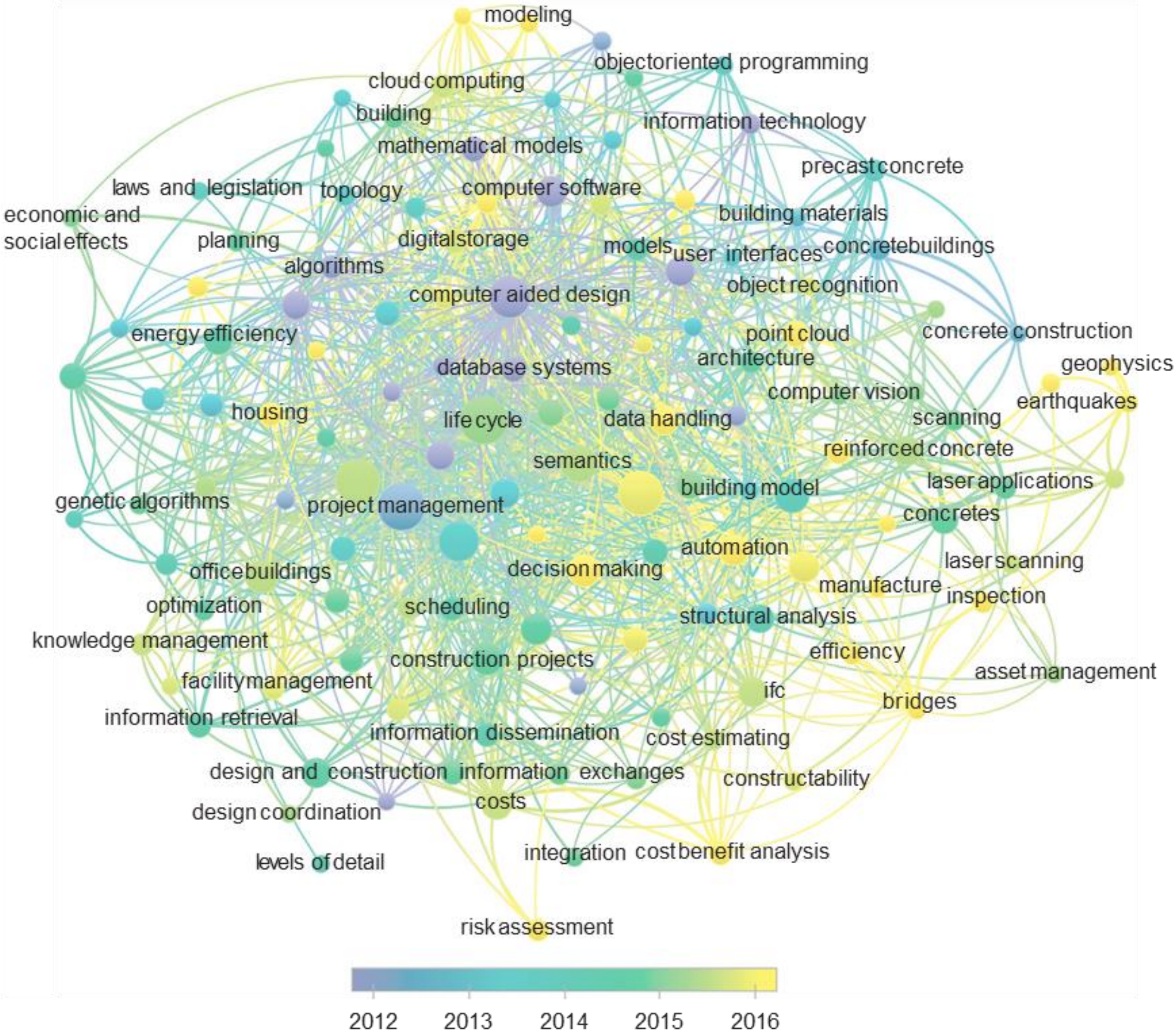


Figure 12: Concurrence map of keywords according to years

Source: Adapted from Vilutiene et al. (2019)

Hamidavi et al. (2020) also conducted a survey with 105 professionals; 83% of those were structural engineers. Besides "automation", "interoperability" and "design optimization" were frequently mentioned by the respondents as areas that require improvements in the relation between BIM and structural engineering. A summary of the reported challenges is given in Figure 13.

Figure 13: Reported challenges in the relation between BIM and structural engineering

Source: Hamidavi et al. (2020)

The findings by Vilutiene et al. (2019) and Hamidavi et al. (2020) demonstrate that the body of knowledge on the integration of BIM with structural engineering is in its infancy. Other authors point out that a coherent strategy or vision is absent for the integration of BIM into the structural engineering domain, and as a result, further research on this area is much needed (HOSSEINI et al., 2018; BARTLEY, 2017; FANNING et al., 2015).

The proposal of the augmented BIM workflow through data visualization has a strong relationship with the decision-making topic, presented as a relevant recent area of research by Vilutiene et al. (2019). In fact, the workflow could be an enabler to a better-informed decision-making process in structural engineering.

Additionally, as the tool that implements the augmented BIM workflow intends to congregate data from both FEA and BIM models, interoperability, presented by Hamidavi et al. (2020) as an important challenge to be overcome, is also a topic addressed by this thesis.

2.2.2. Relation between information technology and structural engineering

The structural engineering community is widely recognized as being an early adopter of computational technology for the construction industry. From a historical perspective, the reduction of computer power cost was crucial for establishing this close relation between technology and structural engineering, as was highlighted in Figure 3, in the Introduction of this thesis.

2.2.2.1. Structural analysis

Generally, structural engineers formulate a structure according to the response from simulations, following design constraints and code requirements. These simulations and checks can take many forms, from hand calculations to complex computer formulations, such as FEM.

Computational capabilities have been intensively enhanced in structural engineering since analysis and design adopted computers (CARPENTER, 2005). This increased the limits to the size of models that can be solved in a daily process.

On the other hand, structural simulations methods have changed less. Many methods from decades ago are still valid and useful. Solnosky (2016) conducted a study in which one of the investigated topics was the calculation methods used in structural engineering for structural analysis. The survey used phone and in-person interviews with structural professionals, as well as by an e-mailed survey. There were 68 respondents, with an average of 14 years of experience in structural engineering and 5.7 years in BIM. Table 2 summarizes the calculation methods cited in the survey.

Method class	Method subclass	Specific types
Early	N/A	Prescriptive measures
		Rules of thumb
		Approximate methods
		Engineering's judgment
		Decision rule sets
		Parametric studies
		Generative studies
Traditional	Analysis methods	Linear
		Non-linear
		Static
		Dynamic
	Design methods	Performance-based design
		Stress design
		Strength design
		Limit design
		Limit state design
		Plastic design

Table 2: Common analytical method classes

Source: Adapted from Solnosky (2016)

It is clear that early methods, such as rules-of-thumb, still coexist with non-linear analysis. Structural engineers have a large toolbox of analysis and design techniques. The type of analysis chosen may vary according to the type of project. According to that survey, while linear static analysis is the most common type for low-rise commercial office buildings, when it comes to stadiums structure, for instance, it becomes as common as sophisticated higher-order FEA.

Parametric and generative studies also appeared in Table 2. Although presented as early methods, the use of computation made it a lot more common recently. In essence, parametric design generates many alternative solutions that need to be narrowed either by automation or by hand. Often the purpose for doing these generative studies is to provide a broader viewpoint that can be used to determine what is best for a project.

The use of higher-order FEA and parametric or generative studies contribute to instituting the “big-design-data”, as previously described in this thesis.

2.2.2.2. Errors in analysis

A discussion topic that often appears in the structural engineering community is the relation between the use of software and the risk of errors. There is a misguidedly spread idea that structural engineering is nowadays only a matter of “pressing a button”.

In fact, there are different software available for FEA in the market, and software output can easily become too complex to effectively be managed. With the increased computation capabilities, there could be actually a rise in the number of errors that can be introduced into the process, particularly if there is a lack of proper knowledge on the process of modeling.

There is a balance between increasing productivity by using tools and limiting the risk of errors. For checking results, validation methods are generally used. They are typically done at project milestones defined by the project team and the discipline team. The most popular methods as compiled in Solnosky's (2016) survey are shown in Table 3, with visualization of structural behavior being the most cited.

Validation methods	Frequency of use (%)
Random spot checks	69
Static equilibrium checks	75
Comparison against industry standards and rules of thumb	75
Visualization of structural behavior (movement animations and color coding for stresses and forces)	94
Secondary verification model (different software)	63

Table 3: Validation methods used for structural engineering

Source: Adapted from Solnosky (2016)

2.2.2.3. Documentation software

In structural engineering, knowledge converges from various design and analysis models into structural drawings – and this is a process that exists whether the design team employs BIM methodology or not (HO et al., 2012).

Figure 14 shows one example of the use of object parameters in ACAD (AutoCAD) to display tags with structural member information such as camber and number of studs.

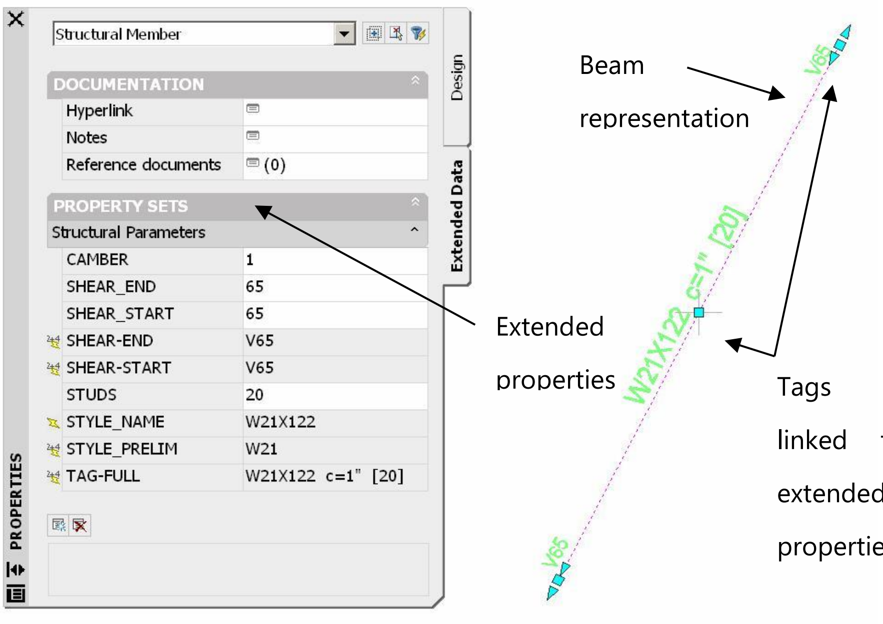


Figure 14: Using extended properties in CAD to hold structural design related data

Source: Adapted from Vilkner et al. (2007)

An important consideration is that to get this type of information to CAD, companies already had the habit of implementing custom-built tools to automate design and documentation processes. Vilkner et al. (2007, p. 5) bring the following description for the tool illustrated in Figure 14:

> Plans with steel framing were generated in CAD, but the properties to be called out on the design documents were held in various analysis models. Data included shear reactions, camber, and studs from a gravity analysis model, as well as moment reactions from a lateral analysis model. A custom interoperability tool was developed to transfer structural engineering design results from both analysis models into ACAD, using their respective APIs. The tool automatically loops through all structural member objects in the ACAD documents and identifies their counterparts in the analysis models. It then populates the extended property sets of the structural member objects in the ACAD documents. With such an automated process in place, tagging becomes a by-product, "free of charge".

Although BIM software has made the tagging process more automatic, interoperability challenges when bringing information to the documentation software still exist. Some other examples of early challenges compiled by Vilkner et al. (2007) that persist and that were found during the development of the PoC in this thesis are the variability in the names of cross-section shapes and the variability in how eccentricities of beam elements are considered. Because of inconsistencies related to that, when developing custom interoperability tools using APIs (Application Programming Interface), often more time is spent translating syntax between different software platforms than transferring actual model-specific engineering data.

In general, the review on information technology and structural engineering demonstrates that although important advances have occurred in the past decades, there is still an opportunity for improvement. Computation has enabled more complex FEA models and parametric design, which are important tools for the structural engineer. For documentation of design, BIM software has made some processes more automatic. However, current models have increased complexity and require higher attention to error prevention. Furthermore, interoperability issues still prevent seamless information integration from analysis to documentation. Visualization, which is presented in the literature as a checking method, and custom scripts are used in this thesis for achieving the augmented BIM workflow for structural design through data visualization.

2.2.3. BIM implementation for structural engineering

A publication in the "Engineering News-Record" described in 2014 results from a survey in the United States, in which 67% of the responding structural engineers stated to be using BIM, compared with 33% in 2008. Most respondents used BIM for steel structural projects. The use of BIM for cast-in-place concrete structures was also growing, with 10% of the firms reporting they used BIM for concrete. Five years before that, only a few firms reported using concrete. In this survey, more than 75% of the firms reported that their BIM training was either "horrible, nonexistent, or only moderately effective". Their deliverable was still mostly 2D drawings, in the form of pdf files, thus not based on models (POST, 2014).

In the last decade, BIM methodologies have affected both engineer's profession and research efforts. In several European countries, the adoption of BIM methodologies has become mandatory (JOURNAL, apud CIOTTA et al., 2019). Consequently, engineers that are mainly involved in public procurements for major projects had to innovate and revise their workflows, tools, and reference standards.

2.2.3.1. Advantages and challenges

Structural engineering firms often decide to implement BIM aiming at increasing their productivity. In two case studies with pre-cast concrete projects, Kaner et al. (2008) reported productivity gains from 20% to 47%. Nevertheless, as for any process change, BIM presents also several challenges. The literature review on this subject is described in this subchapter.

Table 4 summarizes the main advantages of BIM for structural engineering found in this systematic literature review.

Advantages	Cited by
Better project and team coordination	Solnosky (2013, 2016), Fink (2018), Liu et al. (2016)
Error reduction	Solnosky (2013, 2016), Fink (2018), Kaner et al. (2008), Chi et al. (2015)
Easier communication with visualization of results	Solnosky (2013, 2016), Kaner et al. (2008), Ciotta et al. (2019)
Improved quality of project documentation	Solnosky (2013, 2016), Fink (2018), Kaner et al. (2008), Chi et al. (2015)
Overall project delivery enhancement	Solnosky (2013, 2016), Kaner et al. (2008), Liu et al. (2016)
Field and on-site improvement	Solnosky (2013, 2016), Kaner et al. (2008)

Table 4: Advantages of BIM for structural engineering

Table 5 summarizes the main challenges of BIM for structural engineering found in this systematic literature review.

Challenges	Cited by
Lack of interoperability	Solnosky (2013, 2016), Kaner et al. (2008)
Cost and time for educational training	Solnosky (2013, 2016), Kaner et al. (2008) , Chi et al. (2015)
Legal and contractual issues	Solnosky (2013)
Lack of software understanding	Solnosky (2013, 2016), Kaner et al. (2008)
Need to change practices in the firm	Solnosky (2016), Kaner et al. (2008)
Changes in the design outcome	Solnosky (2016)

Table 5: Challenges of BIM for structural engineering

Since BIM requires careful planning of how a building is to be modeled, which is a level of sophistication unnecessary for CAD operation, Kaner et al. (2008) showed that productivity gains are more easily seen after a first test project, as the learning curve of BIM is quite steep at the beginning.

2.2.3.2. Future trends

According to Solnosky (2016), the potential for BIM in the structural profession has not reached its pinnacle - there is an opportunity for growth and improvement. Table 6 summarizes the main opportunities of BIM for structural engineering found in this literature review.

Opportunities	Cited by
Design authoring modeling improvement	Solnosky (2016)
Detailing/component modeling improvement	Solnosky (2016)
Construction modeling advancement (e.g. BIM as-built model generation)	Solnosky (2016)
Generic software availability	Solnosky (2016)
Analysis and Design (A&D) modeling automation	Solnosky (2016)
Use of BIM as a data model (e.g. to generate quick insight on the proposed design)	Chi et al. (2015), Ciotta et al. (2019)
Parametrized structural modeling	Chi et al. (2015)

Table 6: Opportunities of BIM for structural engineering

Additionally, Chi et al. (2015) cite as future trends innovative methods, such as: design tools combined with BIM visualization platforms generating an integrative structural design environment; novel modeling approaches, e.g. scale models using 3D printers; effective decision-making support tools based on BIM database and related visualization technologies; high-performance numerical methods for large-scale optimization problems; and strengthened cooperative works with data exchange abilities of BIM.

Lastly, Ciotta et al. (2019) previews enhanced information exchanges between BIM and FEA models utilizing open formats; integration of BIM and Internet of Things (IoT) to manage monitoring data and enable better management of structural engineering data in the operation phase; and integration of BIM and City Information Modeling (CIM) to support large scale analysis on the built environment.

2.2.3.3. People and processes

BIM is a complex type of technology. Its implementation in structural engineering firms requires leadership and persistence, as well as careful planning. Software tools alone are insufficient for successful BIM adoption. Deep changes in terms of work practices, human resources, skills, relationships with clients, and contractual arrangements are required for success (KANER et al., 2008). As also corroborated by Smith (2014), this is not a trivial task.

Harrington (2010) exemplifies that by describing the implementation at Walter P. Moore, a large civil engineering company in the United States. According to this article published a decade ago, the era of 2D CAD drafting was slowly giving way to BIM. The implementation in question had started in 2005, with the creation of a task group, comprising drafters and engineers. The author highlighted the need of developing a completely new set of standards for the new workflows, along with procedures for the dissemination of information.

Chi et al. (2015) extend on that indicating that, for successful implementation, people involved in the whole design process are required to openly embrace the innovative modeling methods, information management, tools, and applications coming with the adoptions of BIM.

Furthermore, the implementation must be aligned with the objectives, vision, and mission of the company. It needs to take advantage of available resources and generate a suitable plan. Rivera et al. (2019) complement that from the initial contact with the company, management staff must be instructed on BIM to bring people closer to the methodology and show them its potential.

This is not limited to a single organization. Construction projects are accomplished by multidisciplinary teams. Human iteration is necessary and provides lesson learning beyond each discipline-specific procedures (LONGWE et al., 2015). With the integrated interactive abilities provided by BIM, the opportunities for cooperation between different design professions, and with clients, are increased. The information on the BIM database can be shared and discussed through the Internet, ideally with cloud computing technologies facilitating access from team members (SHEN et al., 2012).

However, working behaviors are not easily changed. Ozturk (2019) administered a questionnaire survey to 256 building design professionals, including architects and structural engineers, to gather data for analyzing and the relationship between BIM implementation and individual-level collaboration between the members of the project team. The variables chosen to explain were technical skills, openness to share, engagement in each other’s work, openness to communication, and established personal relationships. This survey proves quantitatively that there is a positive relationship between individual-level collaboration and BIM implementation.

In summary, regarding implementation, productivity and quality enhancement are important advantages that are pursued in BIM for structural engineering. The idea of the augmented BIM workflow is to increase this potential. Interoperability, which was previously cited in Sections 2.2.1 and 2.2.2, also appeared as an important challenge and will be addressed specifically in the next subchapter. Regarding opportunities, the trend of focusing on a data model, raised in the review, is intensively connected with the approach used for the construction of the PoC in this thesis. Of course, no technological feature can trigger a successful implementation alone, not for BIM in general nor for the PoC in this thesis. Therefore, given the best practices for BIM implementation in the literature review, getting feedback, bringing people together for building technology, and connecting the use of technology with the workflows was part of the approach taken for developing the proposal of the augmented BIM workflow.

2.2.4. BIM workflows for structural engineering

Rivera et al. (2019) highlight that structural design must be rigorously analyzed in obedience to regulatory provisions and professional practices. This is also highlighted by other authors in this literature review: in its basic form, structural design tends to be lengthy, rigorous, and an evolving process that starts after planning and continues until fabrication starts (SOLNOSKY, 2014; CHI et al., 2015). Traditionally, structural engineering processes are organized in workflows to comply with those requirements.

In the context of BIM, these workflows must be adapted. Kaner et al. (2008) highlight that optimum BIM workflows are not an ordinary evolution from the traditional ones, built for paper drawings and CAD tools. They should enable seamless integration between disciplines, incorporating structural area information and processes into the workflow of typical projects (LIU et al., 2016; ROBINSON, 2007).

In this context, for proposing the augmented BIM workflow for structural design, it is essential to analyze traditional workflows for structural engineering and existing proposed adaptations for the BIM reality.

2.2.4.1. Traditional workflows

Solnosky (2014) proposes the division of structural design into three phases:

- Conceptualization design: feasibility stage where all acceptable system types and configurations are determined and then narrowed to the best possible ones;
- System-level design: when the gravity, lateral stability, and foundation systems options are condensed and refined through analysis until converging to a final solution;
- Component level design: a continuation of the previous design phase, with a focus on the details or components of the system.

Chi et al. (2015) propose a more complex division of structural design workflow, as shown in Figure 15.

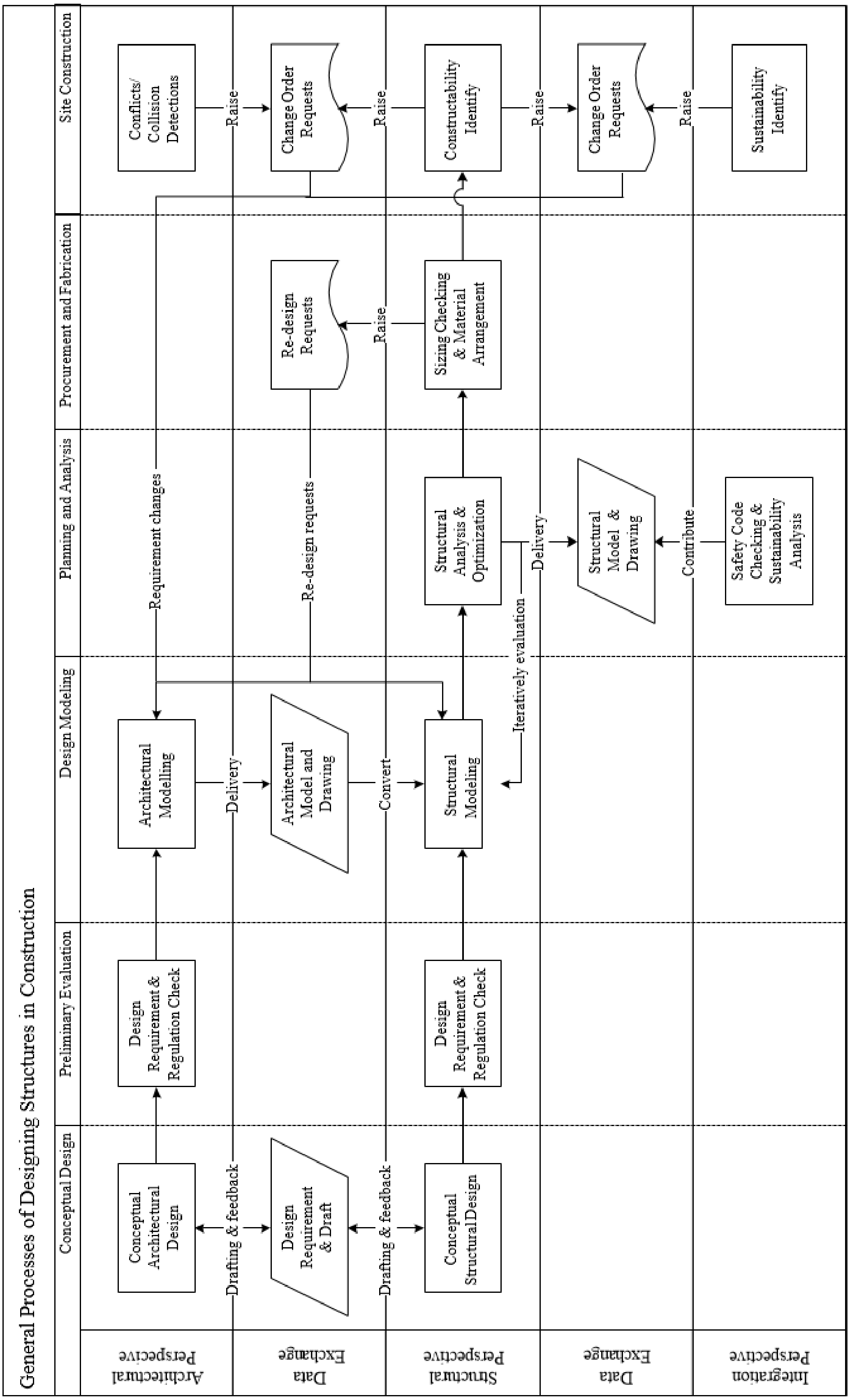


Figure 15: Cross-functional flowchart for a general structural design in construction

Source: Adapted from Chi et al. (2015)

Regarding time, the cross-functional flowchart by Chi et al. (2015) extends more in the project life cycle than the proposal by Solnosky (2014). It is divided into conceptual design, preliminary evaluation, design modeling, planning and analysis, procurement and fabrication, and site construction. In each of those phases, the processes are divided into architectural perspective, structural perspective, integration perspective, and data exchanges between them.

The process starts with conceptual formulations at architectural and structural perspectives, considering clients' design requirements, design theme, and mechanical principles. Once the ideas are proved feasible, the detailed architectural and structural modeling step starts. With this basis, analysis, optimization, and code checking are performed by the structural engineer. After an iterative process, structurally optimized models and drawings are proposed for the following procurement and fabrication steps. Even after that, the structural design plan can be required to change due to manufacturing and material arrangement concerns. During the actual construction phase, change order requests are still common, due to reasons such as conflict detection, constructability, and sustainability issues.

Chok and Donofrio's (2010) work does not specify different phases, but rather examines the collaboration in general, adding an important consideration: the traditional workflow is usually based on a responsive approach by structural engineers. The geometry is either provided by the architects or generated by the engineer from an architectural model. It is imported into FEA and the pre-processing is performed by an engineer via the graphical user interface. This is exemplified in Figure 16.

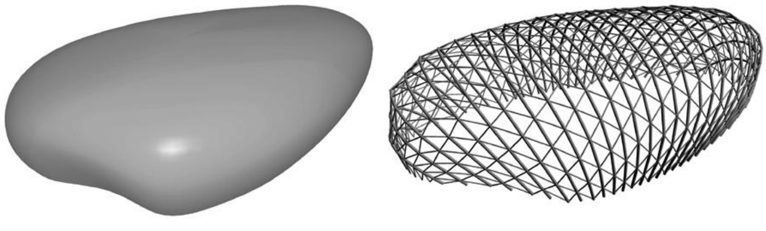


Figure 16: Architectural surface model (left), structural discretization of surface (right)

Source: Chok and Donofrio (2010)

This method, called a point-and-click method, requires all structural information (material properties, section properties, boundary conditions, loads, etc.) to be applied by the engineer at each phase. For simple geometries or models of a rather small scale, this approach is reasonable for analyzing the performance of a structural system. It begins to be problematic when multiple options are being explored and the engineer is required to model manually all the options proposed. Often the engineer finishes a preliminary analysis and design of a structural scheme and begins to communicate this scheme to the architect, only to find that the design has been changed (Figure 17).

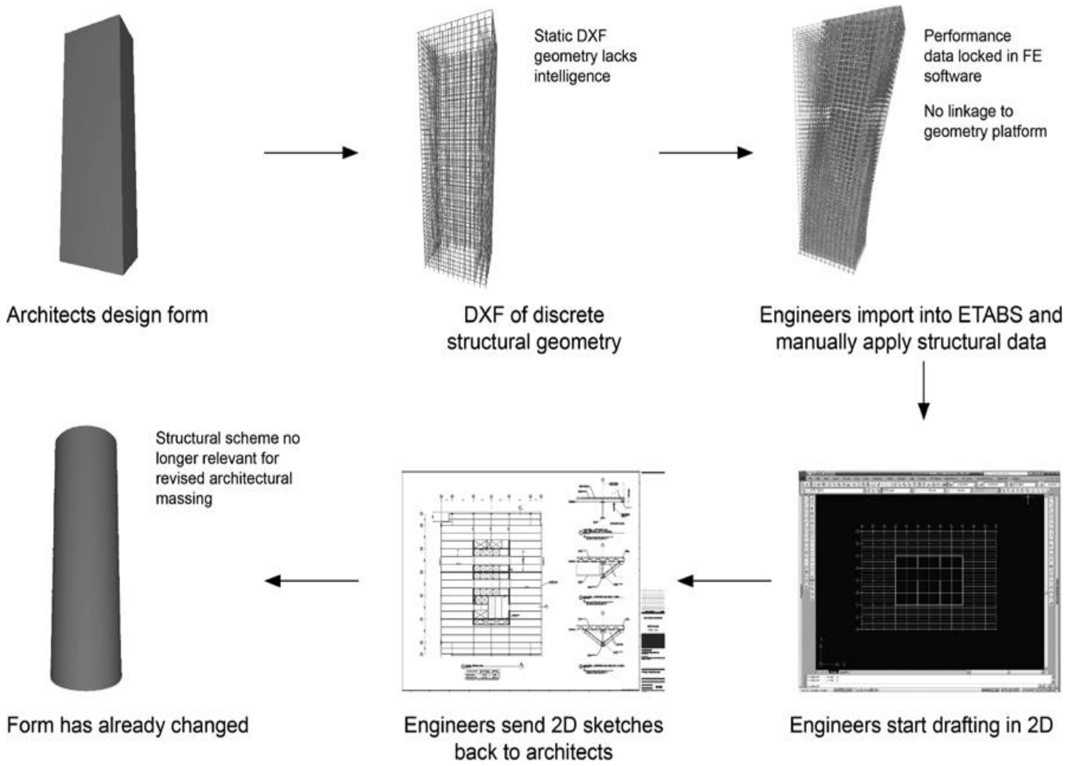


Figure 17: Traditional structural workflow

Source: Chok and Donofrio (2010)

2.2.4.2. Changes proposed in traditional workflow

Kaner et al. (2008) studied the differences between the traditional (generally using CAD) and BIM workflow for precast concrete projects. The process chart shown in Figure 18 presents the differences between CAD and BIM workflows as observed in the case studies conducted by those authors and others reported in the literature (SACKS; BARAK, 2008).

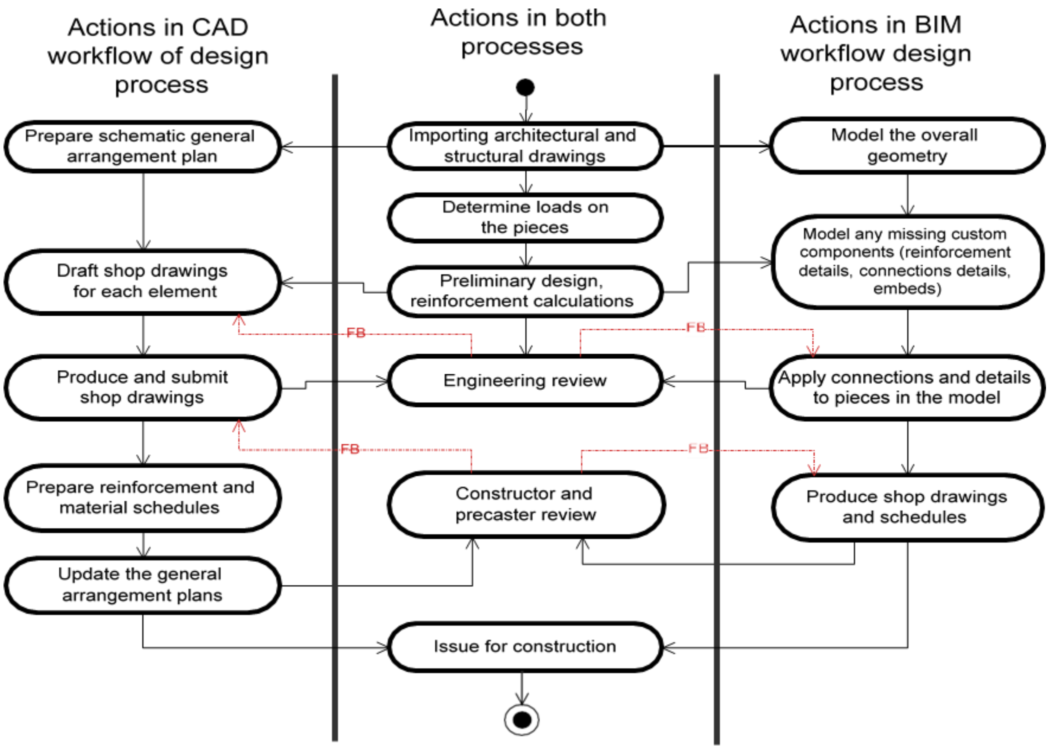


Figure 18: Comparison of CAD and BIM workflows

Source: Kaner et al. (2008)

As illustrated, the focus of the BIM workflow is placed on modeling and analysis, with drawings becoming secondary. This contrasts with CAD, where all the work must be performed on the drawings, and the building is not modeled as a whole.

Chi et al. (2015) propose a modified workflow for BIM projects in which the integration perspective is at the center of the project as shown in Figure 19. The number of interfaces considerably increases in comparison to the traditional workflow proposed by the same authors in Figure 15. This supports the claim that BIM increases the need for effective collaboration in structural design.

Rivera et al. (2019) propose the workflow for structural engineering in the context of BIM shown in Figure 20. Instead of analyzing per project phase, as Chi et al. (2019) did, this proposal details the process at each phase, even specifying what would be the responsibility of each member of the structural engineering team (project engineer, senior engineer, review engineer, etc).

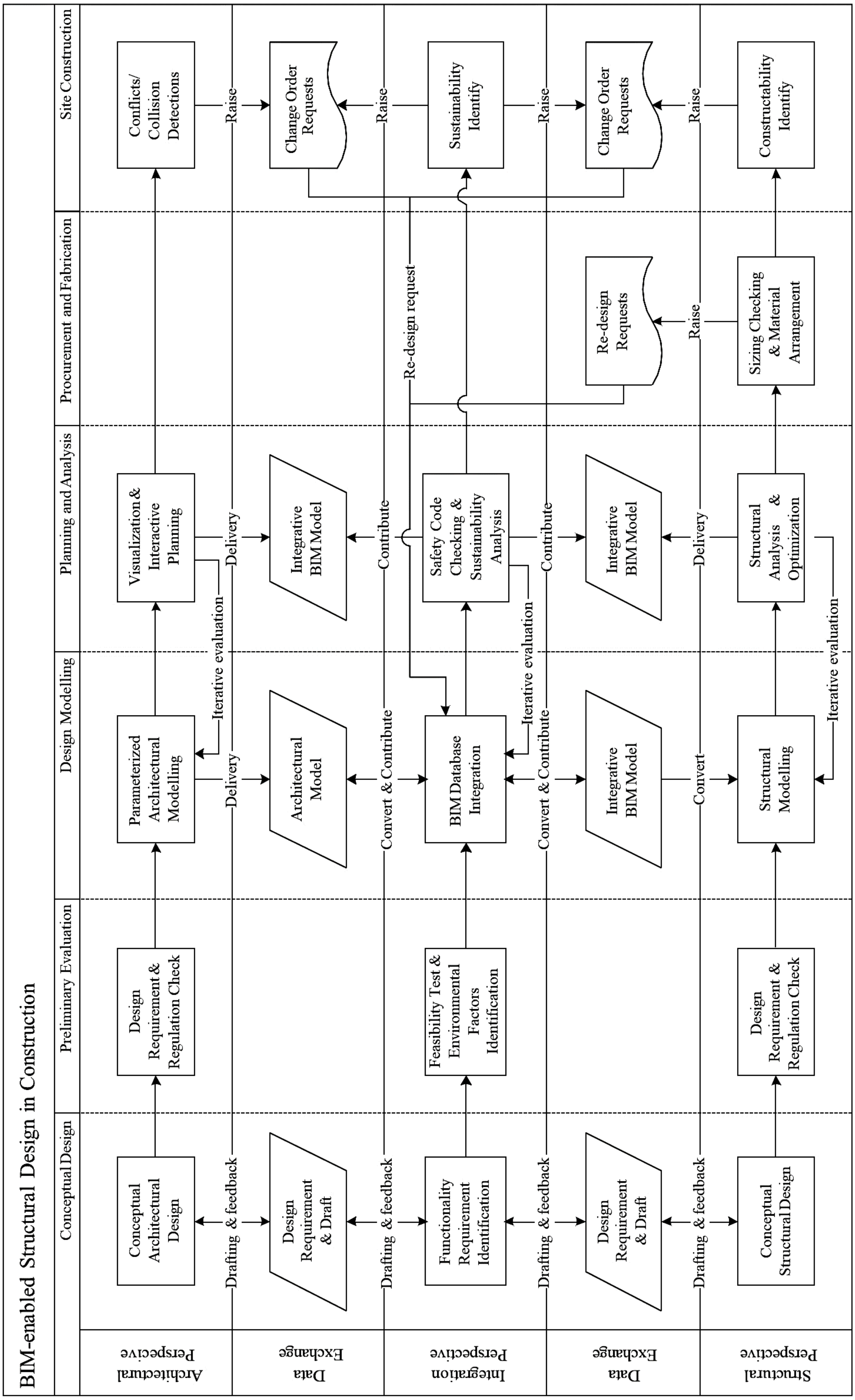


Figure 19: The expected cross-functional flowchart for a BIM-enabled structural design
Source: Chi et al. (2015)

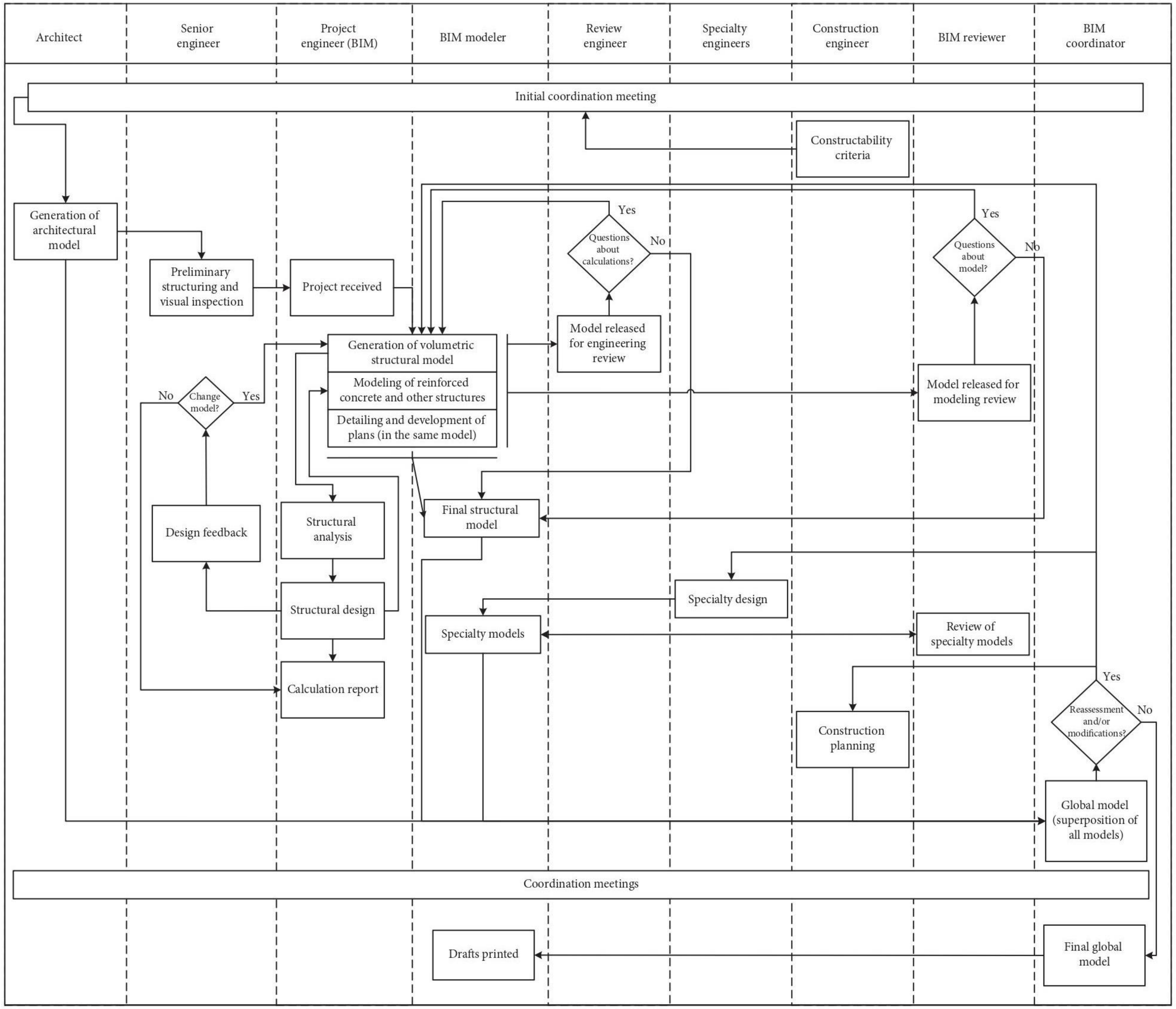


Figure 20: Workflow under the BIM methodology
Source: Rivera et al. (2019)

Chok and Donofrio (2010) proposed a modified workflow that would happen at each project phase, in response to what is called in the study a "compressed design environment" – consequence of more powerful technology and increasing client demands, in which the design team is routinely challenged to propose original designs and to do so at an unparalleled velocity. Rather than manually applying structural information to the wireframe geometry in a point-and-click manner, it leverages parametric modeling, form-finding, optimization routines, and software APIs to transfer data across various software packages. The modified workflow is shown in Figure 21.

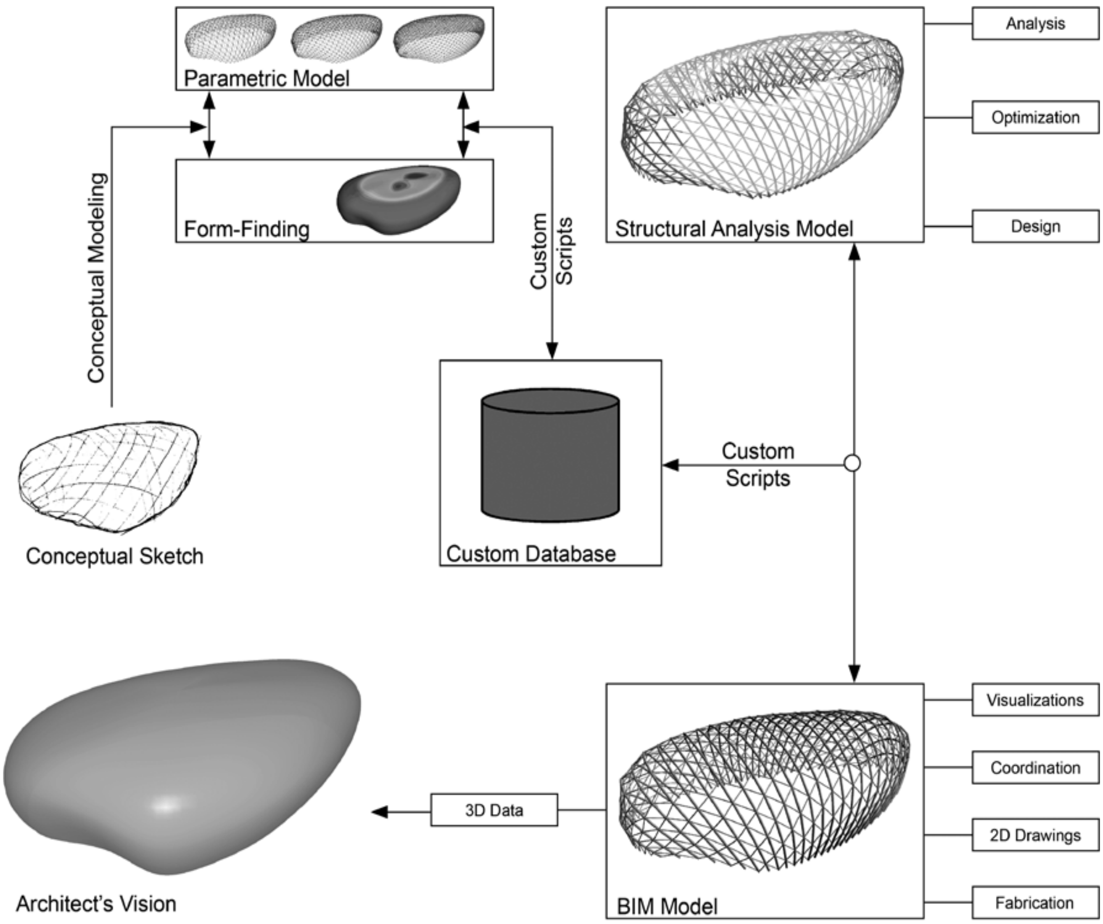


Figure 21: Proposed structural workflow

Source: Chok and Donofrio (2010)

In this workflow, parametric modeling is used to respond to architectural massing models and have complete control over the corresponding structural discretization. This ensures that structural analysis models can be generated quickly and respond easily to changes in the underlying form so that the structural engineer is not always trying to catch up on a design that has already changed.

The idea is to utilize a custom central database with a series of custom scripts, not relying on vendor-developed interoperability tools. In comparison to the workflow by Rivera et al. (2019), it relies on more custom technological features.

Chock and Donofrio (2010) also highlight that the exploration of numerous design options quickly and efficiently has resulted in the need to manage large datasets, as shown in Figure 22, with information from different sources. This culminates in the "big-design-data", which was previously described in this thesis.

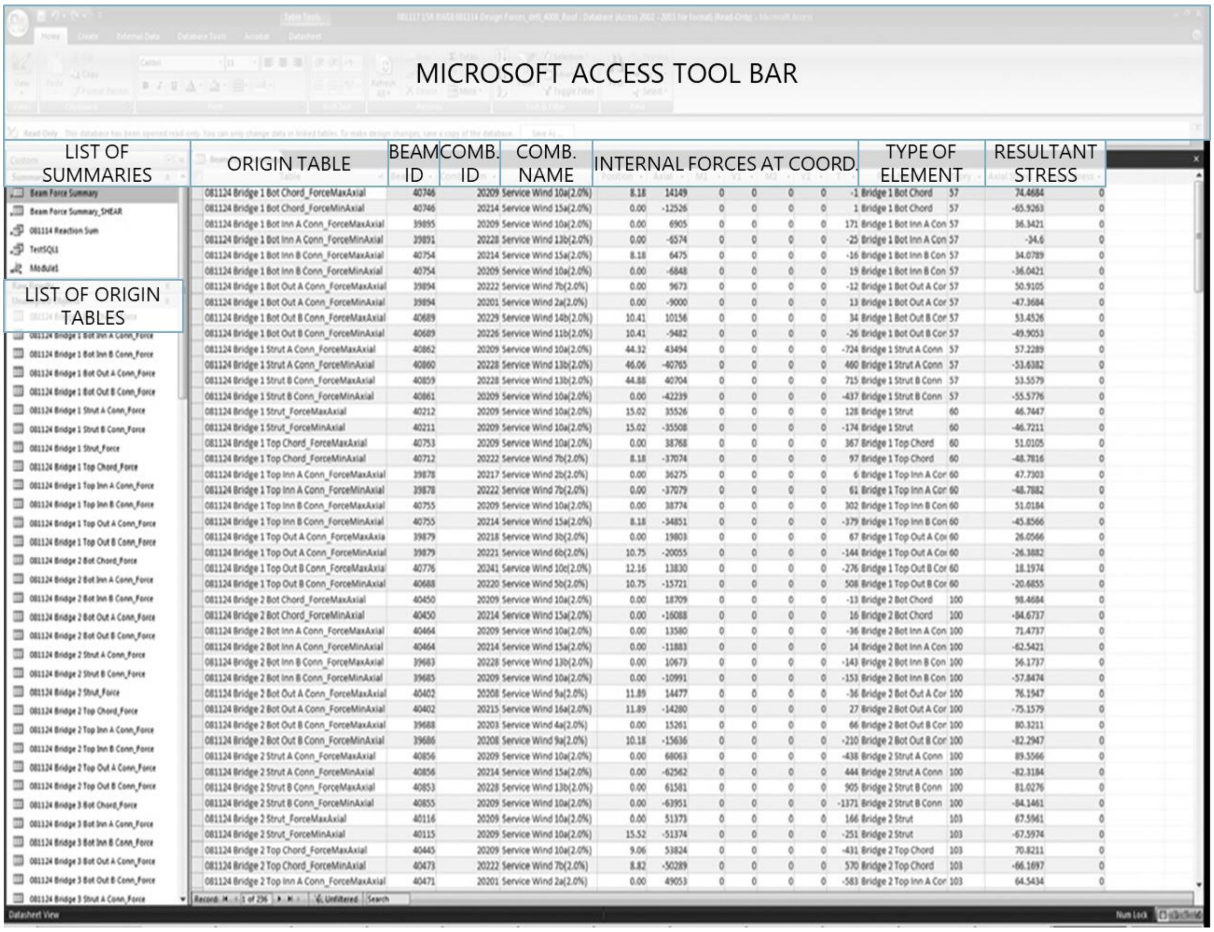


Figure 22: Example of a large dataset representing beam force summary

Source: Adapted from Chok and Donofrio (2010)

To efficiently manage this data, Chok and Donofrio (2010) rely on a centralized database, which is utilized for the exploration of analysis results from hundreds of code-specified load combinations. The database is hosted on a network server. In this way, analysis results are available to all design team members for use in the design of specific elements, visualization purposes, or generation of submodels. Additionally, the proposed centralized database allows revision tracking. Data that might be considered outdated is not lost, but rather versioned.

This proposed centralized database is programmed to generate the geometry of the submodels. The submodels typically involve a much higher level of detail, which is necessary for the design of a specific element, but would unnecessarily complicate a global behavior model. An example of a submodel is given in Figure 23.

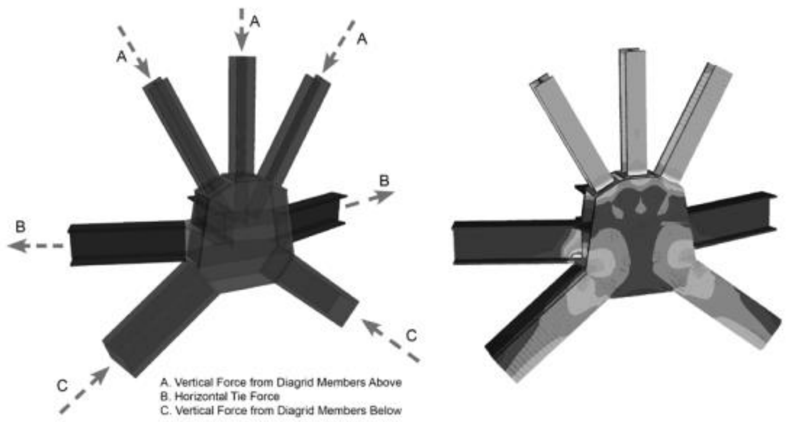


Figure 23: Submodel of diagrid node

Source: Chok and Donofrio (2010)

2.2.4.3. Interoperability between BIM and FEA

Medium and large construction projects typically involve multiple structural consultants who use a wide range of structural analysis applications. Traditionally, the information is exchanged between project participants through 2D drawings and other paper documents, such as cost plans (FEDORIK et al., 2016).

As design evolved to be based on BIM methodology, information sharing must also improve to enhance work efficiency. In fact, to attain maximum efficiency of BIM applications, information sharing between different construction phases and disciplines is essential (EASTMAN et al., 2014; LIU et al., 2016).

Full interoperability of involved parties could improve productivity, efficiency of the structure and its maintenance, safeguarding environmental and structural health in the whole life cycle of the construction, which is among the goals of BIM (FEDORIK et al., 2016; SOLNOSKY; LUTH, 2015). However, the studies found in this literature review indicated that despite efforts to attain information interoperability, structural engineers still have difficulties in using optimum workflows for BIM and FEA.

Liu et al. (2016) highlight the need of moving from analysis and detailed models that need to be manually updated once the BIM structural model is changed, to full interoperability, deriving analysis models directly from the BIM one. This is illustrated in Figure 24 and Figure 25, respectively.

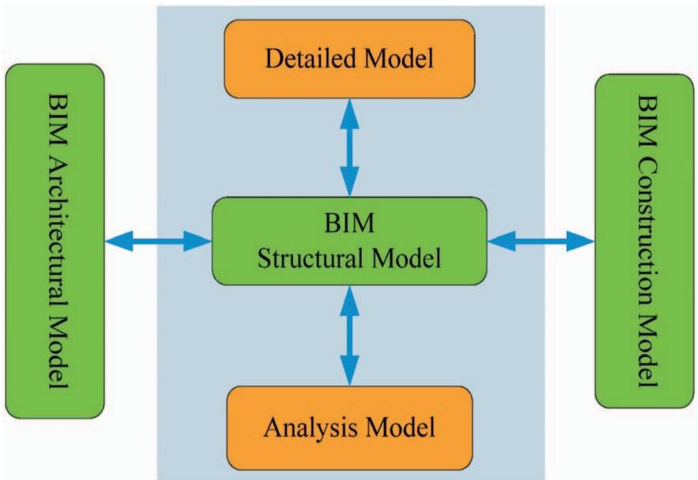


Figure 24: Data transfer among analysis and BIM models

Source: Liu et al. (2016)

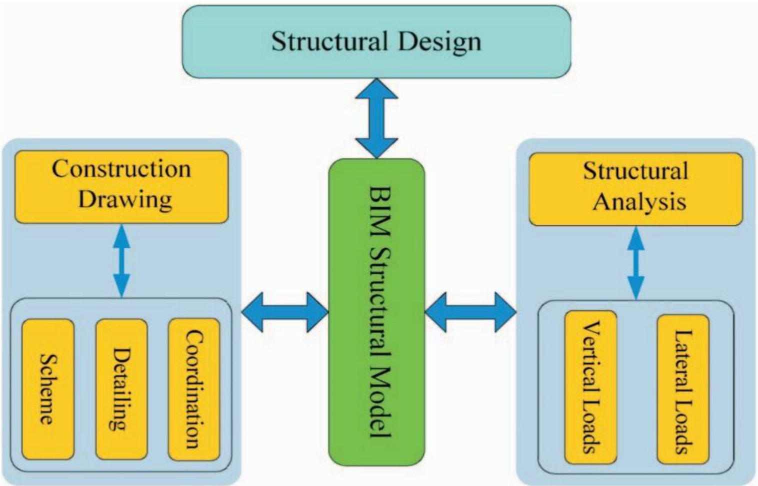


Figure 25: Analysis and drawing derived directly from BIM structural model

Source: Liu et al. (2016)

Table 5, from section 2.2.3.1, also hinted that interoperability is an area that needs considerable work for BIM and structural engineering. There is certainly a lot of work being done in this area by academia and software vendors – but the link between analysis and design software and sharing information across different platforms has yet to deliver more than simplistic results (SOLNOSKY, 2013).

<u>Which information is in which model?</u>

In the simplest case, structural engineering purposes require two different models, the geometric and the analytic models, which interact with one another. This can be accomplished either by using a common database or by referencing the corresponding elements. An example of a two-span slab is given in Figure 26.

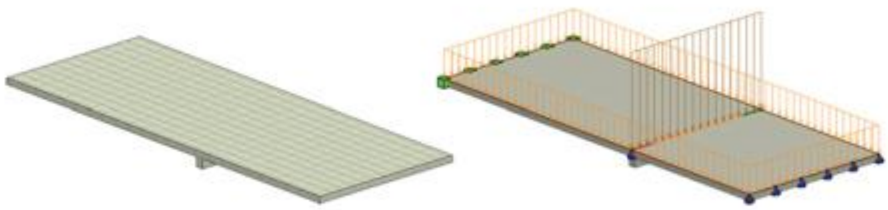


Figure 26: Geometric and analytical mode of a two-span slab

Source: Fink (2018)

Figure 27 exemplifies the difference in architectural (or geometric model), structural model (which has only geometry simplified for structural analysis), and advances the discussion to structural analysis model (which includes also loads and other analysis specific input). Depending on the workflow, how these models interact with each other and even if they exist in separate environments depends may vary.

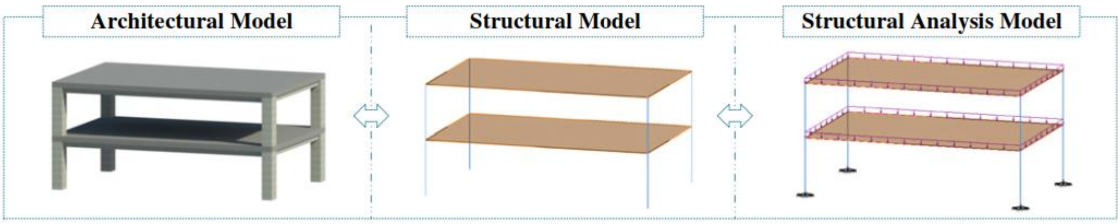


Figure 27: Different representations of three kinds of information model

Source: Fink (2018)

Qin et al. (2011) illustrate the relationship of information between the architectural (or geometric) and structural (or analytical) models in the diagram of Figure 28.

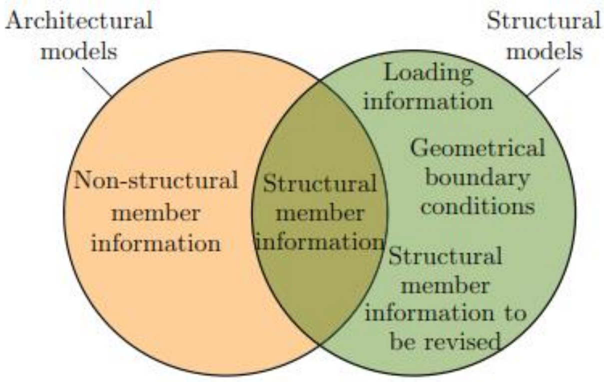


Figure 28: Relationship of information in the architectural (geometric) and structural (analytical) models

Source: Qin et al. (2011)

As explained by Qin et al. (2011) and Fink (2018), the geometric model includes the structural and non-structural member information. For this model, a beam consists of a three-dimensional solid body with material, and additional properties. Non-structural elements such as gutters, for instance, may also be represented.

The analytical model represents a simplified geometry of an element, frequently with reduced dimensions. Each geometric element is generally divided into several analytical elements. That provides the basis for stress and deformation calculations through FEM. For this model, a beam consists of a system line, cross-section, constraints, boundary conditions, and relates to different load cases and their combinations expected during the building lifecycle.

Current integration possibilities

The current market already offers many software applications allowing the cooperation between BIM and FEA. According to Liu et al. (2016), more than 150 types of software applications have been certified by BuildingSMART[2] to support output and input of Industry Foundation Classes (IFC) format data.

For standard elements such as walls, floors, columns, and beams, some BIM software allows the analytical model to be generated automatically. However, Fedorik et al. (2016) and Fink (2018) highlight that many companies offer interoperability of BIM and FEA by transferring only geometrical entities, requiring the user to complete the analytical model (with inputs such as loads, load cases, action effects, and boundary conditions) in FEA software. In fact, software available on the market differs in this respect. Autodesk Revit, for instance, makes it possible to provide these additional inputs directly within the BIM software.

Even when FEA software is in theory integrated with BIM, issues arise during information exchanges, especially when more complex geometry is involved (FEDORIK et al., 2016). Further difficulties appear if special analyses are required: although BIM software may allow the simpler analysis described in Table 2, structural engineers often prefer specialized FEA software, in which more advanced simulations can be performed. These analyses are usually time-consuming and have high requirements for hardware,

[2] International organization that aims to improve the exchange of information between software applications used in the construction industry.

hence certain simplifications must be used, such as the creation of submodels. This implies that, in general, there is not only one, but several models for the structural discipline.

In summary, the interaction between BIM and FEA can be performed via direct or indirect links. The direct link is a direct connection between two software via APIs. This allows the transfer of data such as geometry, loads, and material properties. Applications that allow BIM and FEA data transfer via direct link, limit the cooperation of project parties by the software they use. Indirect link is performed via IFC or other intermediate file formats, generally allowing geometry and material properties transfer only. On the other hand, the indirect data transfer through IFC is satisfactory for a wide range of designs, while direct link requires specific development.

From the case study with two precast concrete companies, Kaner et al. (2008) highlight the following: "Despite the fact that BIM vendors have made integration of structural analysis and design software with their BIM tools a priority, neither firm used the functions in practice" (KANER et al., 2008, p. 19). The explanation was that the version of FEA that integrated with the used BIM software did not support the local standard code, while the software commonly used that conforms to standard code was not integrated with the BIM tool. Another reason was that even if there is a direct link allowed by their FEA and BIM software one of the firms decided to postpone integration. This was to focus firstly on gaining expertise in modeling and then on automating drawing production and parametric components.

FEA models require a lower level of detail than geometric models. Thus, an automatically converted model generally needs to be manually post-processed by the engineer to simplify it for reasonable meshing and consequent time to process the calculation. Kovacic et al. (2013) give the example of a small rounded wall opening for a drainage pipe. This will produce a complex mesh in the FEA model when being imported. This opening is irrelevant for the structural system. Nonetheless, it would cause massive effort in the calculation. Hence, it would be manually deleted by the engineer. Once simplified, this wall element cannot be re-exported into the central model, otherwise, the opening would be missing. These specific cases need to be considered for full interoperability.

In addition to all the technical challenges raised, BIM and FEA implementations for interoperability should carefully tackle the definition of rights (e.g. "who may change what and when?"), related to change management.

2.2.4.4. Research attempts of connecting FEA to BIM

The literature review showed some examples of researches that investigate the construction of connections between FEA and BIM models. This custom connection can be either direct or indirect, as defined in the previous subchapter.

Liu et al. (2016) present an indirect connection approach, between an IFC-format BIM model, originally from Revit, and a FEA software called YJK, and then to other FEA software. Figure 29 illustrates the proposed data workflow.

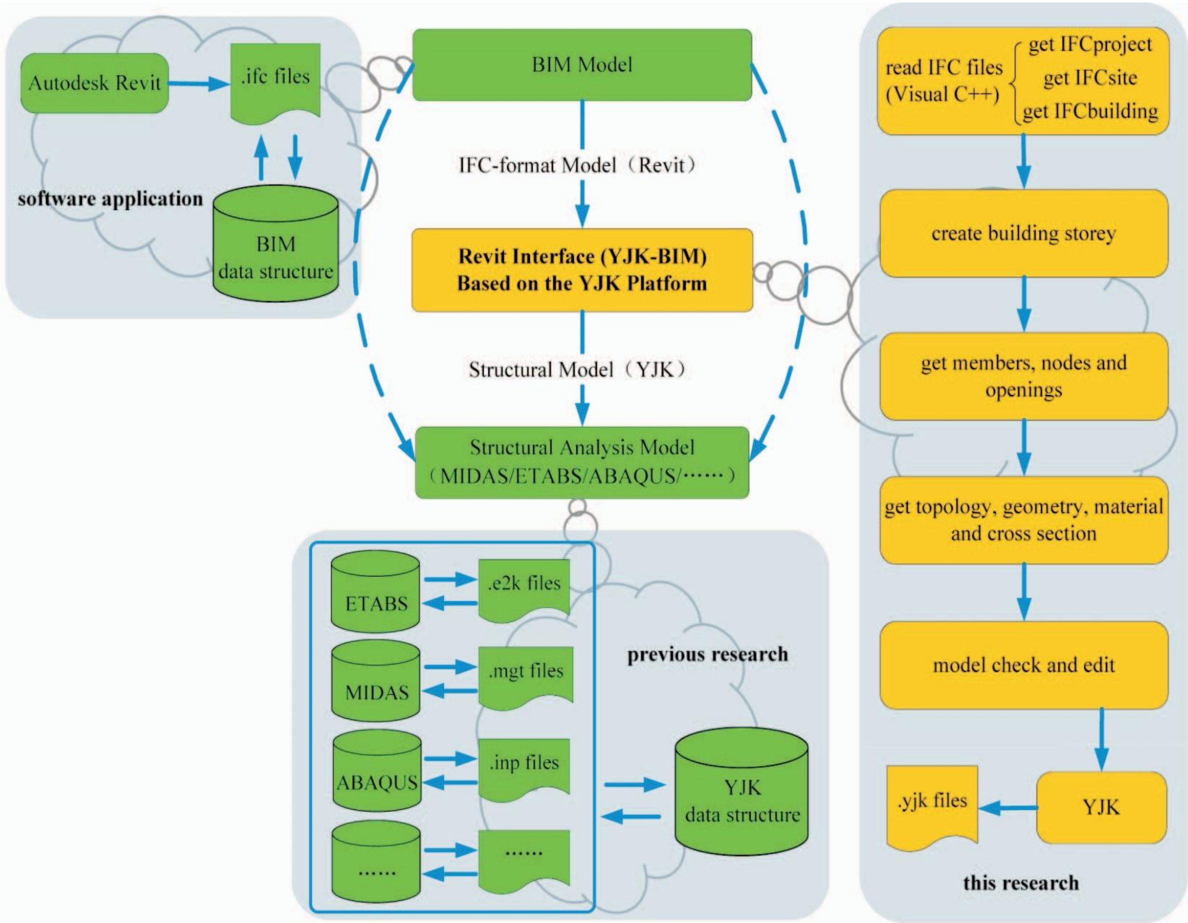


Figure 29: Workflow of data transformation

Source: Liu et al. (2016)

In this case, Revit model is exported to IFC. The resultant file is extracted by a custom-built interface, coded in C++, to YJK. This interface is responsible for data transformation. In YJK, the model is edited and checked. From YJK, the model is extracted to other analysis software applications, using interfaces that have been programmed in previous research.

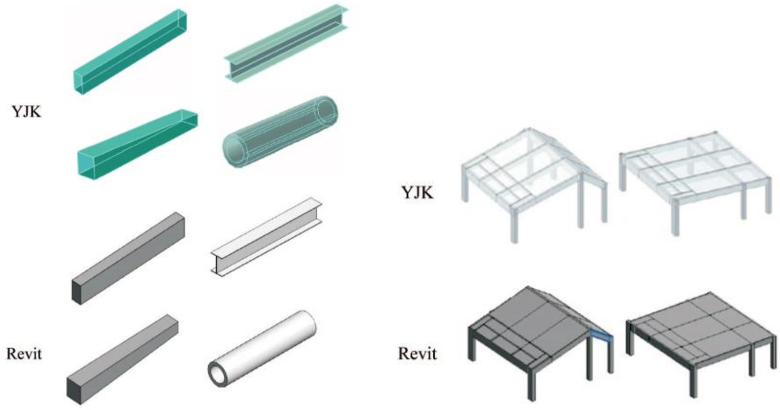


Figure 30: Visual representation of elements in the BIM and FEA software

Source: Liu et al. (2016)

Liu et al. (2016) highlight that the use of the indirect connection makes it easier to achieve data transformation, although it implies that multiple transformation interfaces are needed. The adopted method exchanges mostly geometrical information. It also focuses on one direction of data transfer: from BIM to FEA.

This resonates with the findings of the literature review by Hu et al. (2016). It indicated that the majority of the reviewed research efforts in interoperability provide one-way trip conversion only, and cannot convert between both an architectural BIM and a structural BIM and among multiple structural analysis models.

Hu et al. (2016) introduce the proposal of a “Unified information model”, which acts as an integrated information layer for the functions of model conversion (two-way trip) among multiple structural analysis models and technologies. This approach is enabled by algorithms that overcome the differences in the representation syntax and grammar of various structural analysis tools. The idea is to create shared data models that organize data elements and standardize their representation, as shown in Figure 31.

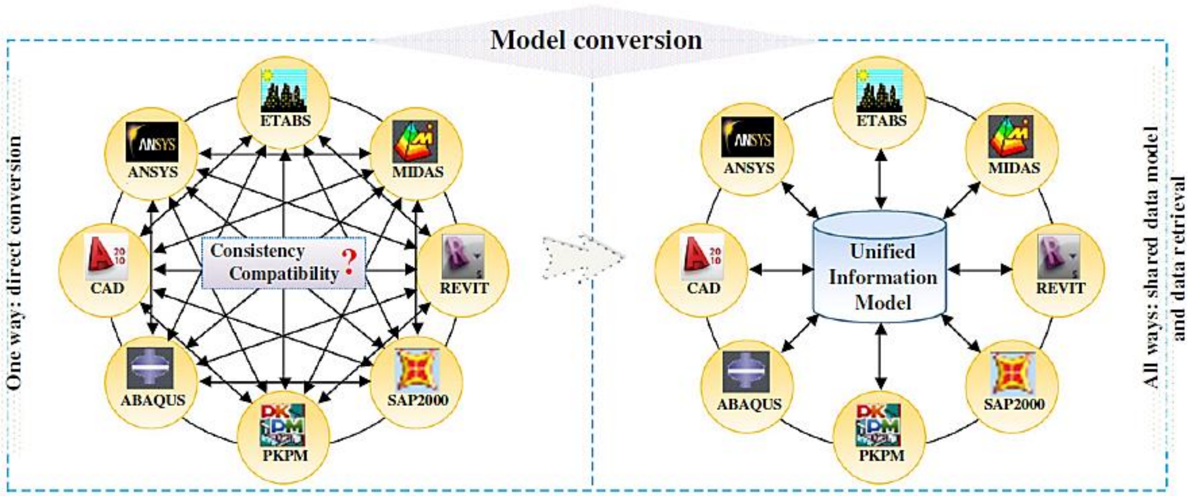


Figure 31: Different types of model conversion among various software applications

Source: Hu et al. (2016)

According to Hu et al. (2016), the advantage of having a unified model is that: it avoids the need to make changes to the data structure of commercial structural analysis tools; and enables an open bidirectional conversion between several commercial structural analysis tools through the "Unified information model"; and has the scalability to accommodate new tools in the future.

Overcoming semantic and syntax discrepancies between the different models and technologies is a key challenge for the conversion process. Figure 32 illustrates the differences in the data structure, semantic, and syntax affecting geometry, material, and section definitions among different software. In the approach and tools proposed by Hu et al. (2016), this challenge was addressed for the following technologies/file formats: ETABS, SAP2000, MIDAS, ANSYS and IFC supported technologies.

		Information expression
File type		ETABS (*.e2k) SAP2000 (*.s2k) MIDAS (*.mgt) ANSYS (*.mac) IFC (*.ifc)
Geometry	ETABS	POINT "pt name" {x} {y} LINE "line name" [COLUMN / BEAM / BRACE] "pt1" "pt2" [1/0] [1/0]
		AREA "area name" [FLOOR/PANEL] {number} "pt1" "pt2" "pt3" "pt4"…… [1/0] [1/0] [1/0] [1/0] …
	SAP2000	Joint={pt name} CoordSys=GLOBAL CoordType=[Cartesian/Cylindrical] XorR={value} Y={value} Z={value}
		Frame={line name} JointI={pt1} JointJ={pt2} IsCurved=[Yes/No] Length={value}
		Area={area name} NumJoints={number} Joint1={pt1} Joint2={pt2}… Perimeter={value} AreaArea={value}
	MIDAS	{pt name}, {X}, {Y}, {Z} {line name}, "TYPE", {mat number}, {sec number }, {pt1}, {pt2}, {angle}
		{area name}, "TYPE", {mat number }, {sec number }, {pt1}, {pt2}, {pt3}…, { [1/2], 1-thick, 2-thin}
	ANSYS	K, {point number}, {X}, {Y}, {Z} LSTR, P1, P2 A, P1, P2, P3, P4… V, P1, P2, P3, P4, …
	IFC	IfcProduct—ObjectPlacement: spatial location information + Representation: geometric shape information
Material	ETABS	MATERIAL "mat name" M {mass} W {weight} TYPE ["ISOTROPIC" / "ORTHOTROPZC"] E {e} U {u} A {a}
	SAP2000	Material={mat name} Type=[Concrete/Steel/…] SymType=[Isotropic/Orthotropic /…] TempDepend=[Yes/No]
	MIDAS	{mat number}, {Type[Concrete/Steel/…]}, <Data>
	ANSYS	MP, [ex/alpx/prxy/gxy/dens/……], [material number], C0, C1, C2, C3, C4…{value}
	IFC	IfcMaterialProperties
Section	ETABS	FRAMESECTION "sec name" MATERIAL "mat name" SHAPE "type" {parameters}
		SHELLPROP "sec name" MATERIAL "mat name" PROPTYPE ["WALL"/"SLAB"…] TYPE ["SHELL"/"PLATE"] {thickness}
	SAP2000	SectionName={sec name} Material={mat name} Shape=[Rectangular/Circle…] {parameters}
		Section={sec name} Material={mat name} MatAngle={value} AreaType=[Shell/Plane/Asolid] Thickness={value}
	MIDAS	{sec number}, {TYPE}, {shape name}, <OFFSET>, {SHAPE}, <DATA>
	ANSYS	SECTYPE, SECID, Type[beam//joint/shell/…], Subtype[SECDATA/SECOFFSET], Name
	IFC	IfcProfileProperties— IfcProfileProperties + IfcRibPlateProfileProperties
Load / Restraint / Other information ……		

ABC —PropertyName
{Value} —PropertyValue
[A/B/⋯] —OptionValue

Figure 32: Different types of information expression among various software applications

Source: Hu et al. (2016)

In summary, the literature review demonstrated that successful implementation of BIM requires a change in the workflow of structural engineering. Different proposals are presented, and in most cases, there is an augmented presence of data exchange and collaboration, which correlates with the idea of the augmented BIM workflow.

More specifically, interoperability of BIM and FEA models is perceived as an important barrier for seamless use of data across the structural engineering design. While interoperability is a topic that goes beyond the scope of merging databases for data visualization, the questions it raises about collaboration and technical information exchange were also faced when planning and implementing BIM augmented workflows for structural engineering.

2.2.5. Data visualization for engineering

Hundreds of years ago, one architect could design a whole building, as there were only a few major disciplines. Since then, construction technology has developed, new disciplines have appeared, and collaboration became imperative. Depending on the scale of a project in the AEC (Architecture, Engineering, and Construction) industry, it can take dozens of designers from different disciplines working on smaller or larger portions of the building. As highlighted by Micsik and Kovacs (2018), this situation is unmanageable without proper tools and proper methods to share information.

Following that, Broekmaat and Brilakis (2019) propose that visualizing project information is key to be able to exploit the full potential of BIM in disseminating information in the construction sector. The study also points out that suboptimal information sharing is a factor that negatively affects the construction sector’s massive productivity gap when compared to other sectors of the economy. This is illustrated in Figure 33.

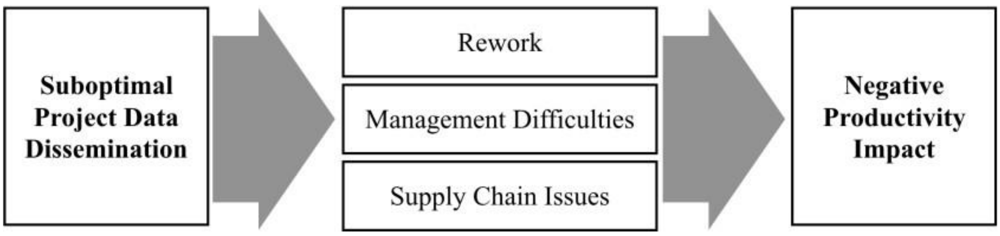


Figure 33: Impact of suboptimal dissemination of project data

Source: Broekmaat and Brilakis (2019)

Chok and Donofrio (2010) also advocate for the importance of visualization of information, as digital workflows have led to a rapid expansion of datasets for each project. Loos and De Laet's (2018) argument in the same direction, highlighting that “convenient visual representations of all structural data can help structural designers in both the understanding of structural design alternatives as well as in making comparisons between different alternatives”.

Decision-making can be facilitated by displays of statistical data, as clearly shown in the publication "Visual and Statistical Thinking: Displays of Evidence for Making Decisions" by Tufte (1997). Furthermore, adding interaction to those displays leads to visual data exploration. In this case, the user becomes directly involved in the data mining and interpretation process (KEIM, 2002).

This makes data visualization very suited to represent data obtained by finite element analysis of a structural model and facilitate an informed decision-making design process.

2.2.5.1. Custom visualizations

Structural engineers have traditionally used the FEA native visualization tools within the structural analysis software to visualize results. This approach is adequate for global views of forces and deflection characteristics (Figure 34).

Figure 34: Example of native structural engineering visualizations – deflection and stress diagram

Source: Chok and Donofrio (2010)

Chok and Donofrio (2010) studied some methods to enhance data visualization for structural engineering, towards more flexible visualization. One example is the generation of charts within Microsoft Excel and in Rhinoceros 3D (a 3D CAD software), showing data graphs and geometry at the same time (Figure 35).

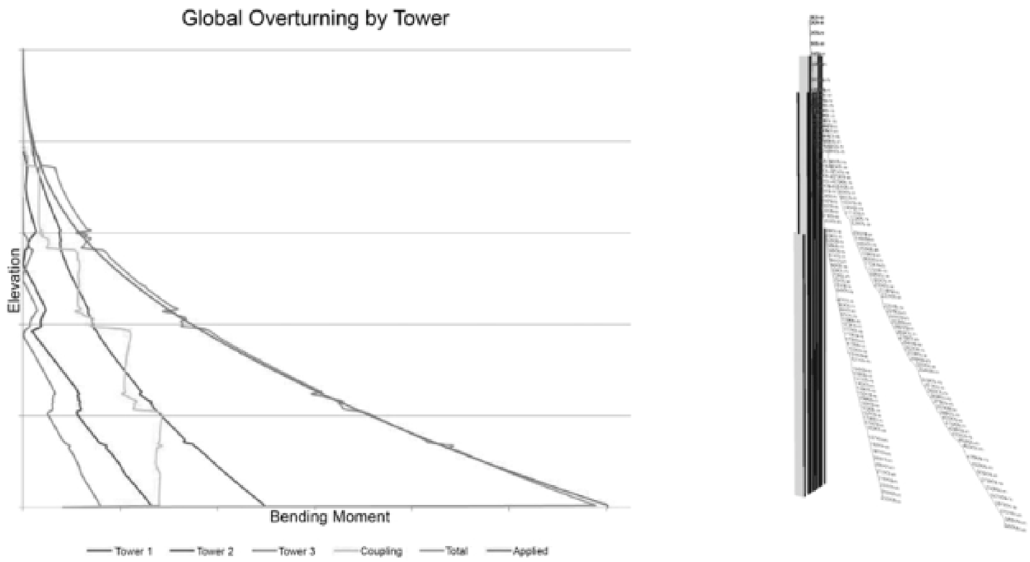


Figure 35: Example of custom-built visualizations using Rhino and Microsoft Excel – overturning moment diagram for different Tower shapes

Source: Chok and Donofrio (2010)

Other examples of custom-built visualizations created by Chok and Donofrio (2010) are: beam density and load flow visualizations, using FEA API, Rhinoceros 3D software, and Grasshopper plug-in (Figure 36).

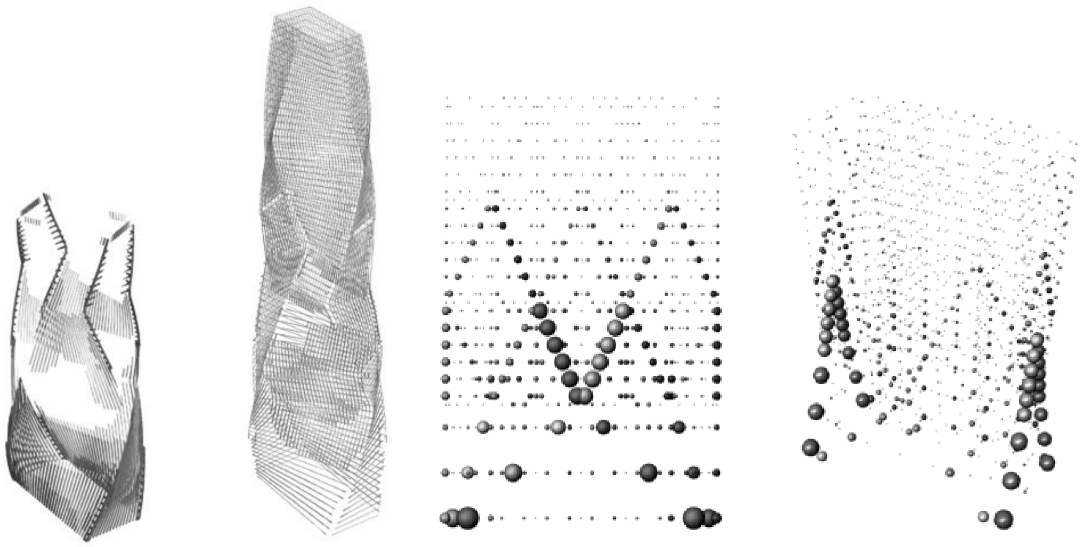


Figure 36: Example of custom-built visualizations using Rhino and Microsoft Excel – beam density studies (left) and load flow in diagrid structure (right)

Source: Chok and Donofrio (2010)

Loos and de Laet (2018) developed a custom tool that could create this type of graph while comparing design alternatives. The process is named by their study as an "informed design approach". The generation of graphs is intended to be as automatic and interactive as possible. As an example, Figure 37 shows five possible designs for a stadium structure.

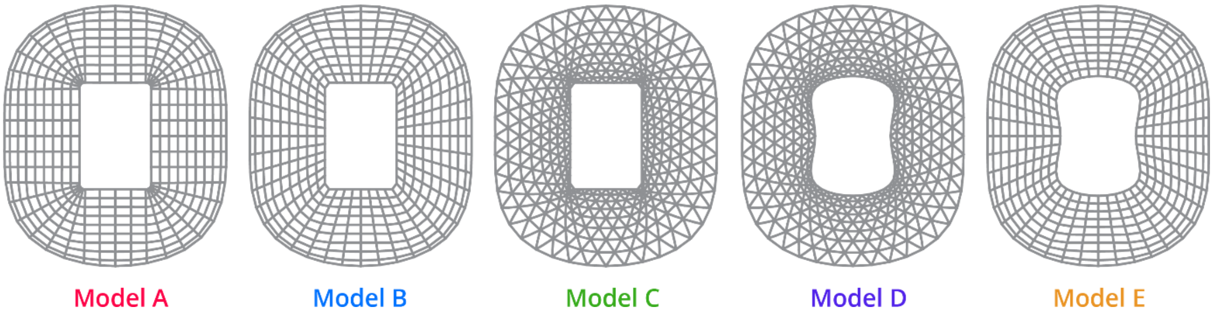


Figure 37: Various arrangements for stadium structures

Source: Loos and de Laet (2018)

For this stadium example, Loos and de Laet (2018) propose the comparison of different alternatives using strain energy. This is the energy stored in a structure due to deformations, resultant from the loads that are applied. A structure with low strain energy under a given load case is considered as more efficient, compared to structures with higher strain energy under the same load case.

The strain energy is directly linked to the stiffness of the structure; and the stiffer the structure, the more efficient, according to this principle. Figure 38 shows that for self-weight, models C and D would be much stiffer, which for distributed load, this would be the case of models A and B.

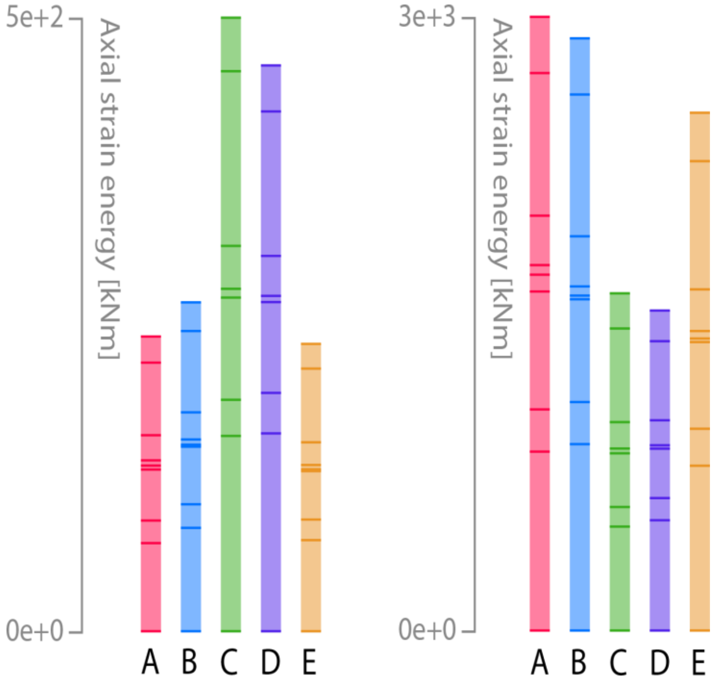


Figure 38: Total strain energy of the structures under self-weight (left) and distributed load (right)

Source: Loos and de Laet (2018)

When comparing alternatives of form-found geometries, it is especially interesting to know how sensitive the structures are to different load cases, particularly the more asymmetric ones.

Figure 39 shows one example of a graph that does that in more depth than the previous one. It has different colors representing the different design alternatives. The vertical axis shows the strain energy due to axial forces and the horizontal axis represents the total strain energy due to bending moments (internal reaction in the structural element when subjected to external forces that cause the element to bend). The strain energy states are indicated in the graph for each model and multiple load combinations.

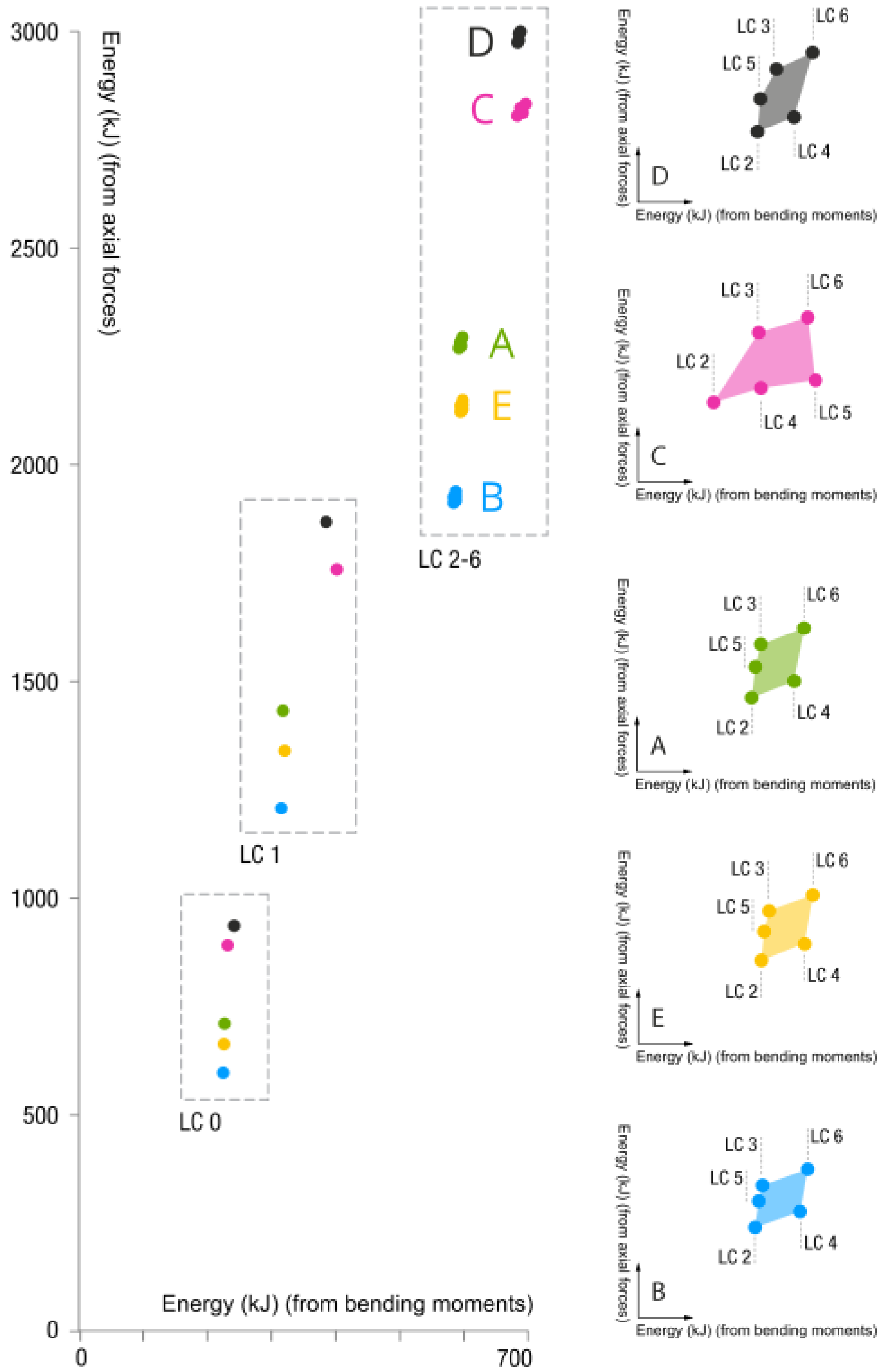


Figure 39: Sensitivity chart showing four structures under different combinations

Source: Loos et al. (2019)

Based on some other case studies, Loos et al. (2019) presented the idea of making use of multiple graphs, assembled in a dashboard or indicator panel together with geometry, rather than compressing the design results in a single value (as a utilization ratio, for instance). This “informed design approach” would not aim at the single best structurally performing solution, but rather inform the designer and create awareness of the consequences of the different architectural and structural choices.

Of course, the use of graphs only becomes helpful in the design process when it is seamlessly integrated within the workflow of the designer. One difficulty that may appear is that some FEA software does not allow the engineer to extract easily structural and geometrical data. In this case, data is often exported in chunks of tabular data, which can lead to a time-consuming graph creation process. Furthermore, well-known tools like Microsoft Excel can create graphs, but not necessarily the ones useful or best suited for representing structural data in a meaningful way (LOOS et al. 2019; LOOS, DE LAET, 2018).

In terms of implementation, Loos et al. (2019), use data linked from Grasshopper, Karamba 3D to a web browser. Figure 40 presents a diagram that shows the parametric design tools considered, the server used, the web browser, and the libraries chose.

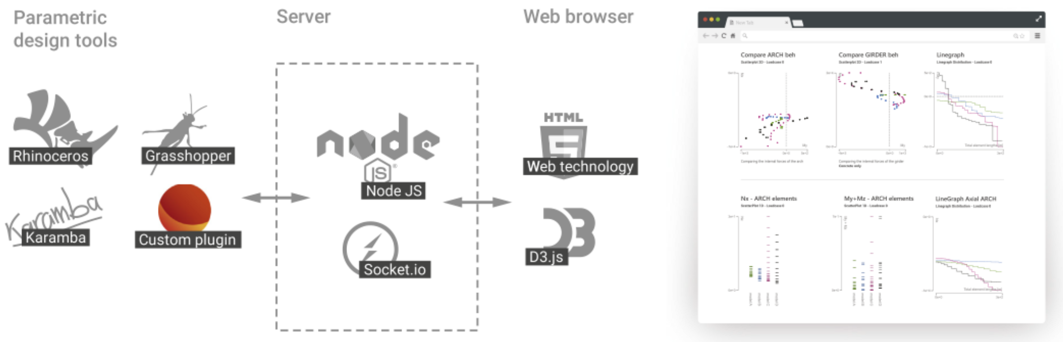


Figure 40: Implementation arrangement for real-time visualization

Source: Loos et al. (2019)

Figure 41 gives one example of a user interface on a web browser for the dashboards.

Figure 41: Screenshot of a proposal of a dashboard

Source: Loos and de Laet (2018)

2.2.5.2. Useful features

For implementing data visualization for structural engineering, two useful features emerged from the literature review: coupling of information-driven and visually driven tools, and real-time interaction.

Solnosky (2016) defines that information-driven or data-driven tools are more focused on database and routine and do not need to rely on sophisticated user interfaces for visual interaction. On the other hand, visually-driven tools rely on the communication of simulations, design intents, results, and situations through two-dimensional (2D) and 3D visual interfaces. To maximize the value of these technologies, these two types of visualization should be coupled within a software package; however, this is often out of the control of the structural firm.

Loos et al. (2019) and Loos and de Laet (2018) highlight that the real-time interaction between the design visualization and the graphs in the browser is important for a qualitative informed exploration of different alternatives. This implementation allows, for example, to visually identify a beam or a group of beams in the graphs and in the 3D model, by selecting one or more elements with the cursor (Figure 42). In other words, elements that are exhibiting a certain behavior in the graphs can be identified in the 3D model immediately. The designer then understands the relation between geometry and data in a specific model. This relation would be difficult to understand if using tabular data or multiple 2D diagrams of various structural models. Therefore, interactivity is a valuable feature.

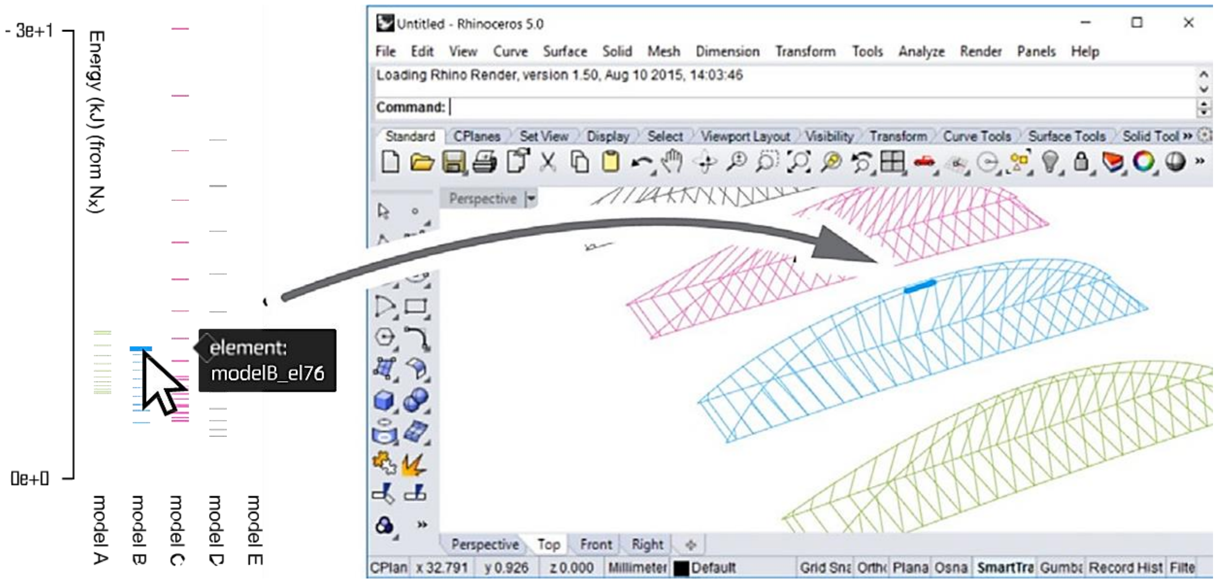


Figure 42: Interactivity allows hovering and selecting data points in the graph and identifying these elements in real-time in the 3D models

Source: Loos at al. (2019)

2.2.6. BIM model as a database

Kovacs and Micsik (2018) highlight that BIM models provide a vast database with a great deal of data that should be used. Chok and Donofrio (2010) also state that BIM can be a design information center for handling massive data and different tasks involved in the structural design processes, helping to speed up communication and cooperation time through its visualization and interactive abilities.

To meet the growing performance demands for buildings, Deutsch (2015) suggests that structural engineers should act according to “Data driven design”. This implies making models that are more precise and attaching more detailed information to them, so that deeper analyses and more accurate simulations can be performed. This corroborates the research of Chok and Donofrio (2010), which emphasizes that the current "compressed design environment" in which engineers work, as explained in Section 2.2.4.2, can only lead to better design if more effective collaborations and a paradigm shift towards information-based design is realized, with all stakeholders engaged.

During the design process, it is desirable to have a support tool that makes it possible to view all the aggregated information data of the project and to consider them when making decisions (Porkoláb et al. 2017 apud Kovacs 2018). In this context, researchers have explored the use of BIM as a data source for visualization, in a broader context than that of structural engineering.

2.2.6.1. General use of BIM as a data source

Kovacs and Micsik (2018) propose a Building Information Dashboard, which displays the meta-information of the BIM model on different diagrams and charts. The idea is that the decision-makers (lead architect, contractor, or owner) can see the "big picture" of the building in many discipline dimensions and can tell if the project satisfies all the requirements and regulations. It is possible to zoom in on one part of the overview and investigate any irregularities or errors in the building data. During the design iteration process, there are several versions of the building. This representation method would allow comparing performance between different versions.

In their work, an example of dashboard layouts is given for different use cases, focusing on the thermal performance of the building. Moreover, dashboards are developed for three different types of users:

- The first is the decision-maker who is not a professional, but who would like to see the overview and the actual status of the project (Figure 43);

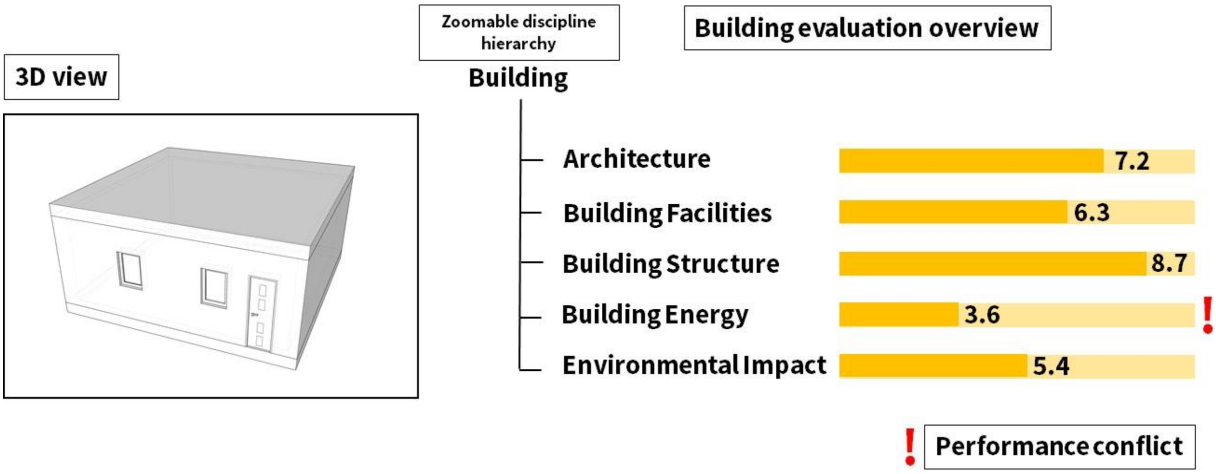


Figure 43: Dashboard for non-professional decision-makers

Source: Kovacs and Micsik (2018)

- The second is the decision-maker who is a professional - for example, the lead architect who is responsible for the design of the building. He/she would like to see the overview and the details, and explore the model for anomalies (Figure 44);

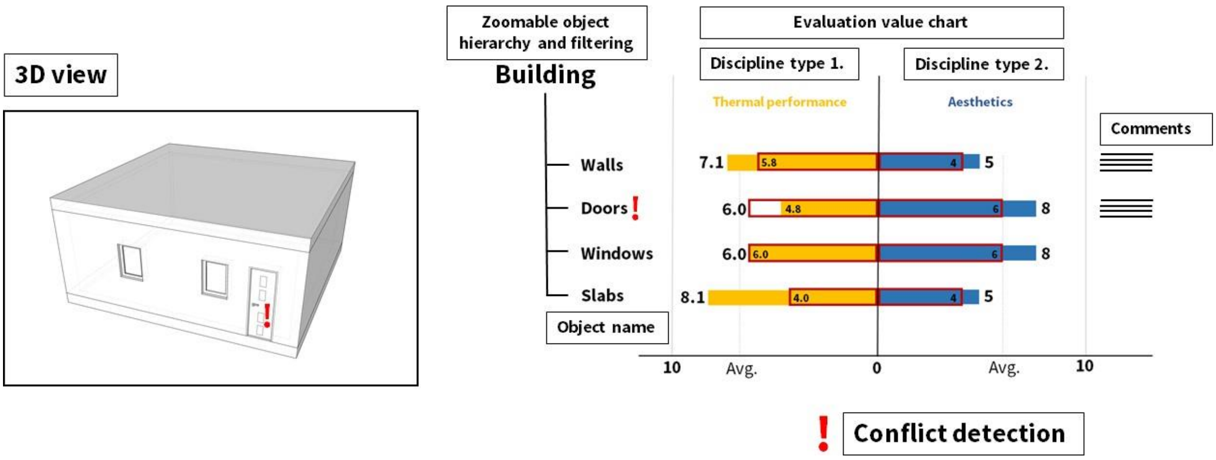


Figure 44: Dashboard for professional decision-makers

Source: Kovacs and Micsik (2018)

- The third is the discipline designer, who actually created the model, added meta-information to it, and made the evaluations (Figure 45).

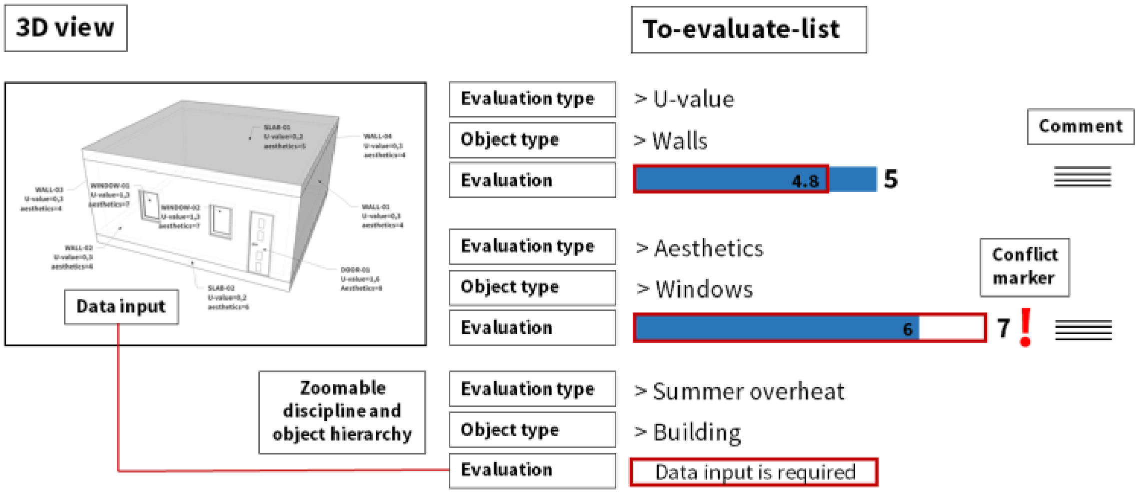


Figure 45: Dashboard for discipline engineers

Source: Kovacs and Micsik (2018)

2.2.6.2. Structural engineering use of BIM model as a database

Aiming to understand the data content of BIM models for structural engineering, Solnosky (2016) did a survey on the frequency in which each structural element is modeled (Table 7). Concrete and steel columns and beams are among the most modeled elements.

Material type	Type of element	Responses			
		Always	Sometimes	Seldom	Never
Steel	Columns and beams	81	13	-	6
	Trusses	69	19	6	6
	Connections and details	6	13	31	50
Concrete	Columns and beams	81	13	6	-
	Slab systems	75	25	-	-
	Shear walls	69	25	-	6
	Precast	44	25	-	31
	Reinforcing	6	6	31	56
Wood	Beams and columns	44	13	13	31
	Shear walls	44	13	6	38
	Studs and plates	19	19	13	50
	Connection hardware	-	6	19	75
Foundations	Pile caps	75	13	6	6

	Piles	81	6	-	13
	Cassions	63	13	6	6
	Mat	75	13	6	6
	Spread and strip footings	81	6	-	13
	Grade beams and ties	75	13	6	6
	Retaining walls	75	19	6	-

Table 7: Frequently breakdown of materials and components modeled

Source: Adapted from Solnosky (2016)

The survey also asked which was the main structural information entered into the model, for a variety of different applications. Three areas of information were acknowledged (Table 8): geometric and member properties, which are modeled 60% or more of the time for all projects; personal record-keeping information, which is present 40–60% of the time; and A & D information, present in 0-40% of projects.

Information class	Common information	% of projects present	Type of update occurrence (%)			
			Never	Once	Each iteration	End of phase
Personal record-keeping	When an element is designed/changed	44	54	7	36	4
	Who designed the element	44	4	4	14	4
A&D information	Analysis assumptions	13	29	7	4	-
	Analysis results	19	25	4	18	-
	Design assumptions	13	32	7	4	-
	Design results	25	25	4	11	-
	Loads	25	29	7	7	-
Geometric and member properties	Material properties	63	14	21	14	-
	Shape properties	75	11	14	25	-
	Geometric properties (length)	63	14	14	25	-

Table 8: Occurrence of different information modeling and updating frequencies

Source: Adapted from Solnosky (2016)

Among the classes and subclasses of information types, the frequency of updating information once modeled was also examined. Most of the time, once information is added, it is never updated. The category of "after each iteration of the design/analysis" was the second most common response for when to update a BIM model with new content.

The respondents reported that in 69% of all projects, the information was generated manually, whereas 38% used software transfer with commercial software, and 31% used generated custom scripts to communicate from software to software.

Table 9 lists common parameters per parametric domains that may appear and that directly or indirectly relate to the structural system.

Parametric domain	Key parameters
Lateral systems	Member sizes and offsets
	Outrigger locations
	Location in plan
	Brace orientations
	Shear wall configuration
	Useable area
	System depth
Sustainability	Embodied carbon
	Embodied energy
Gravity systems	Member sizes and offsets
	Length and width
	Useable area
	System depth
	Floor-to-floor height
	Column spacing
	Useable area
	System depth
Shape forms	Site constraints
	Boundary
	Building orientation
	Building height restrictions
	Panelization
	Material quantity
	Cost efficiency
	Material availability
Constructability	Panel size requirements
	Structural beam width/length
	Potential clashes
	Steel fabrication constraints

Element level	Member orientation
	Member curvature
	Member taper
	Truss configurations
	Length, width, and depth

Table 9: Key parameters in structural parametric modeling

Source: Solnosky (2016)

Computational advancements made larger data models possible, but to limit data size and complexity, structural engineers traditionally divide models for easier/faster manipulation and computation time. Table 10 lists the most common frequencies at which different separations are done.

Method of separation or division	Analytical (%)	BIM (%)
Never divided	13	25
By material	0	0
By structural trade (concrete, rebar, finishing)	25	6
By floor	31	13
By expansion joint	88	13
By gravity, lateral, and foundation systems	69	0
By discipline	-	63

Table 10: Occurrence of different model separation types

Source: Solnosky (2016)

The results from Solnosky (2016) survey are important to understand which type of information may be retrieved from structural BIM models, including geometrical and structural information. It also corroborates the claim that often there is not one BIM and not one FEA model, but several of them. From a BIM standpoint, in most cases, those are only divided by discipline or not at all. Structural models division is most commonly done where building expansion joints are located or through system decomposition.

2.2.6.3. Interfaces and the use of Dynamo

Data can be extracted and input into BIM models in several different ways. For Autodesk Revit software, one of the easiest ways to automate the data exchange is using Dynamo, a visual programming plug-in within Revit (WEI et al., 2020).

Wei et al. (2020) highlight the following features about Dynamo:

- Its calculation engine can process many conventional mathematical operations and logic decisions, and the flexible input and output can export and store data;
- Its flexibility to allow the use of open-source programming languages provides convenience for users to develop and compile. Developers, according to their different needs, can import Python or other languages into Dynamo to extend it into a more professional and powerful software system.

For those reasons, Dynamo is frequently used within Autodesk Revit for data transformation. Figure 46 exemplifies its interfaces.

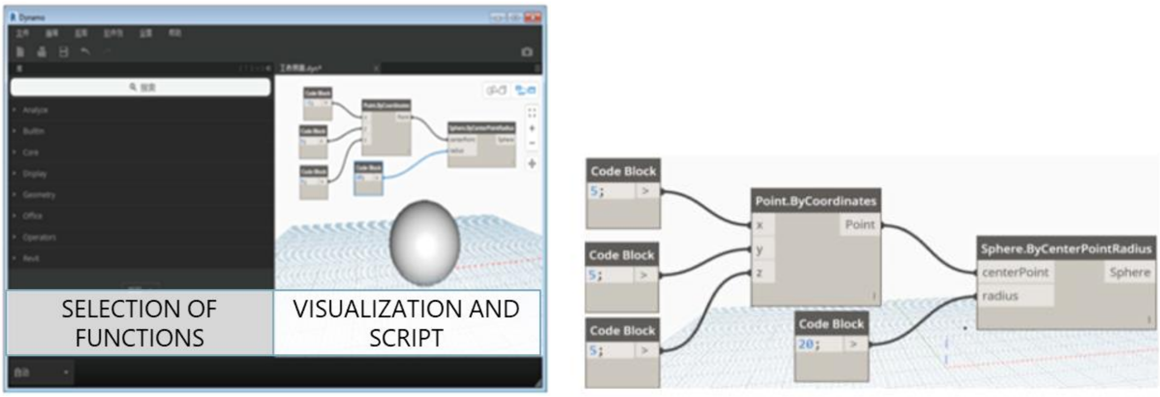


Figure 46: Screenshots of Dynamo interface

Source: Adapted from Wei et al. (2020)

For its flexibility in terms of combining programming languages and its user-friendly interface, Dynamo is used within the implementation of the augmented BIM workflow presented in this thesis.

2.2.7. Key insights from the systematic literature review

Table 11 summarizes the main insights derived from the literature review, and how they were used for the construction of the augmented BIM workflow for structural design through data visualization. This is a non-exhaustive summary.

Theme	Insights	Application to this thesis
Bibliometric analyses	Decision-making in BIM for structural engineering is a topic of recent interest Interoperability is presented in bibliometric studies as a challenge to be overcome	When building the dashboards, considered the inclusion of graphs for specific decision-making situations Included interoperability as a subtheme in the literature review for learning from previously proposed scripts
Relation between information technology and structural engineering	Advances in computation allowed more complex models which can lead to errors, and visualization is a fairly used checking method Use of custom script is a possibility to enable direct data transfer from analysis to documentation software	When building dashboards, considered the inclusion of graphs for checking the design of elements Inspired by the same concept, developed custom scripts to enable the data transfer to the proposed data warehouse
BIM implementation for structural engineering	Exploration of BIM models as a database is an important opportunity People and processes are key to a successful implementation	Inspired the proposal of the general thesis objective (the augmented BIM workflow) When proposing the tool, special attention was given to how it would fit the workflow and to what potential users actually wanted to have on it, which led to the conduction of several interviews with professionals in design and structural engineering
BIM workflows for structural engineering	BIM implies moving towards a more collaboration centric workflow	When choosing a specific objective of the PoC, enhancing design team collaboration was set as the specific goal For the PoC, chose to transfer all data to a unified

	Data transfers can be done directly between different software or using a unified intermediate format	format, the one for the data warehouse so that the tool could be more easily extended to other proprietary software if desired
Data visualization for structural engineering	Importance of coupling visual driven tools and information-driven tools Importance of interactivity to facilitate understanding and decision-making	This was the basis for the dashboard proposal, with 3D model data coupled to all other related information and visualized side-by-side When selecting how to implement the PoC, a tool that allowed interactivity (rotation and zoom of a model, coupled filtering of geometry and information on graphs) was prioritized
BIM model as a database	Importance of proposing specific dashboards for different types of users Information that is generally present in structural BIM models	This was included in the PoC, with a proposal of different types of information that would be shown to users with different specialties This helped guide the focus of the PoC in linear steel elements and corroborated the hypothesis that a flexible merging database tool would be required as multiple models may coexist

Table 11: Summary of insights from the systematic literature review

3. TYPICAL BIM WORKFLOW IN A MEDIUM-SIZED STRUCTURAL ENGINEERING OFFICE

The literature review demonstrated the importance of adapting structural engineering workflows to the context of BIM and indicated that this creates an opportunity for information management and the enhancement of collaboration.

Following the methodological steps from the DSR, for the identification of artifacts and class of problem and the proposal of an artifact for the specific problem as per Section 1.3, the typical workflow of a medium-sized engineering office was analyzed and used as a basis for the general proposal of the “augmented BIM workflow”.

3.1. Typical BIM workflows

Semi-structured interviews were conducted with structural engineers (SEs) and BIM specialists of the mid-sized engineering office, as described in Section 1.4, to understand the typical workflows.

In the specific context of the office in which this research was based, the BIM model is generally created on Autodesk Revit and the FEA model is created on the German software SOFiSTiK. Although SOFiSTiK has an interface for FEA geometric input directly through Revit, this is not commonly used in the studied company. This is a similar situation as described in the literature by Kaner et al. (2008). For most projects, Rhinoceros 3D is used for geometry input, or geometry is parametrically coded in the FEA software interface directly.

Initially, for understanding the status and the challenges to intensify the information focus of current BIM workflows, the following questions were addressed:

1. What are the types of projects in which you used BIM?
2. Can you describe the general workflow that you used?
3. How were design updates done per type of workflow?

4. How standardized is the information content of the BIM models?
5. What are the main issues that you faced with model creation and updates?
6. Do you think that having a dashboard for visualizing the data from the structural BIM model would be helpful? What would you like to see?
7. Do you think that having a dashboard for visualizing the data from the FEA model would be helpful? What would you like to see?

In a second round, more specific questions were made, such as:

8. When a BIM project starts, what is the initial geometry input received from the architects? Is it already a BIM model?
9. From this input, how is the structural model created (step-by-step)?
10. Have you ever used the SOFiSTiK direct interface for Revit? How was it?
11. How is the work divided among different engineers in the project?
12. Which other tools are used besides FEA and BIM software?
13. Have you ever created project-specific parameters to input information inside Revit?
14. In which cases exactly is model comparison required and not easily solved?

From those conversations, with four different engineers and BIM specialists in the office, and from the author's personal experience with structural design, a typical workflow for the set of tools used in the office was mapped, as which is shown in Figure 47.

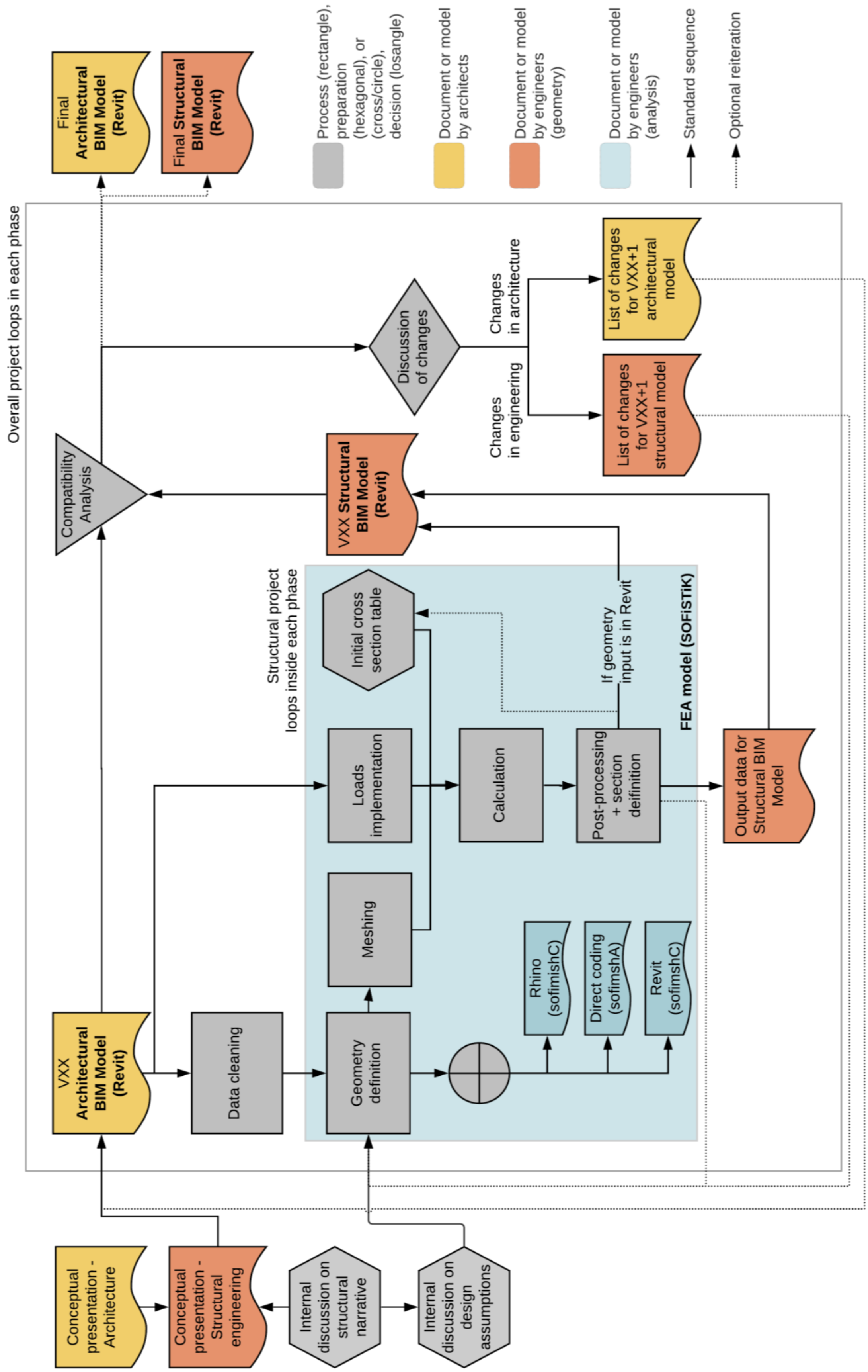


Figure 47: Workflow of structural engineering and BIM

1) Conceptual presentation – architecture: at the very beginning of the project, architects or client provides the overall concept. This is generally given in the form of pdf files with 2D plans and sketches or as a 3D model;
2) Structural narrative: an internal discussion with the project managers about the structural narrative occurs. This is based on sketches and quick estimations of quantities from knowledge acquired in past projects. In the conceptual design phase, a general check is carried out. For frame structures, this may be done with simple hand calculations, checking for instance if spans are reasonable for the structural height restriction and if suitable bracing systems are possible. More complex shapes can require a more sophisticated feasibility check. All those checks are generally made through limited examples and simple models. The conceptual design is achieved by an incremental learning process consisting of the generation and evaluation of a set of design alternatives. The nature of these processes is divergent and convergent, respectively. In the end, it is expected that the designer can provide a final shape and topology, estimate the quantity of material that the project requires and confirm its feasibility from the structural point of view;
3) Conceptual presentation – structural engineering: a concept of structure is proposed, generally through pdf files with 2D plans and sketches or as a 3D model;
4) VXX Architectural BIM Model: after some iterations, the architect would propose a preliminary architectural model. It is supposed for the sake of illustration that this would be already a BIM model, although, in reality, the exact phase in which BIM models are introduced varies from project to project;
5) FEA Model pre-processing - loading: the SE discusses design assumptions, and puts together a "basis of design" document, which lists the base codes that the design needs to comply with, loads to be applied, and other general requirements;
6) FEA Model pre-processing - initial cross-section table: the SE defines an initial cross-section table with materials, sizes, and properties;

7) FEA Model pre-processing - geometry: after cleaning the data provided in the BIM architectural model, the engineer defines a preliminary structural grid. The software used for geometry at this step varies depending on the project:
    a. Direct coding: SOFiSTiK has an interface that reads a certain proprietary language (sofimishA) in which the engineer can code the geometry by establishing the location of points and connecting them with elements (beam, truss, cable, surfaces, etc.);
    b. Rhinoceros 3D: SOFiSTiK has an interface that allows points, lines, and surfaces to be given certain properties in Rhino and be directly exported to a text file in a language understood by the FEA software (sofimhsC);
    c. Revit: SOFiSTiK also has a Revit interface called "SOFiSTiK Analysis + Design". To use that, the "analytical model" must be on in Revit and then through an export command a text file in a language understood by the FEA software (sofimhsC) is exported, similarly to option B.

    When describing geometry, it is important to specify which attributes each geometry can have for structural engineering, as presented in Table 12.

Dimensions	Element	Attributes
0D	Points	Point number, local system orientation, supports specification, springs specification, constrains specification.
1D	Lines	Line number, start/end points number, start/end hinge conditions, start/end cross-section number, local system orientation, group, type of element (centric beam, eccentric beam, truss, cables), meshing instructions, supports specification.

2D	Surfaces	Structural surface number, group, thickness, material, meshing instructions, supports specification, local system orientation, bedding, stiffness formulation (slab, membrane, in-plane rotation).

Table 12: Attributes of FEA geometry for pre-processing

8) Calculation: with the geometry defined, including cross-section and loads, the analysis parameters are chosen, e.g., the combination of loads to be considered and the type of analysis (linear, non-linear, second-order analysis, etc.);
9) Post-processing: the output is checked and if it complies with all design requirements, the geometry is prepared for being exported to Revit. Post-processing is generally done with the help of Microsoft Excel and two SOFiSTiK interfaces, Result Viewer (information-driven tool, similar to a spreadsheet) and Wingraf (visually-driven tool). The most relevant attributes of each element are shown in Table 13.

Element	Attributes
Points	Point number, coordinates, nodal displacement, nodal rotation, support forces, support moments.
Lines	Element number, nodes, internal forces, stresses.
Surfaces	Element number, nodes, internal forces, stresses.

Table 13: Attributes of FEA geometry for post-processing

The workflow from pre-processing to post-processing reiterates until reaching a complying solution by refining cross-sections and design assumptions.

10) Output data for Structural BIM Model: if the post-processing is ok, the output is prepared. This step is an interface between the structural engineer and the BIM specialist. The information can be passed via a Microsoft Excel table, a Rhino model, screenshots, e-mail, and phone calls. If the FEA geometry was built directly in Revit, this step does not exist;
11) VXX Structural BIM Model: the output to Revit is read by the BIM specialist and input either manually, or via Dynamo interface for more automation. If the geometry was built in Revit, this step is automatic;
12) Compatibility analysis: at a certain frequency, depending on the project, there is a compatibility analysis between the different discipline BIM models, generally done using clash detection enabled software;
13) Discussion of changes: this step is done via BCF files, e-mails with screenshots, and/or phone calls, depending on the project;
14) Changes: the agreed changes are incorporated and the process reiterates.

In the typical workflow shown in Figure 47, the project work is considered to start at the concept design phase. The part of the workflow inside the square area described with the text "Project loops in each phase" represents iterations that happen mostly during the project phases of schematic design and detailed design.

During these two phases, once the design team finishes the analysis and communicates its outputs to the architect, there are new changes, due to architecture and client requirements, that should be incorporated in the design. A similar situation was described in Chock and Donofrio (2010). There are also changes resultant from coordination with projects of different disciplines, such as mechanical, electrical, and plumbing. Once more, similarly to what has been found in the literature review, if design modifications are made in the documentation software, those changes need to be remodeled in the analysis software as well. This time-consuming task needs to be carefully revised to avoid mistakes.

During the construction documents phase, most of the compatibility issues would be already solved. This would be the time when submodels, as described by Chok and Donofrio (2010), would be developed, for producing the final geometry model.

A summary of this whole process is given in Figure 48 as introduced in Boechat and Corrêa (2021).

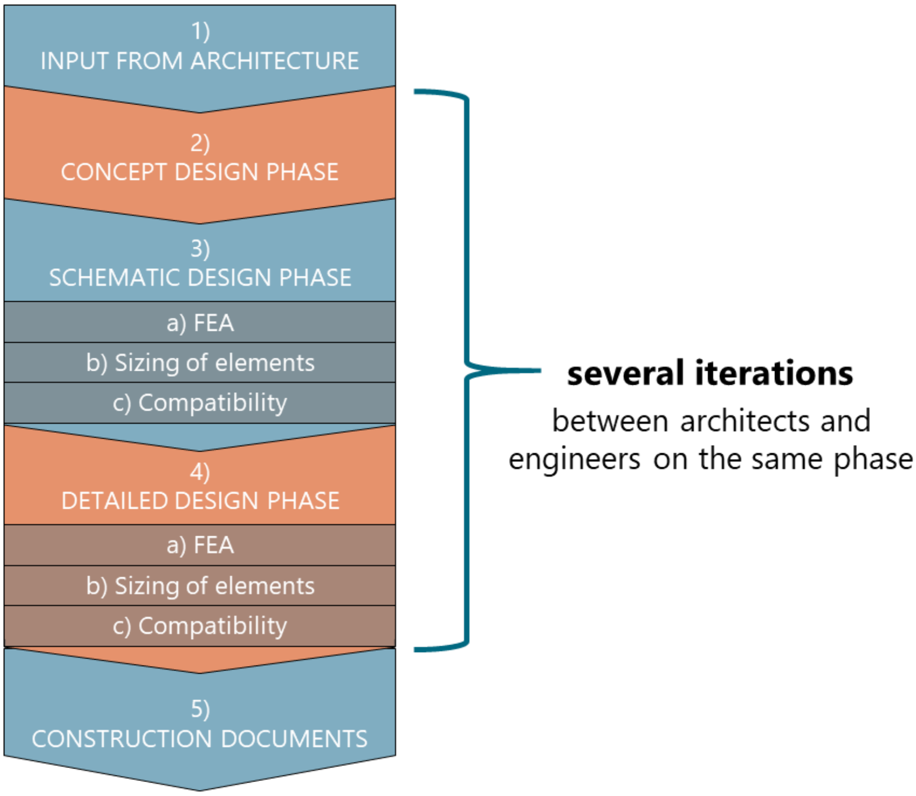


Figure 48: Summary of the existing workflow

Source: Adapted from Boechat and Corrêa (2021)

3.2. Comparison to workflows in the literature

In general terms, this mapped workflow is similar to what has been compiled in the BIM workflows in the Literature Review, but the focus given is specific to the context of this thesis. Some similarities are:

- Following Chi et al. (2015) work, the processes happen along with different design phases, as specified in Figure 48. Furthermore, the data exchange and feedback between architects and engineers were confirmed as relevant aspects in the specific workflow mapped;

- The fact of having a responsive structural design, with manual steps, leading to implementing changes to later discover that the basis for design has changed, as discussed by Chok and Donofrio (2010), appeared in the interviews;
- The focus of the presented workflow is also on models rather than drawings, as suggested by Kaner et al. (2008). In the context of this thesis, drawings were not specifically mentioned neither by BIM specialists nor by structural engineers, which is reasonable given the type of project that they commonly deal with (steel frame structures, with typical details being separately drawn in CAD) and the fact that this workflow was mapped to base the proposal of a data model. In this sense, the final product of the workflow is considered to be the BIM and FEA models, and not the 2D drawings that derive from them.

On the other hand, some particularities of this workflow are:

- As the PoC in this thesis focus on the engineering processes and exchanges of data within the internal design team, the specific workflow focuses on what happens mostly in the Schematic and Detailed Design phases, differently from Chi et al. (2015) work for instance, which tries to map processes from concept design to construction;
- Also given the focus of the PoC, the workflow of Figure 47 goes into more depth on the specific steps performed for constituting the FEA model than other BIM workflows presented in the literature. Thus, it includes the loads' definition, meshing, creation of cross-section table, and post-processing. The way those steps are handled are important to be considered when thinking about extracting information from the FEA model;
- Rivera et al. (2019) also presented a workflow focused on the work of structural engineers, dividing it by function in the design team (which was not considered necessary in this case), but did not specify the steps done in the FEA model.

3.3. Comments on the idea of an augmented BIM workflow through data visualization

During the semi-structured interviews, when asked about the idea of having a BIM dashboard with the most relevant information shown in a standard way, for sharing across the team members, engineers and BIM specialists were enthusiastic about it. For the latter, there was a perception that this could make engineers see more value in the BIM model and consequently on the importance of keeping its information correct, which is inherently the work of the BIM specialist, but needs the collaboration of structural engineers. For the former, this would mean a step towards more automated post-processing and creation of bill of quantities (BoQ), which currently are activities that take a considerable time and work and produce information that is “forgotten” once the project is over.

Furthermore, during interviews for the workflow mapping, some challenges regarding the tracking of changes became apparent. Both BIM specialists and structural engineers pointed out that it would be extremely useful to have a tool that could compare models in terms of geometry more than in terms of names, meaning:

1) Comparison between BIM models – although this seems like something easily done through comparison of tables from schedules of elements, for instance, the interviewed professionals pointed out that they would like to be able to compare the actual geometry, and not names of sections as strings, for instance. So, they suggested a tool that recognizes the actual geometry of an element and compares it with previous model versions;
2) As a further step, the professionals pointed out that it would be useful to have a similar approach for comparing BIM to FEA models – sometimes it was hard to keep track of something important that changed on a BIM model due to architect’s requirements, for instance, was accordingly changed in the structural model.

4. PROPOSED DATA VISUALIZATION WORKFLOW AND TOOL

After this diagnosis of typical BIM workflows, a tool for enhancing a structural engineering workflow with more intensive use of BIM information, and that enabled model comparison, started to be outlined. The basic idea behind the tool is to create a data warehouse, as presented by Sidiqqui (2018), but taking both the databases from BIM and FEA as a data source, as shown in Figure 49.

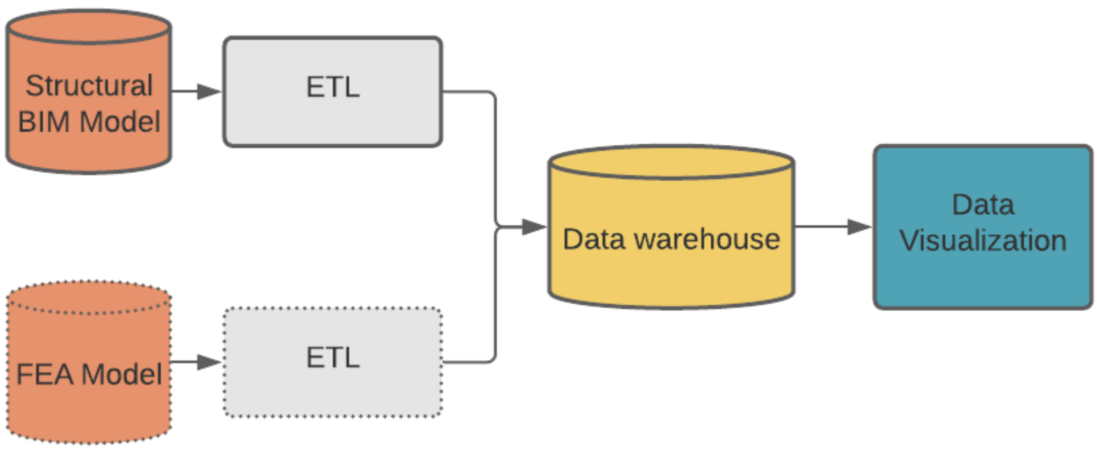


Figure 49: Proposed data warehouse from BIM and FEA model

This data passes an ETL (extraction-transformation-load) process to be gathered in the data warehouse. In this proposal, the goal of the data warehouse is to allow data visualization as a process to enhance collaboration.

For building and testing the ETL implemented, five different projects were: two low-rise buildings; one stadium bowl; and two stadium roofs. They had been designed by different teams, during the years 2018 to 2021. Using projects from different teams was necessary to test that the proposed tool would work for different projects and companies, not relying on specific methods of inputting information in models that could have been chosen on only one occasion. The data warehouse for the proof of concept in this thesis is used for a single project each time, but as briefly described in the Introduction chapter, the target for further implementations should be to apply it to all projects of a given company and constitute an intelligence database.

4.1. Concept of the proposed workflow

Conceptually, in terms of the workflow, this would mean the creation of a "Data and control" (D&C) step, which would run parallel to conventional phases of the project. This is shown in Figure 50 and was introduced by Boechat and Corrêa (2021).

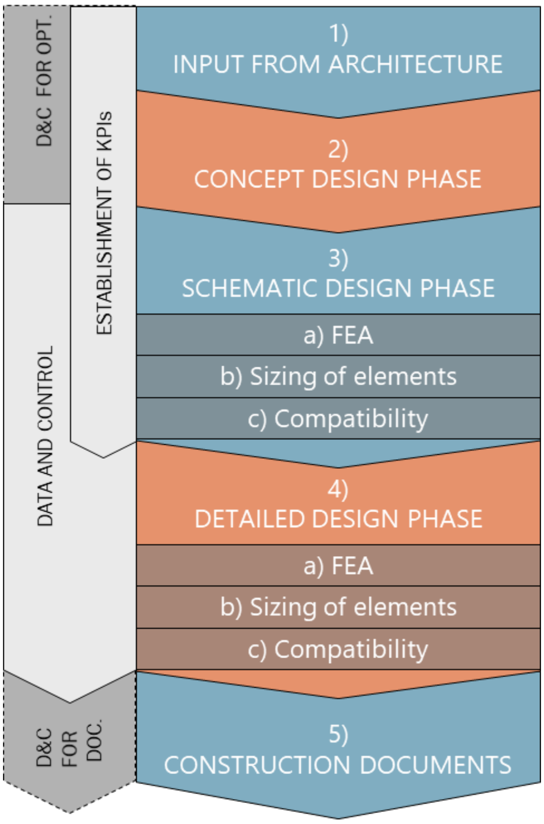


Figure 50: Summary of the proposed augmented BIM workflow of structural engineering through data visualization

Source: Adapted from Boechat and Corrêa (2021)

This D&C step would start with the establishment of "key project indicators" (KPIs), at the beginning of each project. Of course, some measurable criteria are common to every structural engineering project such as the ratio of material quantities per square meter, the number of elements per cross-section, etc. However, especially in the context of large and innovative projects, there are often special considerations that need to be done per project. Therefore, although it is within the scope of this thesis to propose some standard measurements to be presented in the dashboard, KPIs should be refined within the design team during phases 1) to 3) of each project.

The PoC in this thesis focus in the general "Data and control" step, which permeates phase 3) and 4). Given the essence of those phases, the produced dashboards will be dedicated to following up on quantities and model changes.

Other suggested implementations would be to focus on D&C for optimization, more related to the Conceptual phase, during which several different topologies might be envisioned, similar to the work of Loos et al. (2019); or on D&C for documentation, which could concentrate on drawing generation from the BIM model.

The specific augmented BIM workflow, incorporating the "Data and control" step as above explained, with KPIs definition and dashboards update, is presented in Figure 51.

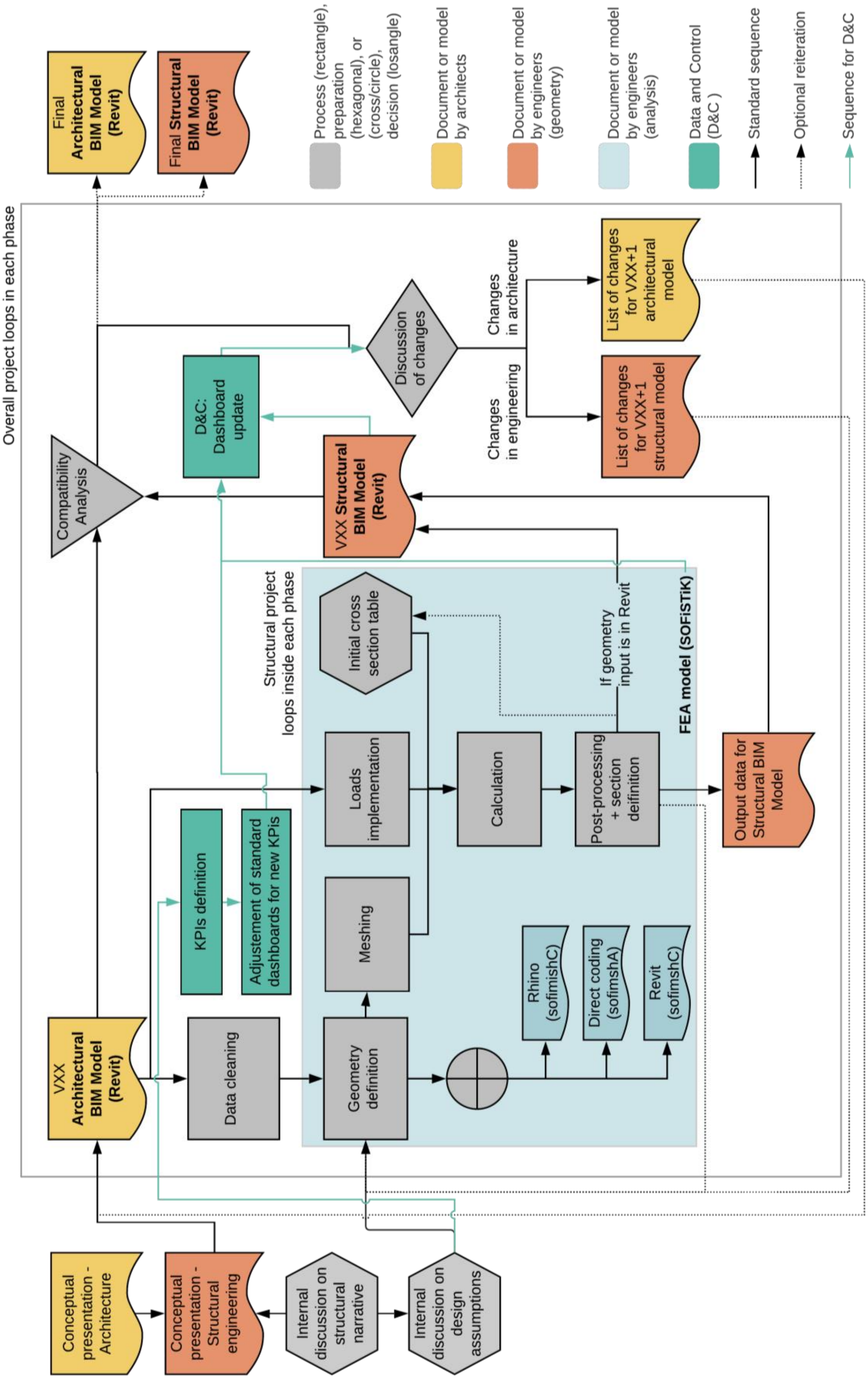


Figure 51: Augmented BIM workflow of structural engineering through data visualization

4.2. Specific objectives of the proposed tool

Even after narrowing the application to the general "Data and control" step, creating a standard project dashboard could serve different specific objectives. Table 14 lists them grouped by type, either related to enhancing internal collaboration, i.e. within the structural engineering office, or external collaboration.

Type	Specific objective	Description
Internal collaboration	Insight on the overall design	Quick visualization of aggregated data of model to overcome the idea from structural engineers that BIM model is a "black box", showing, for instance, the BIM bill of quantities, number of different sections, etc.
	Technical project management	Generally, project managers have a reduced time to look into BIM models, or even structural models, but are very knowledgeable on "big" numbers, such as steel ratio, reasonable number of different sections, etc. In this sense, the tool could provide them an easy way to check and share information to determine if the design is going in an appropriate direction.
	Model comparison	Often, there are many versions of FEA and BIM models and it can be hard to know what exactly has changed between versions and to keep track if this change has been implemented in the structural model. Being able to easily make and show model comparisons could help with that.
	Knowledge management	Once the project information is organized and shown for a given set of projects, this could enhance the work in

		the next projects, creating a knowledge management system.
External collaboration	Output to a client on the quality of data	BIM specialists reported that it would be useful to easily show the client how much of the requirements of the BIM Execution Plan, in terms of information are being followed in the model, to generate value on their work which sometimes is only noticed when there is a problem.
	Communication with architects	Although BCF files are already used, dashboards could be used for a more general overview.

Table 14: Possible goals of an augmented BIM workflow tool

The specific focus of the dashboards generated in the PoC of this thesis is related to insight on the overall design, technical project management, and model comparison.

4.3. Implementation at a proof of concept level

Figure 52 illustrates the implemented information flow, with data extraction from FEA and BIM models, data transformation, and load into a common data warehouse.

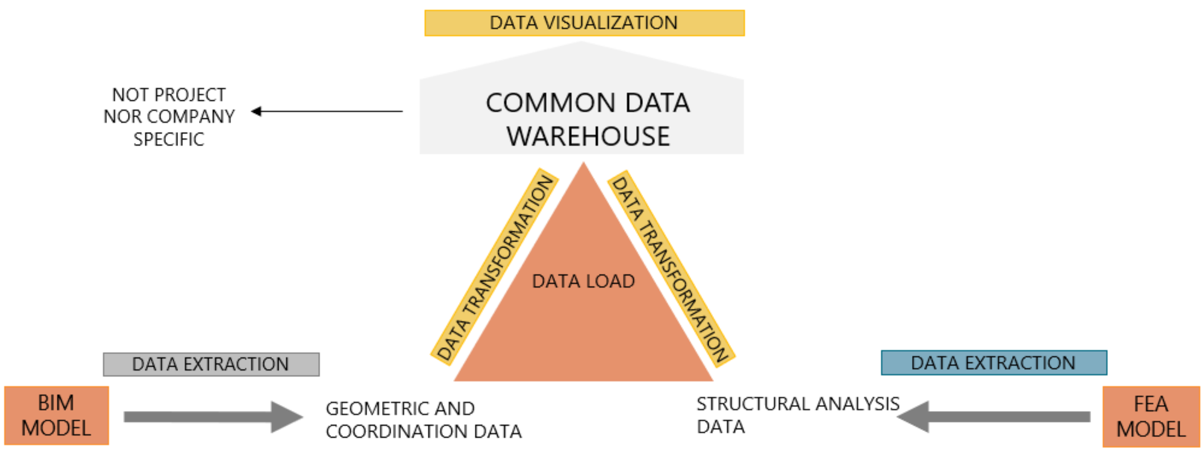


Figure 52: Information flow

The data transformation is applied to conform the data structure in a certain format, which is “understood” by the common data warehouse. This flow was inspired by the Hu et al. (2016) approach with the Unified Information Model. Although implemented for two specific software, Revit and SOFiSTiK, it could easily be adapted to others. It would be a question of applying the right transformation steps so that the extracted data from that other software can be conformed to the data structure used for the common data warehouse.

This software arrangement was chosen to be compatible with the reality of the office in which this research was based. In this way, the PoC would have more chances of being tested, generating relevant feedback, and being successfully used in the future. It was considered to prepare BIM extraction for IFC models instead, but as most of the projects were already using Revit, this would imply an extra step of exporting from Revit to IFC during the data extraction. Beyond that, not every design team member was used to working with the IFC format, so it would be an extra requirement that could hinder the use of the tool in this specific context.

When extracting and transforming data, it is important to be aware of steps that could limit the application to only a specific group of cases. The idea of the tool is that it should be neither project-specific nor company-specific – at least as much as possible.

For example: in a first implementation (BOECHAT; CORRÊA, 2021), to read and understand cross-sections of elements, the name of the “type” within Revit was read and analyzed. This is essentially a string. In that case, it had a particular structure, similar to RHSx300x200x10x10, as an example. It is easy for an engineer to understand this information and code rules to build the knowledge within a database that it represents a rectangular hollow section with 300 mm height, 200 mm width, and thickness of 10 mm. However, if we build this knowledge based on this string simply, this code will hardly be useful for other projects. Often, the naming structure of the sections is determined by project, not because of the engineer’s choice, but because of the client’s choice in the BIM Execution Plan. Therefore, it is realistic to assume that this "RHSx300x200x10x10" may be described as "RHS X 300 X 200 X 10 X 10" or even as "Section 301" in another project that has a section table with that key. This type of specificity is taken into account in the PoC by carefully choosing how to extract information from the FEA and BIM databases, not limiting its application to a given project. Extending the workflow to other software should also be considered.

The choice of interfaces for this implementation considered what would be more user-friendly given the current workflows for the design team. One of the main goals was that the engineer and the BIM specialist should have as little as possible interaction with coding, as this is often seen by those professionals as "too complicated". As presented in the literature review for BIM implementation, this type of technological shift requires individual-level collaboration to be successful (OZTURK, 2019). In this sense, it was preferred to choose tools with user-friendly interfaces, or that at least some individuals in the design team were already used to.

In this context, it was chosen to use:

- For BIM data extraction: Dynamo Player as an interface within Revit. Inside the code, custom-built Python nodes were used, but this is not seen by the user, who just deals with user interface windows;
- For FEA data extraction: Result Viewer as an interface for SOFiSTiK. This works basically like a database viewer that retrieves data from the FEA database and shows it in the form of tables, which are easily exported to Microsoft Excel (.xlsx) files, not necessarily seen by the user;
- For BIM and FEA data transformation and load: the interface of queries from Microsoft Power BI Desktop is used. This is in general a new tool for design teams, but as the structure is a bit similar to some more advanced Excel tools, and Excel is an everyday work tool for structural engineers, the adaptation is not as hard. The

queries allow built-in Python codes, which can be run by users without even seeing the code behind them;

- For Data Visualization: the interface of Microsoft Power BI Desktop. Besides being rather user-friendly, it also allows for custom visuals in some different programming languages. For this PoC, R programming is used.

The possibility of developing a web-based data visualization tool, like the proposal of Loos et al. (2019), was contemplated but not pursued due to the evaluation that the development of actual user-friendly interfaces from scratch would require a level of development that is outside the scope of this thesis.

Figure 53 shows the information flow with the interfaces and software and programming languages used at each step.

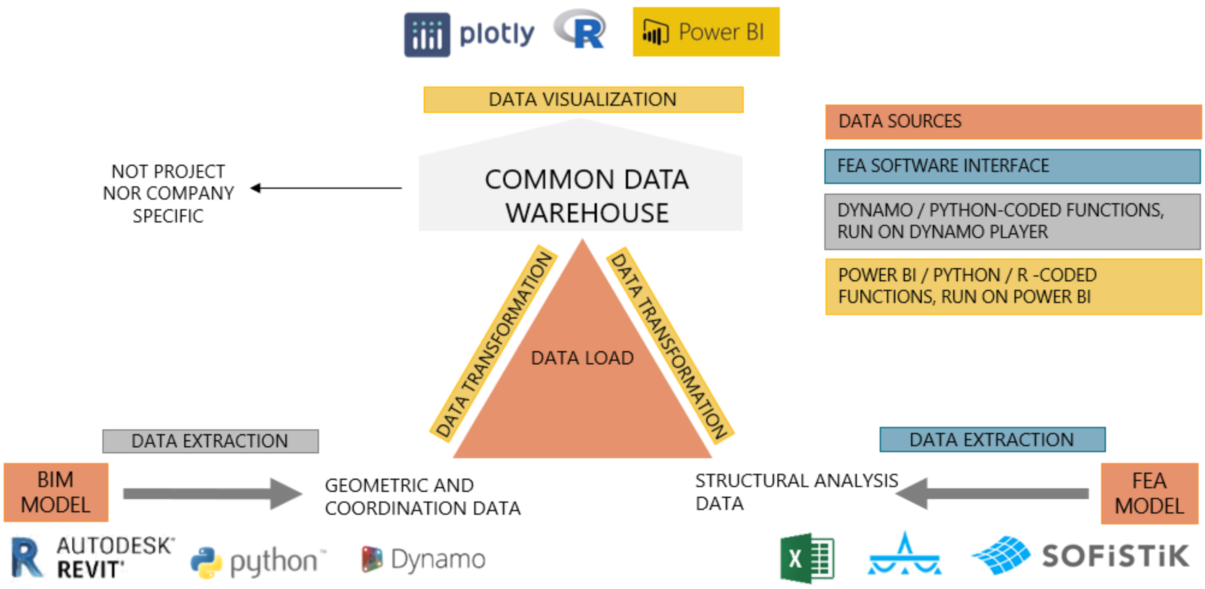


Figure 53: Information flow with software

For this PoC, it was chosen to focus on linear elements (beams and columns), as those are the most commonly represented in BIM models, as found in the survey by Solnosky (2016) and confirmed in the analysis of typical design workflows. Furthermore, as the office for which this research was based worked mostly with steel structures, the common data warehouse was designed for this type of structural project.

4.3.1. Interfaces

Figure 54 shows an overview of the interface of Dynamo Player within Autodesk Revit.

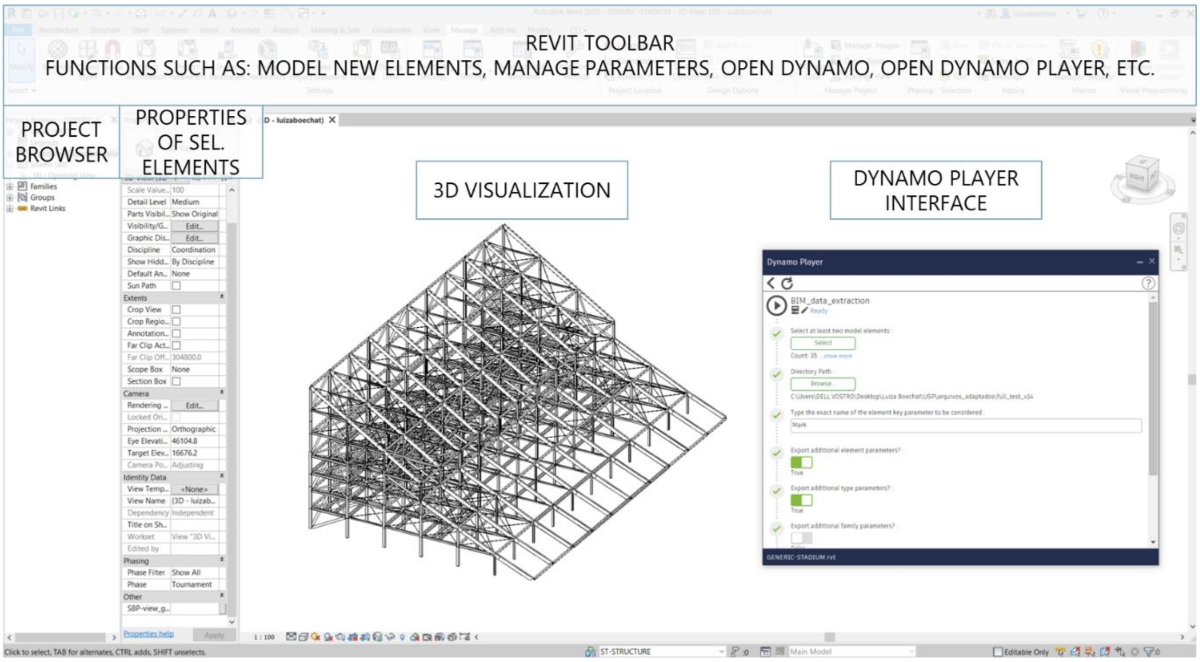


Figure 54: Interface of Dynamo Player within Autodesk Revit

Figure 55 shows an overview of the interface of SOFiSTiK Result Viewer, with tables already prepared for extraction.

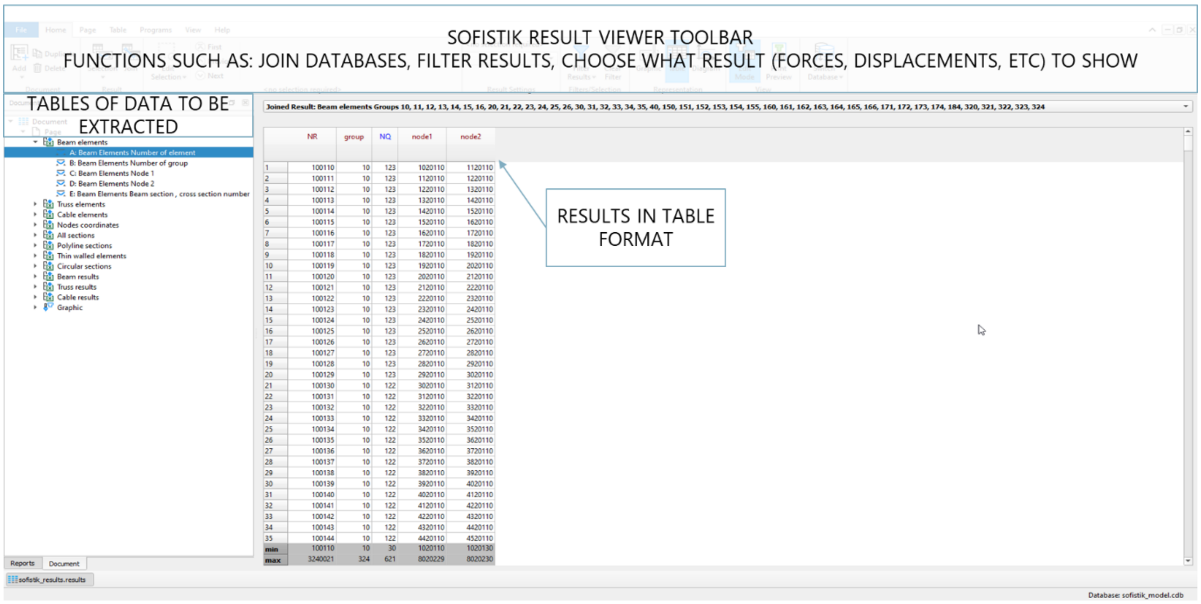


Figure 55: Interface of SOFiSTiK Result Viewer

Figure 56 shows the interface of Power BI Desktop for data transformation, with some loaded tables.

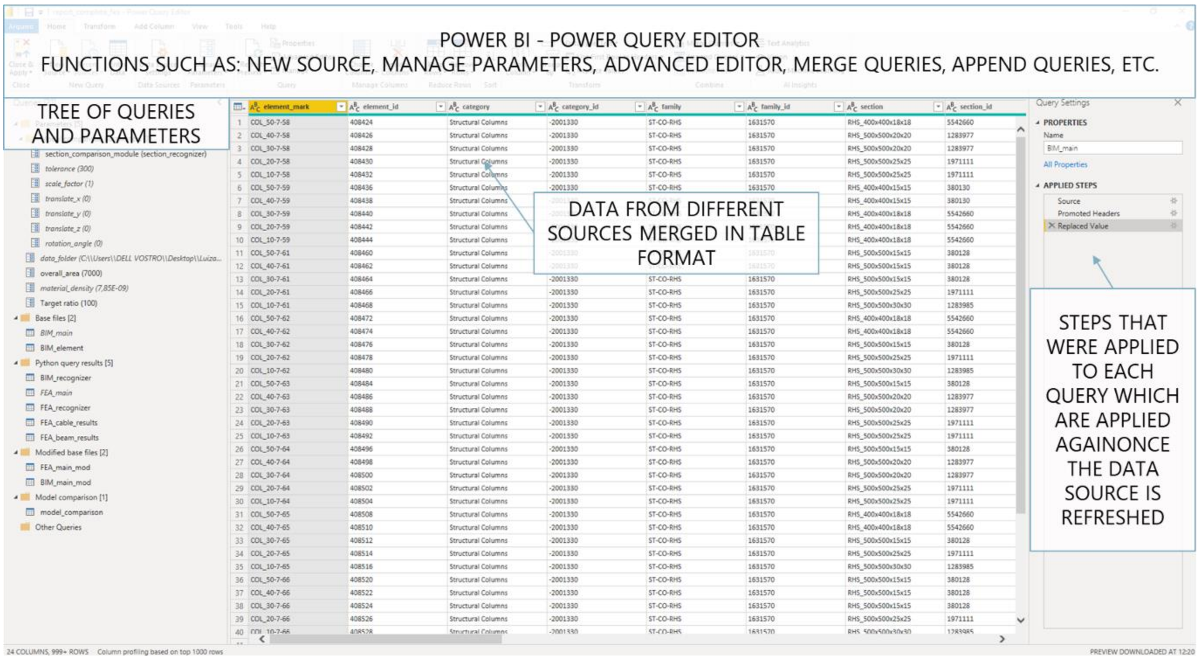


Figure 56: Interface of Power BI Desktop – data transformation window

Figure 57 shows an overview of the interface of the Power BI Desktop for data visualization.

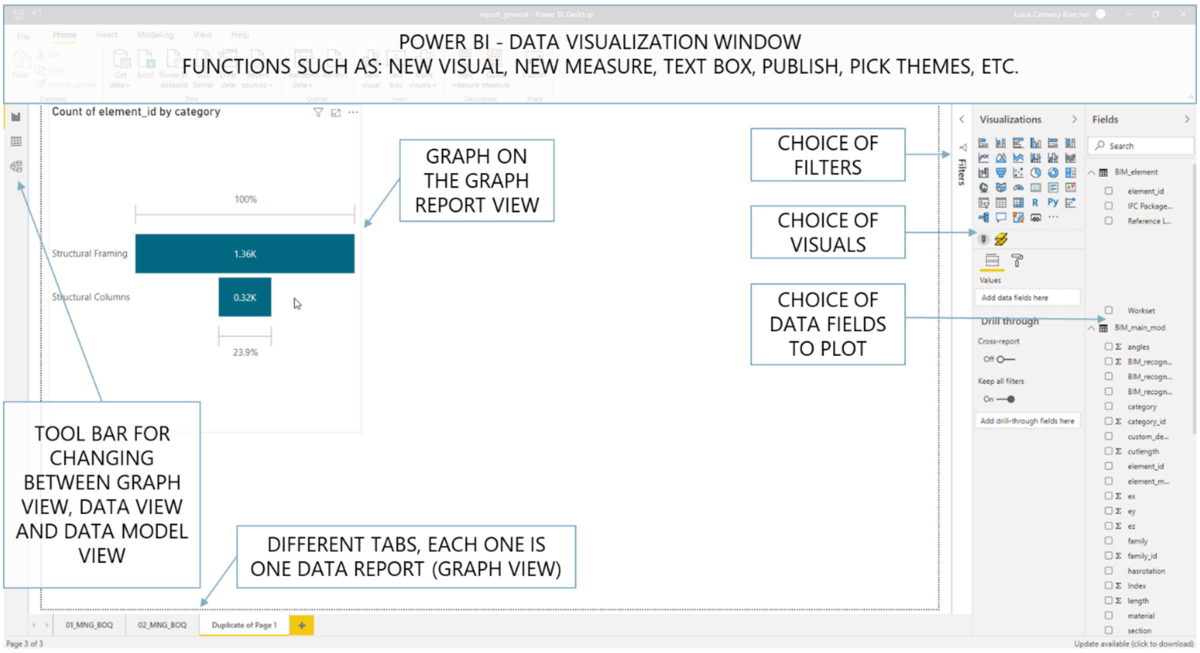


Figure 57: Interface of Power BI Desktop – data visualization window

4.3.2. Data organization

This subchapter explains the information workflow from the user's point of view. This applies to each BIM local model. The use of the tool would start via a standard project folder, containing placeholder files with sample information, as shown in Figure 58.

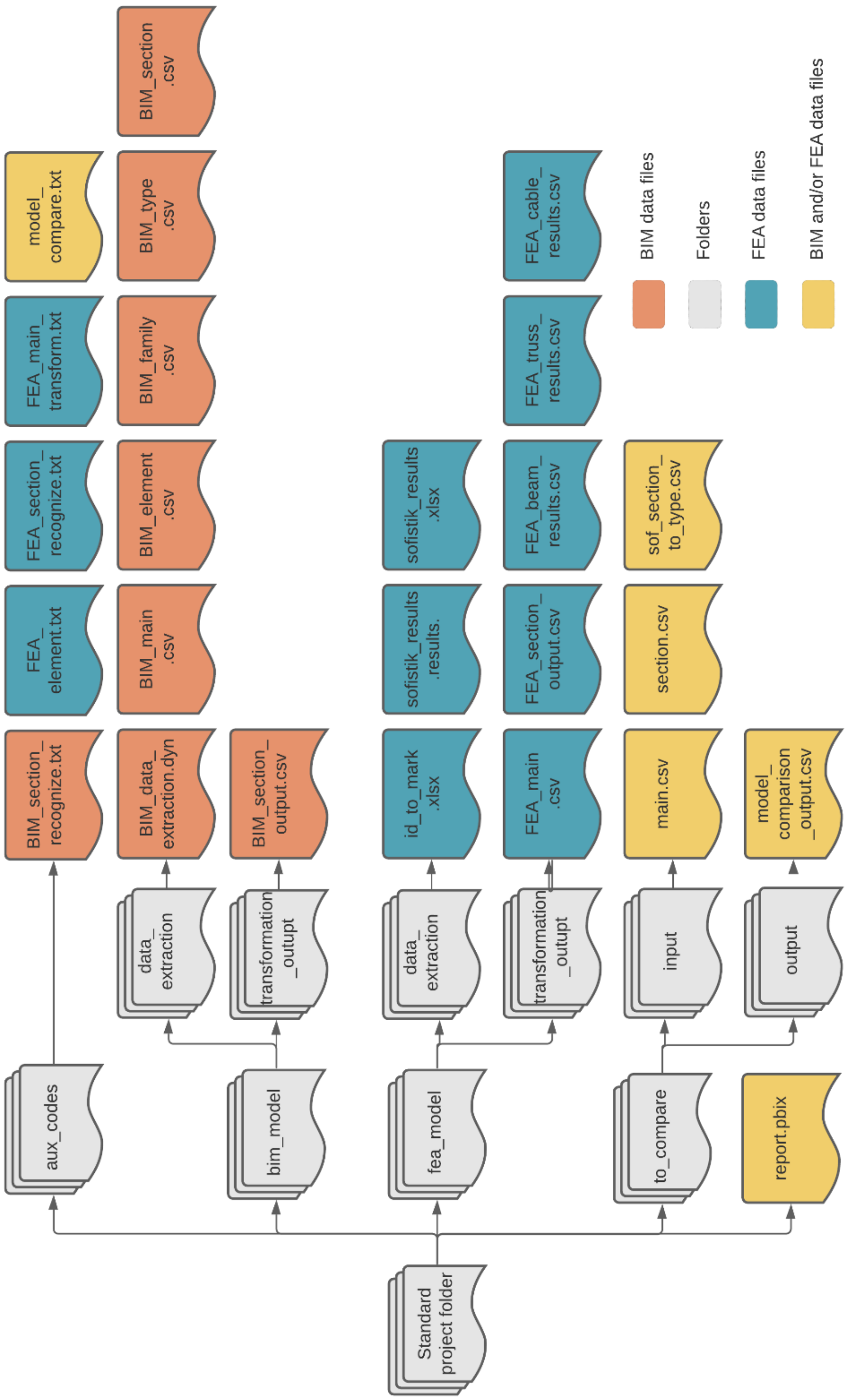


Figure 58: Standard project folder organization

The folder and file's names and structure must not be changed. For all interfaces, when asked to select a folder, the user must select this standard project folder.

4.3.3. Implemented functions

It is important to highlight that the proposed tool has a minimum basic function, which is to extract and visualize the data from the BIM model. All the other functions are optional, as shown in the overall information flow for the user, in Figure 59.

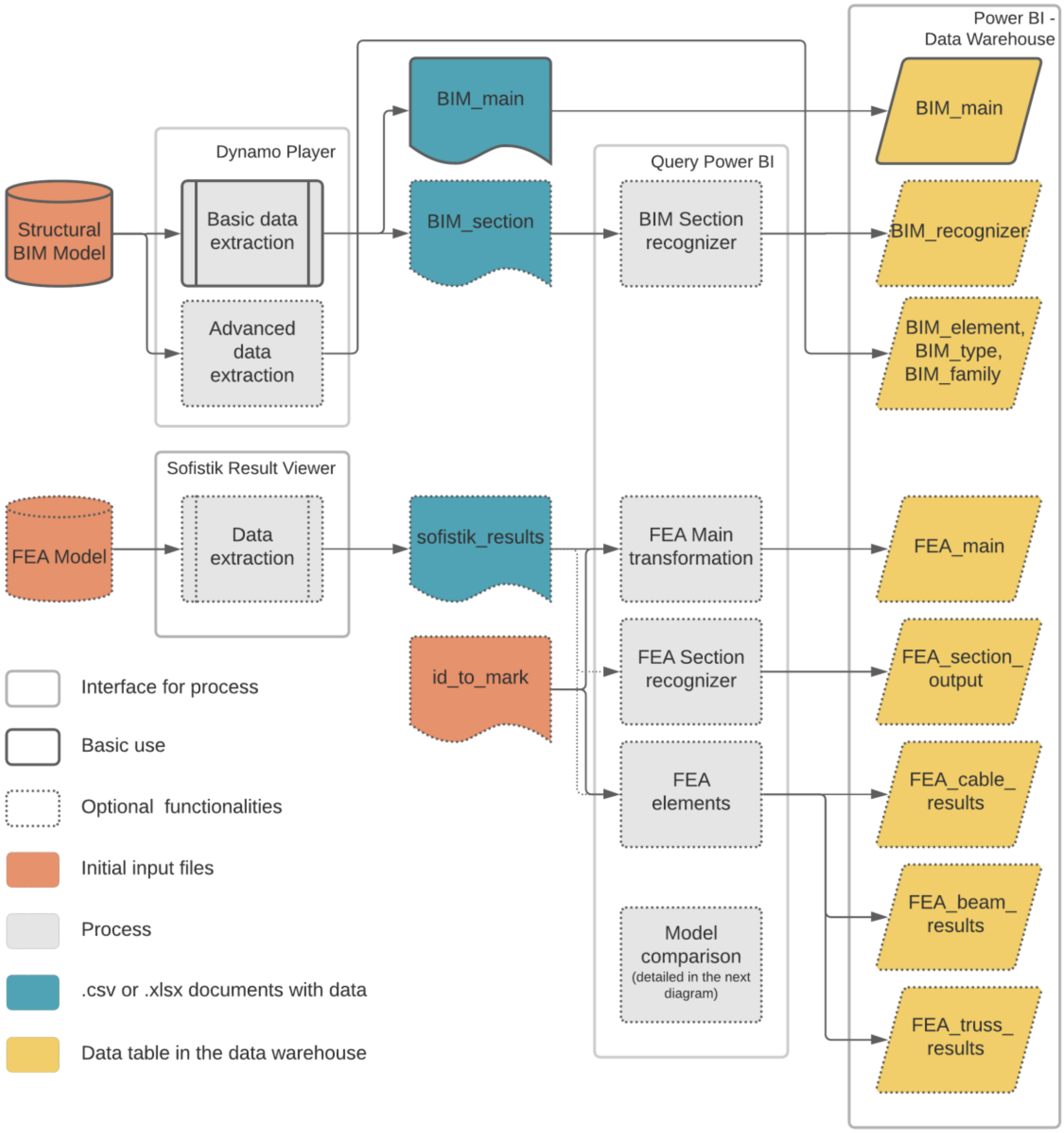


Figure 59: Information flow with software from the user perspective

In this context, the most basic use of the tool is the following:

1) BIM model – Basic data extraction: This is executed within Dynamo Player and it generates a file called *BIM_main.csv*. The correspondent data is directly fed into the Power BI data warehouse as a data frame with the same name. At this step, the user chooses what is to be considered the "element mark". In the proposed tool, this is the most important parameter of the element. It needs to be unique and will be used to track and attach information to the element throughout the workflow.

Optionally, more complete extraction of data from the BIM model is also possible:

2) BIM model – Advanced data extraction: This is executed within Dynamo Player and it generates one or multiple files - *BIM_section.csv*, *BIM_element.csv*, *BIM_type.csv,* and/or *BIM_family.csv*. The three last files can be directly fed into the Power BI data warehouse as data frames with the same name; *BIM_section.csv* can optionally serve as input for the BIM section recognizer at a later step.

After step 2 is performed, the user can optionally execute:

3) BIM model – BIM section recognizer: This step should be performed when a pure geometry comparison of BIM cross-sections is desired. It is executed as a Power BI query and it reads the *BIM_section.csv* file, generating an output data frame with sections described in a standard way. Then, it is automatically fed into the Power BI data warehouse, as a data frame called "BIM_recognizer". An output file *BIM_section_output.csv* is also created in the standard folder.

If desired, FEA data, from SOFiSTiK models, can also be integrated into the data warehouse.

4) FEA model – Data Extraction: This is executed in Result Viewer and it reads the SOFiSTiK database file, generating an output Microsoft Excel file, called *SOFiSTiK_results.xlsx* with several different tabs, each of them containing one data frame.

5) FEA model – Data Extraction – FEA Main transformation: This is the way to feed the most basic FEA information into the data warehouse. After doing step 4) the user needs to update the file called *id_to_mark.xls*x. This table maps all ids in SOFiSTiK to their correspondent mark in Revit. It was chosen to leave this as manual input since the way this relationship is determined varies a lot from project to project, but it is essential to constitute a common data warehouse. Then, the user can execute the "FEA_main" Power BI query, which reads the *SOFiSTiK_results.xlsx* file, reorganizes the geometry data, and creates a data frame called "FEA_main". This is directly fed into the Power BI data warehouse. The output file *FEA_main.csv* is also created in the standard folder.

Optionally, the user can try to recognize the FEA cross-sections and input them into the data warehouse in the prepared standard nomenclature. For that, the user should execute:

6) FEA model – Data Extraction – FEA section recognizer: This step should be performed when a pure geometry comparison of FEM cross-sections is desired. It is executed as a Power BI query and it reads the *SOFiSTiK_results.xlsx* file, generating an output data frame with sections described in a standard way, which is automatically fed into the Power BI data warehouse, as a data frame called "FEA_recognizer". An output file *FEA_section_output.csv* is also created in the standard folder.

If the user wants to go further on the extraction of FEA data, one option was programmed in this implementation, and many other could be programmed in the future. In this case, the user should execute:

7) FEA model – Data Extraction – FEA elements: This is executed as a Power BI query and it reads the *SOFiSTiK_results.xls*x file. It generates an output data frame with maximum and minimum internal forces per mark given a selection of load cases, which is automatically fed into Power BI data warehouse, as data frames called

"FEA_beam_results", "FEA_truss_results" and "FEA_cable_results". Output csv files with the same name are also created in the standard folder.

The last optional step is:

8) Model comparison: This is a complex feature on its own, and therefore its implementation is shown in a specific diagram (Figure 60).

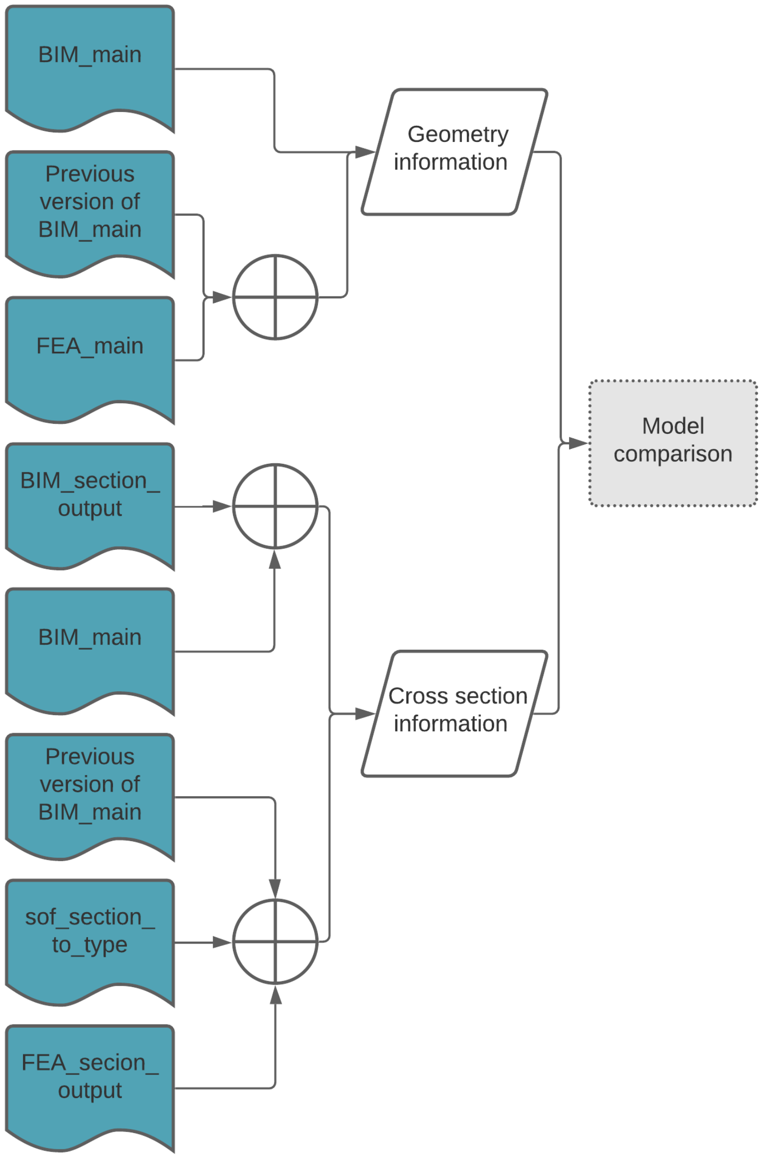


Figure 60: Information flow with software from the user perspective – model comparison

There are some options on how this model comparison may be performed. Regarding overall geometry information:

- Current geometry: reads from *BIM_main.csv* file;

- Comparison geometry: reads from the *main.csv* file in the project folder. The content of this file can be either from a previous version of a *BIM_main.csv* file or from the *FEA_main.csv* file;

Regarding cross-section information:

- Current cross-sections: reads either from *BIM_section_output.csv* or from *BIM_main.csv*;
- Comparison cross-sections: reads from the *section.csv* file in the project folder. The content of this file can be either from a previous version of a *BIM_main.csv* file or from the *FEA_section_output.csv* file or from a manual file. Alternatively, the file *sof_section_to_type.csv,* containing a table that maps SOFiSTiK cross-section numbers to Revit type numbers, would be read.

Figure 61 describes the criteria for model comparison as implemented.

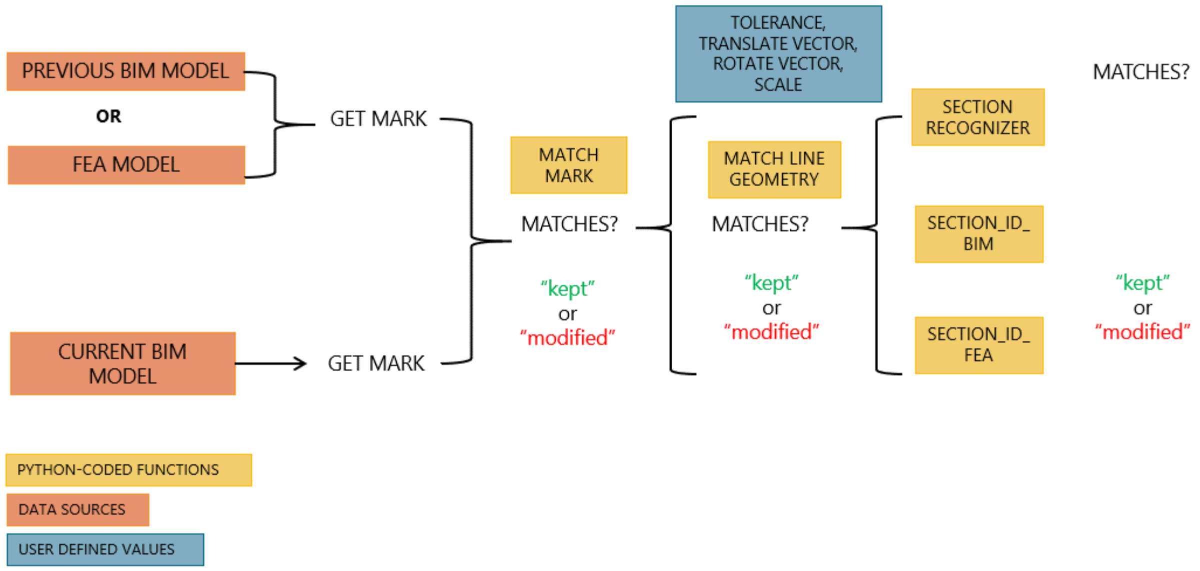


Figure 61: Description of model comparison script

Each of those options is more specifically described, including an explanation of which information is extracted and transformed at each step in Appendix B and Appendix C, respectively. Details of the programming packages that the user needs to install to execute the tool are given in Appendix A.

4.3.4. Data load

The data is loaded in Power BI (the location of the data warehouse) via Python queries and standard queries, which simply read a file containing a data table via manual input. Figure 62 shows the list of queries in the standard report of Power BI. They are grouped into: Parameters, Base files, Python query results, Modified base files, and Model comparison.

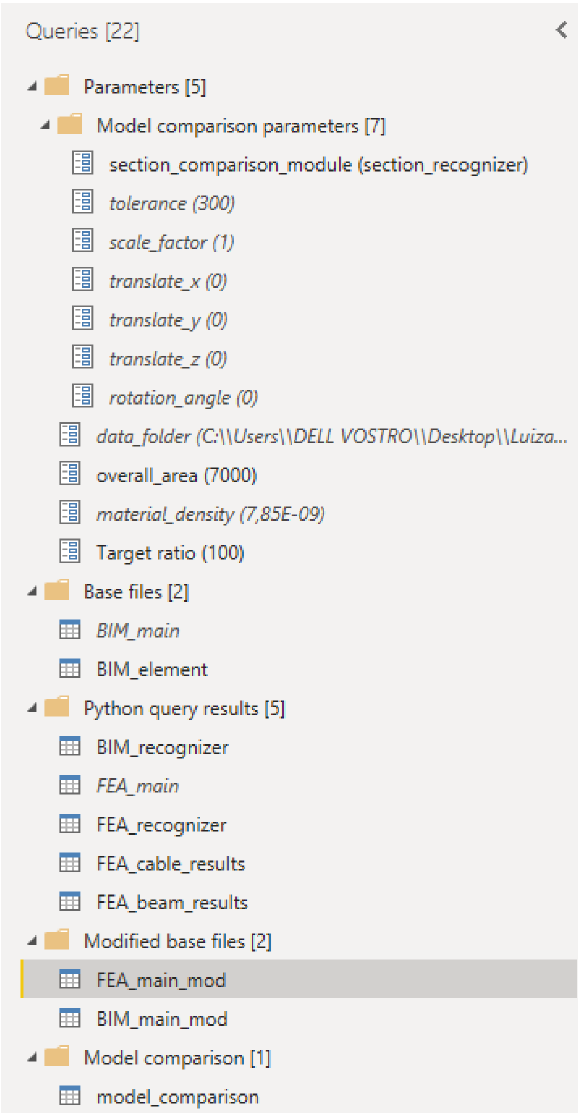


Figure 62: List of queries in Power BI

Some simple transformations are done after the data is loaded to Power BI, such as sorting, adding index do data frames, etc. More importantly, the joining of data in the data warehouse through joining key columns in each imported data frame is also done directly in Power BI. This results in the data warehouse model for a given project, which is illustrated in Figure 63.

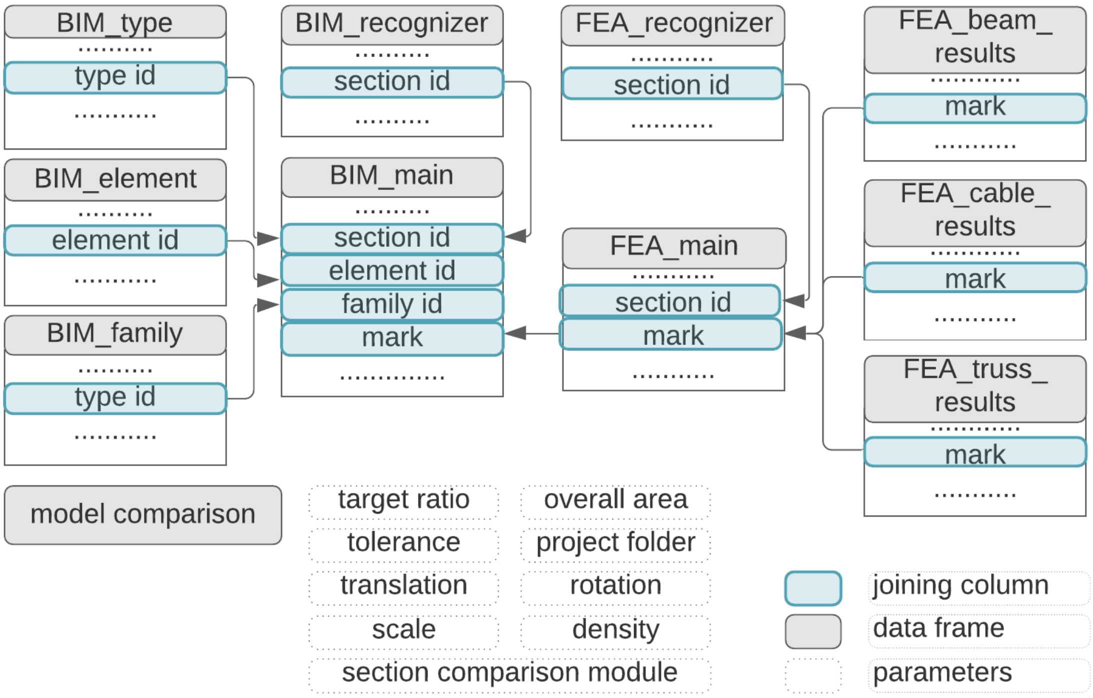


Figure 63: Data model in Power BI

4.3.5. Data visualization

The software chosen for data visualization in this PoC, Power BI Desktop, is primarily intended for the generation of business reports and dashboards. It offers a wide range of visuals for this type of data. Most of the standard ones, mentioned in section 2.1.3 are found either on the standard Visualization toolbar or in an interface for importing visuals called “Appsource”. These interfaces are illustrated in Figure 64.

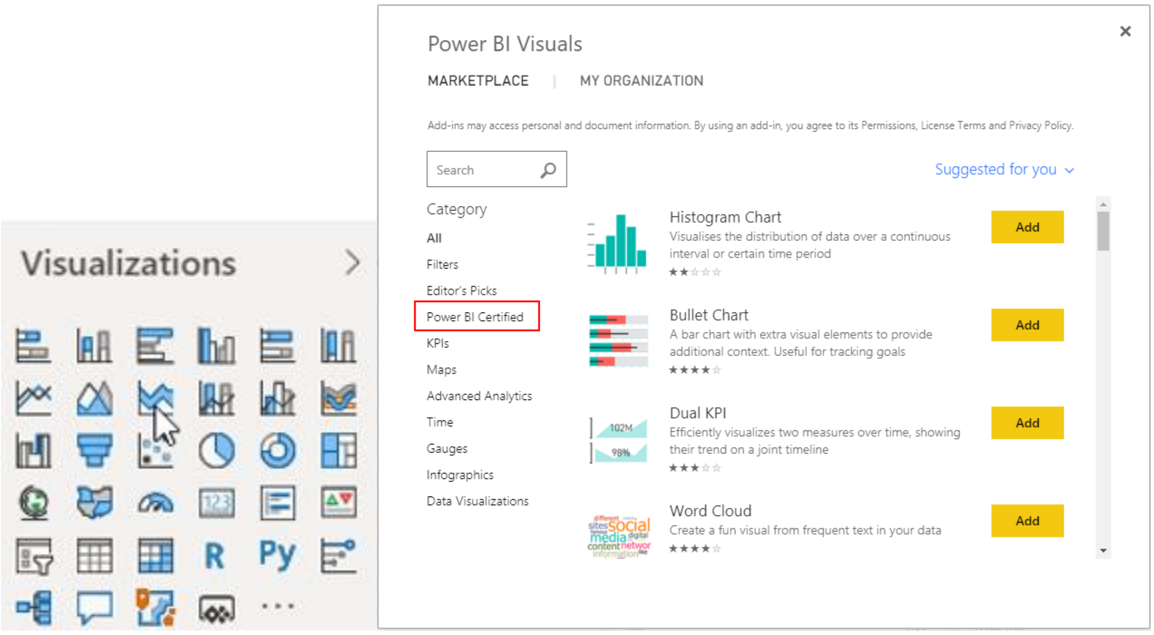


Figure 64: Data visualization available in Power BI

4.3.5.1. Custom visuals

Power BI desktop also offers flexibility, as the user can develop graphs using some libraries of Python and R, developing what is called a custom visual. R language was chosen as the option to develop geometry visuals in this case.

Some important considerations about the functionalities desired for data visualization for the proposed tool are:

- One should be able to represent geometry. In our case, the simplest geometry is given by lines, determined by start and end points;
- As the structural model is given by a network of elements, whose visualization in 3D might be quite complicated, it is important to be able to zoom and orbit in the visualization;
- For complex models, it could still be hard to visualize the elements. Thus, it is important that the visualization can be filtered, showing, for instance, only the elements that have a certain parameter value.

All of that is implemented in Power BI through custom visuals creating .html visualizations inside the report page, using a library for R programming package called Plotly. Two main custom visuals are implemented:

- mark_plot: plot of each element by coordinates of start and end points, with the mark appearing as information when the user hovers over an element node. This is shown in Figure 65 and Figure 66.

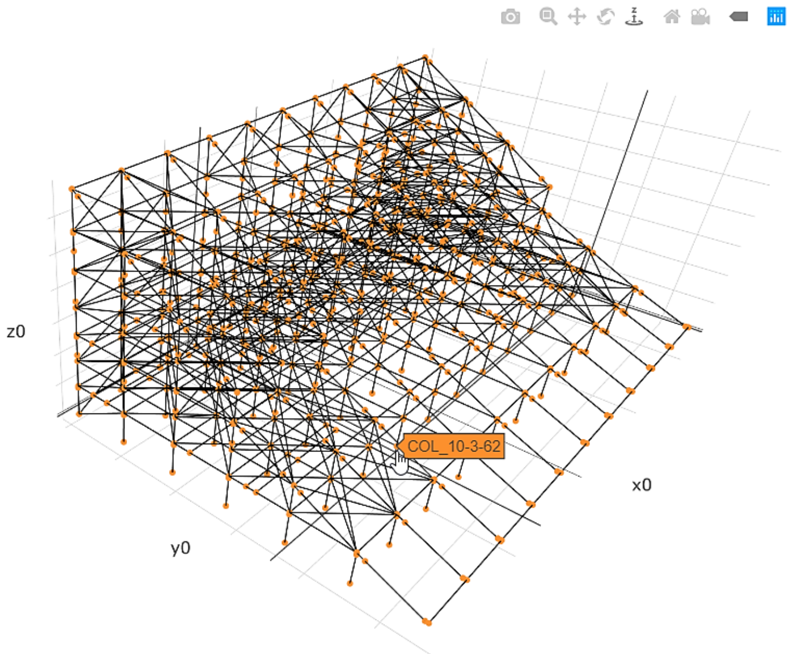


Figure 65: Mark plot custom visual - overview

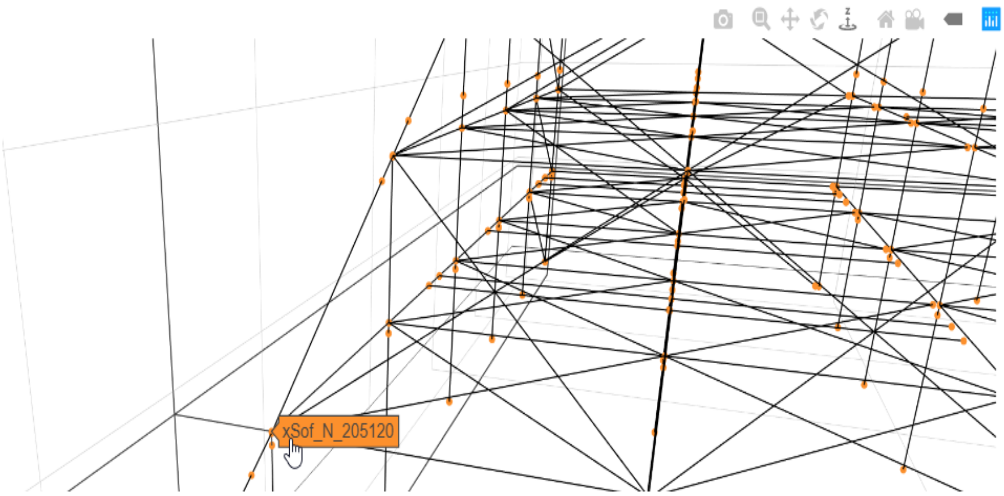


Figure 66: Mark plot custom visual – zoom

- comparison_plot: plot of each element by coordinates of start and end points, with the mark appearing as information when the user hovers over an element node.

The element color is red if the element has been deleted in the current database, yellow if it has been modified or green if it is new. This is shown in Figure 67.

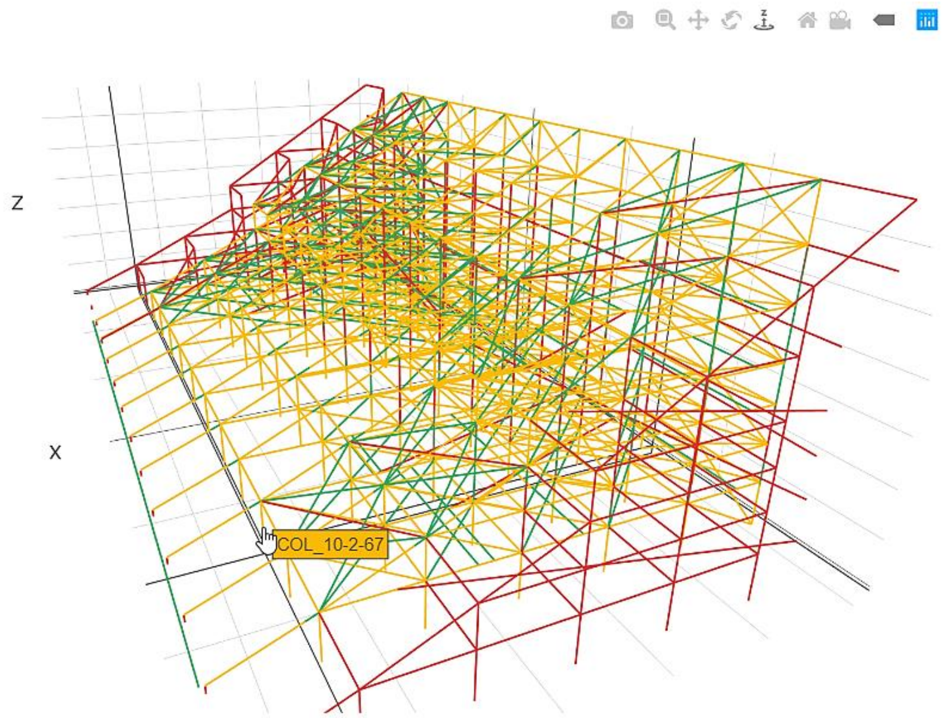


Figure 67: Comparison plot custom visual

Those graphs are available under the standard Visualizations table in the Power BI standard report file as shown in Figure 68.

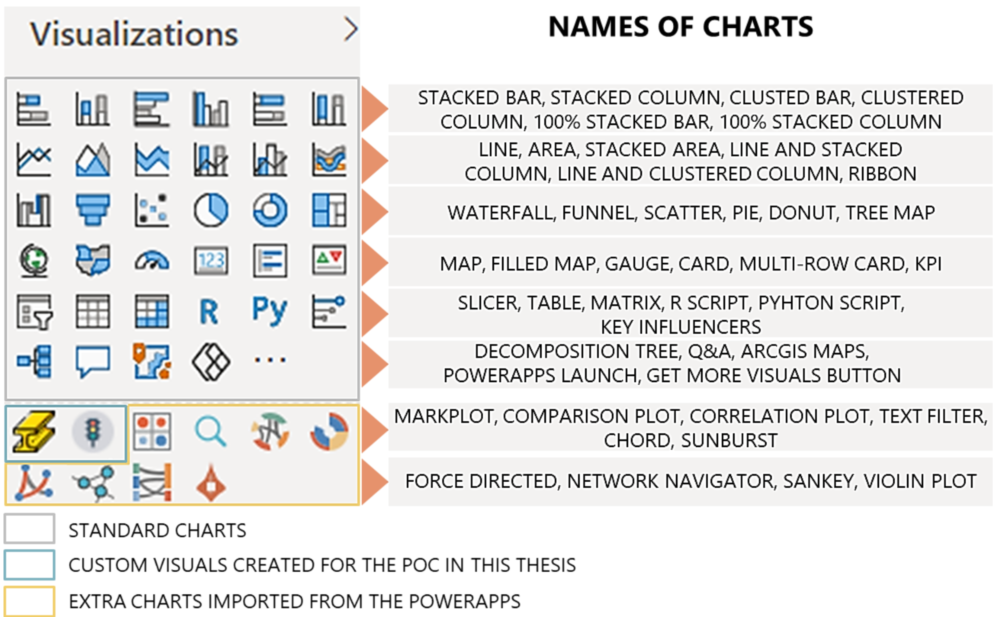


Figure 68: Visualizations explored in this PoC per type (standard, custom, extra)

4.3.5.2. Standard report pages

With the data loaded in the data warehouse in the previous steps, several different visualizations can be generated within Power BI. As the main purpose of this workflow is to enhance collaboration, standard reports (or dashboards) for different uses and users were elaborated.

They were first presented as proposals, illustrating the modified data for two types of projects: stadium bowls and a frame structure building. This is shown in Figure 69, Figure 70, and Figure 71. After receiving feedback from the design team, the dashboards were refined, and the final standard reports are presented in the results of this thesis.

One important reminder is that all data presented in the dashboard is only for illustration purposes, and has been modified from the original projects, as explained in section 1.4.

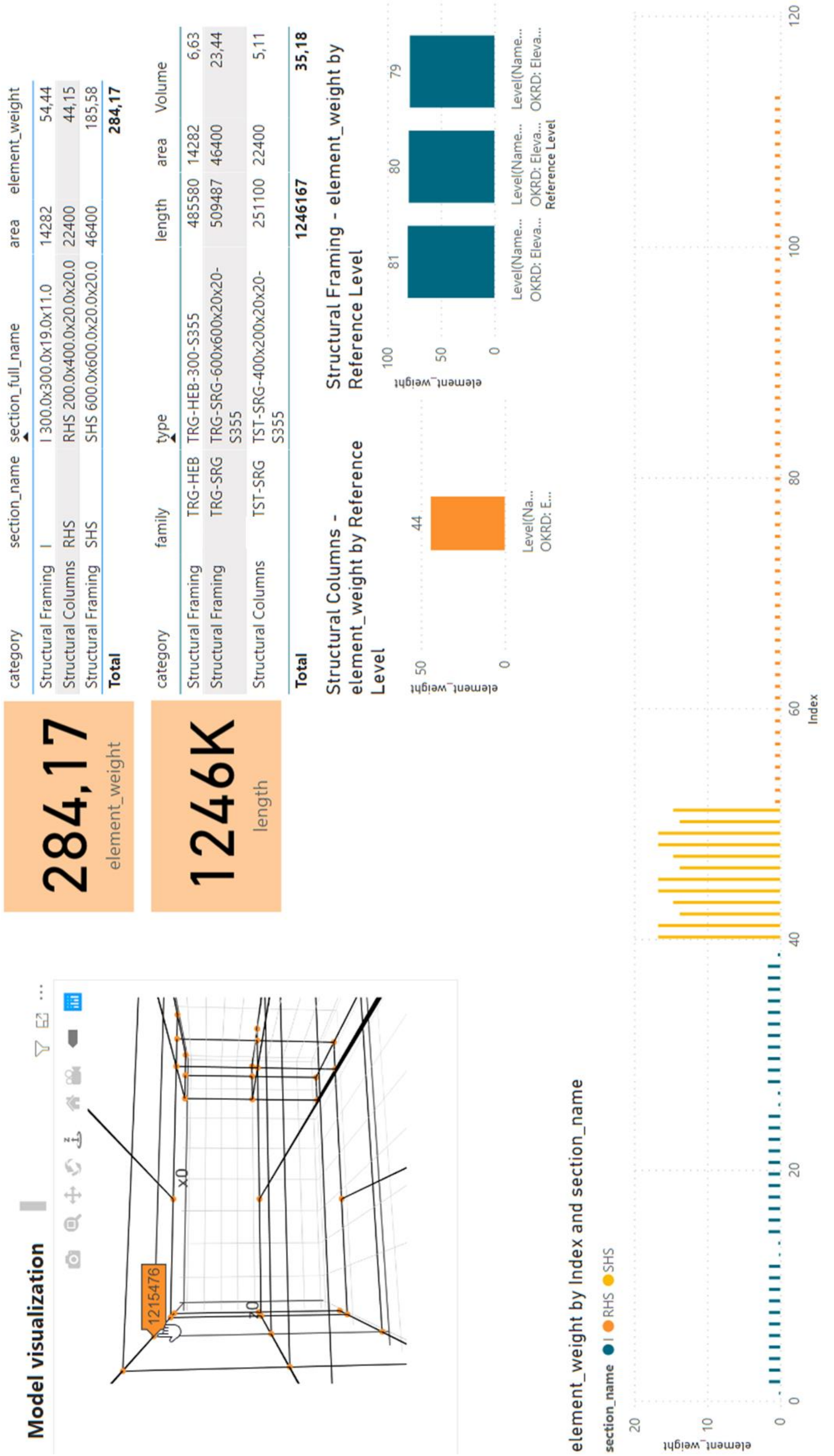


Figure 69: Initial produced report – sample 1

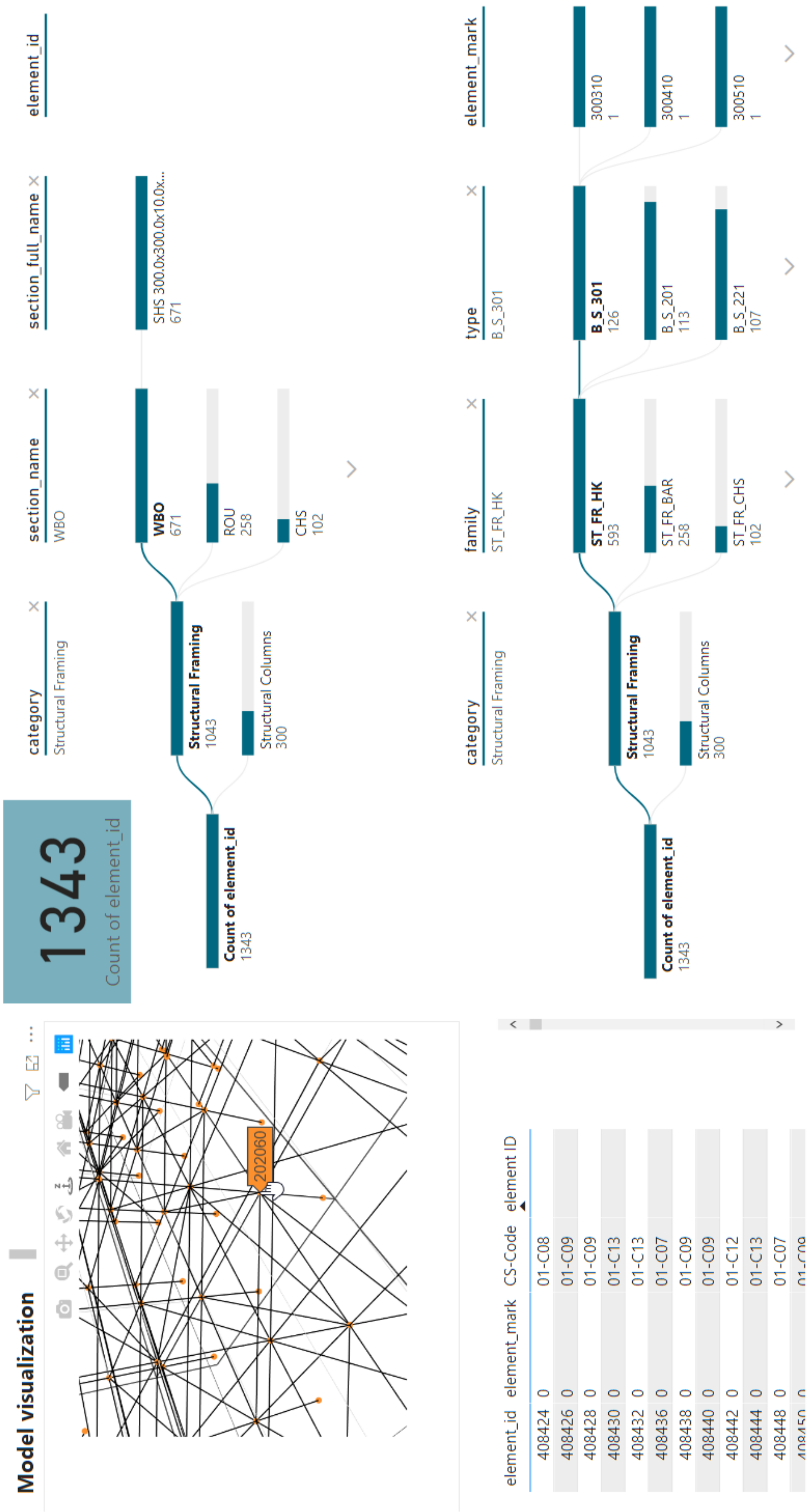


Figure 70: Initial produced report – sample 2

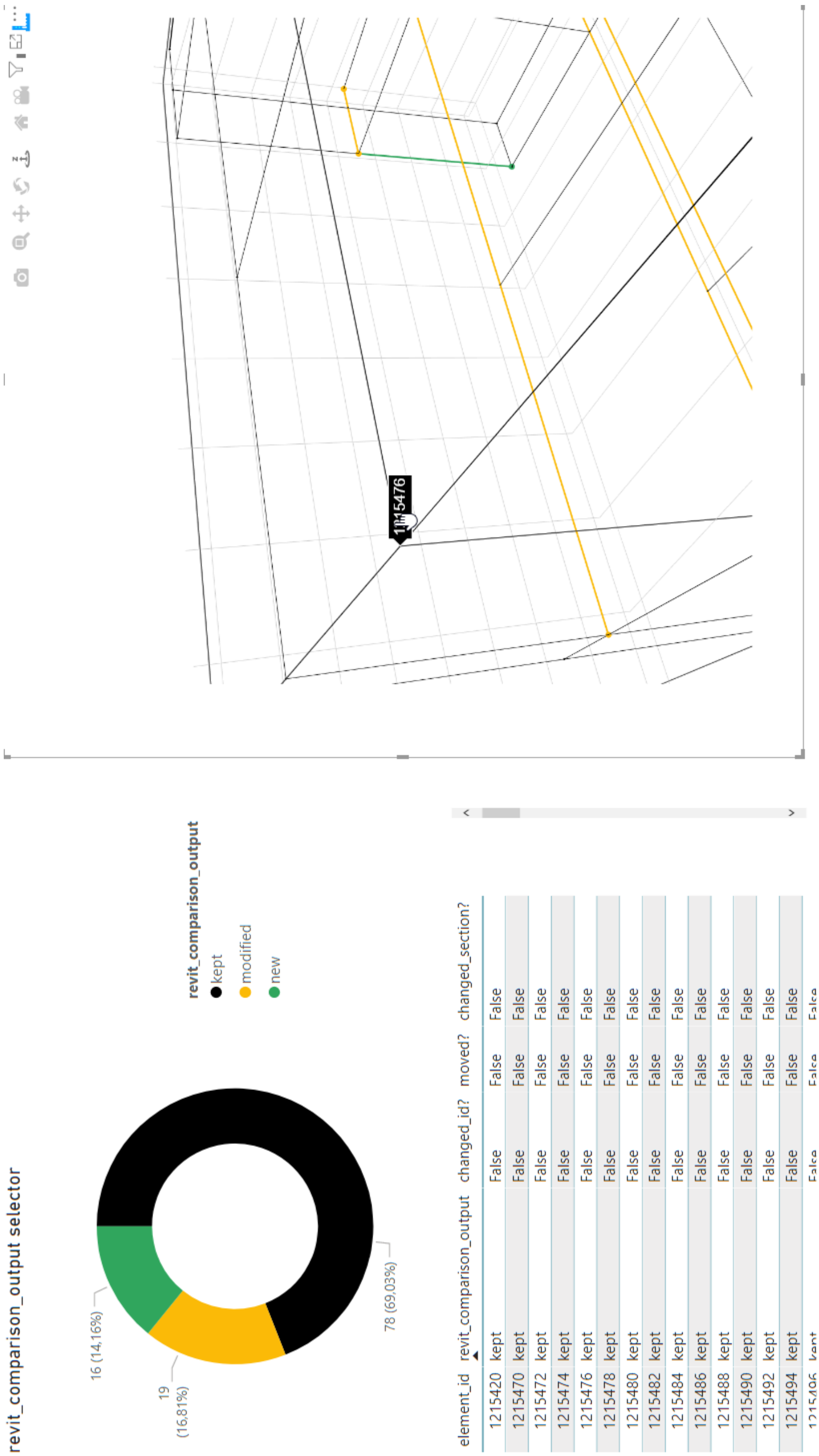


Figure 71: Initial produced report – sample 3

5. RESULTS

5.1. Feedback from potential users

The proposal of the data visualization tool and PoC was presented to ten team members, including design engineers, BIM specialists, and project managers. The latter had not participated in the initial interviews. This was done by demonstrations followed by qualitative semi-structured interviews. Firstly, the interviewees were briefly presented with the context and justification of the idea. The content was very similar to the section with this same name in this thesis. After that, they were shown the initial proposed standard dashboards, as in Section 4.3.5.2. Then, the following questions were made:

- Do you think that having a standard project dashboard somewhat close to these images would have been useful in your current or past projects?
- Which applications of this type of tool and workflow do you think to make sense?
- What type of information would you like to see in such a dashboard?
- With which frequency would you like to see this information?
- Would you rather receive a pdf or be able to explore interactively the dashboard?

Feedback from project managers was positive, with a general agreement that having a tool like the proposed one would be useful in the project. There was an overall wish that the dashboard could be used for controlling the evolution of the BoQ along with the project – from the BIM model and the FEA model, as they often differ due to the way element intersections are considered.

Project managers pointed out that, often, when they request a BoQ from the BIM specialist, it takes at least a couple of days to receive the information, whilst they expected to receive it in a maximum of a couple of hours. According to a BIM specialist, there are frequently many considerations that need to be made in the model or extraction of quantities at each time, so that it makes sense for the structural engineer.

Some examples are: elements only modeled in the BIM model but that are not structural, adjustments on how to cut lengths are considered, material and material density has not been implemented in every project so that weight per element needs to be externally calculated, etc. In this context, finding a common set of rules to calculate a BoQ, that could apply to all projects and implementing them in the Power BI visualization was one of the received suggestions.

Related to this BoQ focus, some project managers reported that, when doing acquisition proposals, it is rather difficult to find the latest detailed BoQ information of past projects, including steel ratios, for use as reference. Once the dashboard is implemented for a reasonable number of projects, it was suggested that the compilation of project data in the data warehouse be executed, to facilitate knowledge management and sharing in this sense.

It was also suggested that from the beginning of the project, managers put a target ratio per element type, such as kilos of cables per square meter in a stadium roof of a certain type, kilos of steel per square meter of stands on a stadium bowl, etc. This target would be followed as a KPI in the dashboard. In an opposite sense, some of the project managers pointed out that the information of target ratio would not be on a standard dashboard as it is a company (or personal) specific knowledge that should not be shared with every person on a team.

In terms of the frequency of updating this report, the answers ranged from weekly to every two weeks. Some of the project managers would like to be able to interact with the graphs, and others indicated that they would have no time for it and would prefer to receive a pdf via e-mail.

This depends a lot on the project manager: some tend to be more controlling of their FEA models and others preferred to delegate more to project engineers. On the BIM model, they seem to delegate the checking work more often – and this is exactly a strength of the data visualization tool, making the engineers and project management more aware of what is going on with the BIM model, which is at the end what will be output to the client.

It was clear that model comparison and any other more specific information are much more an interest of engineers and BIM specialists than of project managers. Engineers were enthusiastic about a tool that could help them to track changes. They had previous experiences in which they needed to compare models rather manually and with no access to standard comparison or visualization to show the results in a way that communicates with project managers. The latter type of professional is much more interested in seeing the "big" numbers.

Regarding the structural results and other parameters, it seems like this would be a more ad hoc use. BIM specialists might find it interesting to see some specific element parameters, such as comments that they use to track model updates. This would not interest project managers or structural engineers as much. On the other hand, engineers might find it useful to track the capacity ratio of elements and cross-check where the elements with the worst ratio, determined via Excel post-processing, for instance, are located in the BIM model.

During the interviews, some project managers presented specific reports that they do for organizing information on their projects. One relevant example was a project sheet with all the main structural information for a given project. This included the main span and any dimension structurally relevant for the overall ratio, the steel ratio per type of element, the material specification, the cross-section sizes of each main element, etc. Although this might seem like pieces of information that should be immediately shared across the office to base other projects, it was also pointed out that this may be competitively sensitive information, and sharing openly and systematically would not be in the office's best interest.

Given the feedback, the initial standard report pages were refined and the final proposals are described in the next chapters.

5.2. Standard dashboards

The following sections show the final proposed dashboards with modified data as described in Section 1.4. The nomenclature was defined as YY_XXX_ZZZ, in which:

- "YY" is a reference number;
- "XXX" specifies the target user of the report, with "MNG" for managers and "COO" for coordinators, either BIM specialists or structural engineers;
- "ZZZ" describes the content, with "BOQ" for the bill of quantities, "COM" for model comparison, "FEA" for specific FEA model information, and "BIM" for specific BIM model information.

5.2.1. 01_MNG_BOQ and 02_COO_BOQ

The reports "01_MNG_BOQ" and "02_COO_BOQ" present only the data taken from the "Essential use" module. As this is supposed to be done with the minimum information from the BIM model, the volume used to calculate the weights is the value of the standard Volume parameter in Revit.

For 01_MNG_BOQ, presented in Figure 72, the following graphs were considered necessary according to discussions with Project Managers and BIM specialists:

- Card - with the total number of elements;
- Card – with the total weight;
- Card – with the overall ratio;
- Card – with the number of different types;
- Donut chart – weight by category;
- Donut chart – weight by workset;
- Donut chart – weight by family;

- Donut chart – ratio by category;
- Donut chart – ratio by workset;
- Donut chart – ratio by family;
- Decomposition tree – weight per category, workset, family, type, section, element mark;
- Mark_plot – element lines and marks.

02_COO_BOQ is shown in Figure 73 and provides more detailed numbers, for coordination control. The graphs shown are:

- Waterfall chart – contribution of each section to the overall weight;
- Table – BOQ table by category, workset, family, and section showing material, density, volume, and weight.
- Clustered column chart – 1000 heaviest elements sorted, with legend per family. When hovering shows element mark.

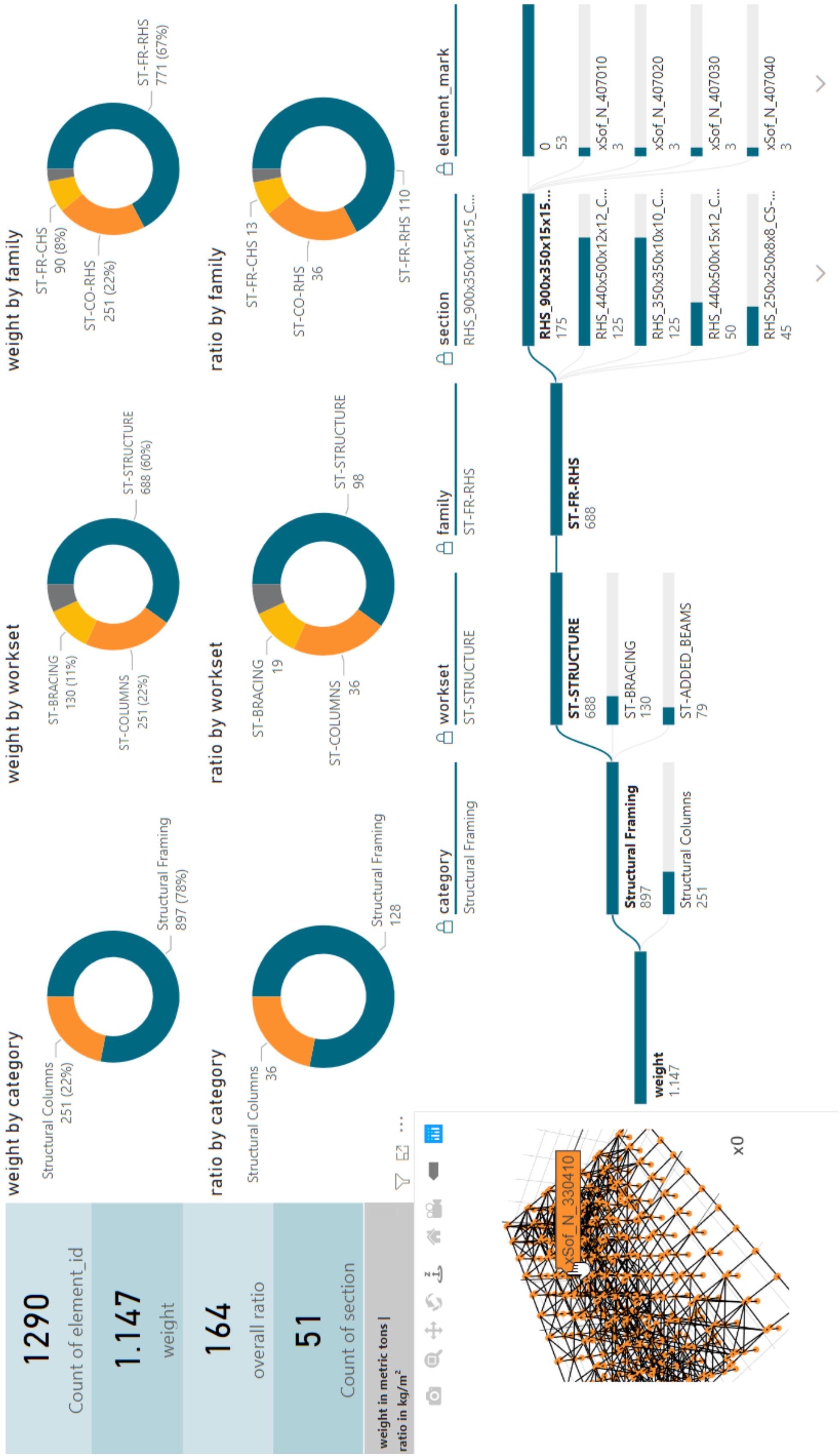
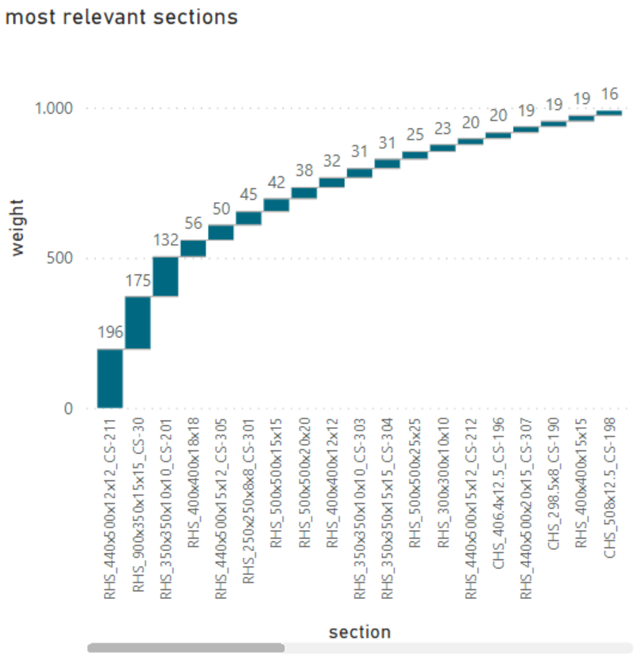


Figure 72: 01_MNG_BOQ overview



BOQ TABLE

category	workset	family	section	material	custom_density	volume	weight
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_900x350x15x15_CS-30		7,85E-09	22,3	175,2
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_440x500x12x12_CS-211		7,85E-09	15,9	124,7
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_350x350x10x10_CS-201		7,85E-09	15,9	124,6
Structural Framing	ST-ADDED_BEAMS	ST-FR-RHS	RHS_440x500x12x12_CS-211		7,85E-09	9,1	71,1
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_400x400x18x18		7,85E-09	7,1	55,6
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_440x500x15x12_CS-305		7,85E-09	6,4	50,0
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_250x250x8x8_CS-301		7,85E-09	5,8	45,1
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_500x500x15x15		7,85E-09	5,4	42,5
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_500x500x20x20		7,85E-09	4,8	37,7
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_400x400x12x12		7,85E-09	4,1	32,4
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_350x350x10x10_CS-303		7,85E-09	3,9	31,0
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_350x350x15x15_CS-304		7,85E-09	3,9	31,0
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_500x500x25x25		7,85E-09	3,2	25,2
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_300x300x10x10		7,85E-09	2,9	22,8
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_440x500x15x12_CS-212		7,85E-09	2,6	20,3
Structural Framing	ST-BRACING	ST-FR-CHS	CHS_406.4x12.5_CS-196		7,85E-09	2,6	20,3
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_440x500x20x15_CS-307		7,85E-09	2,4	19,2
Structural Framing	ST-BRACING	ST-FR-CHS	CHS_298.5x8_CS-190		7,85E-09	2,4	18,7
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_400x400x15x15		7,85E-09	2,4	18,6
Structural Framing	ST-BRACING	ST-FR-CHS	CHS_508x12.5_CS-198		7,85E-09	2,0	16,1
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_900x350x25x25_CS-32		7,85E-09	1,8	14,1
Structural Columns	ST-COLUMNS	ST-CO-RHS	RHS_500x500x30x30		7,85E-09	1,3	10,3
Structural Framing	ST-STRUCTURE	ST-FR-RHS	RHS_440x500x15x15_CS-221		7,85E-09	1,1	8,6
Total						**146,2**	**1.147,4**

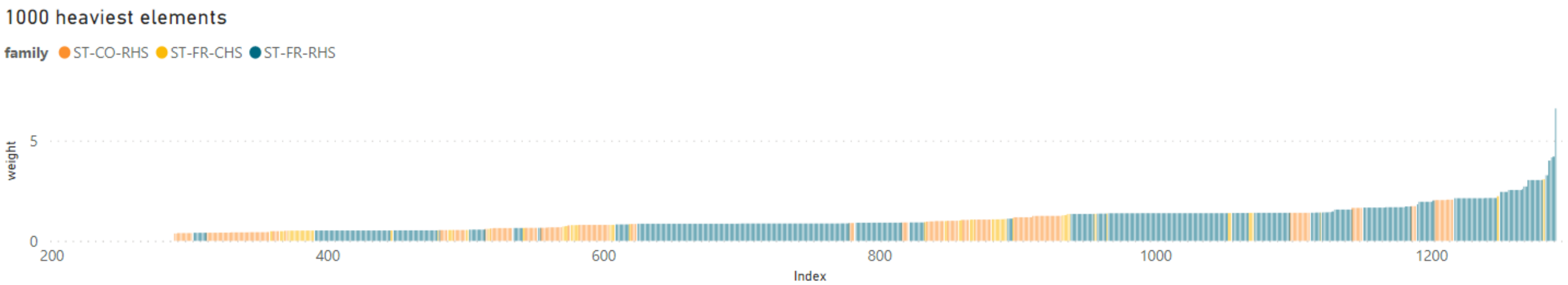


Figure 73: 02_COO_BOQ overview

5.2.2. 03_MNG_BOQ and 04_COO_BOQ

This report presents the data taken from the FEA main transformation module. The same reports as in the previous are prepared but taking the volume from the FEA main data.

For updating, the 01 and 02 dashboards are duplicated, and then the “weight” data is changed to be the column that consists of the multiplication of the element length in FEA and its section area given by the program main output.

If FEA data is not input in the database, these pages can be deleted from the standard Power BI file. 03_MNG_BOQ is shown in Figure 74 and 04_COO_BOQ is shown in Figure 75.

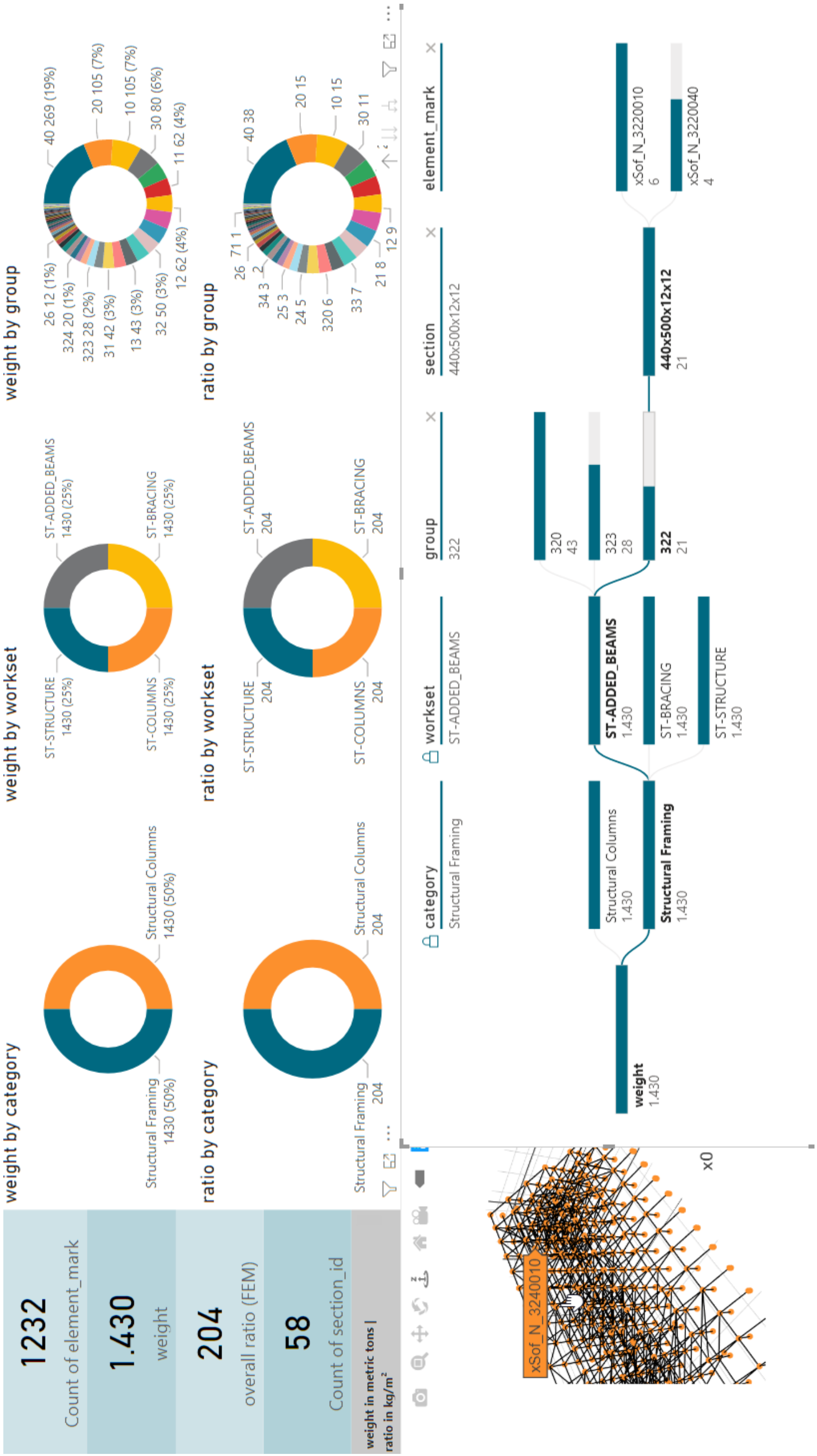
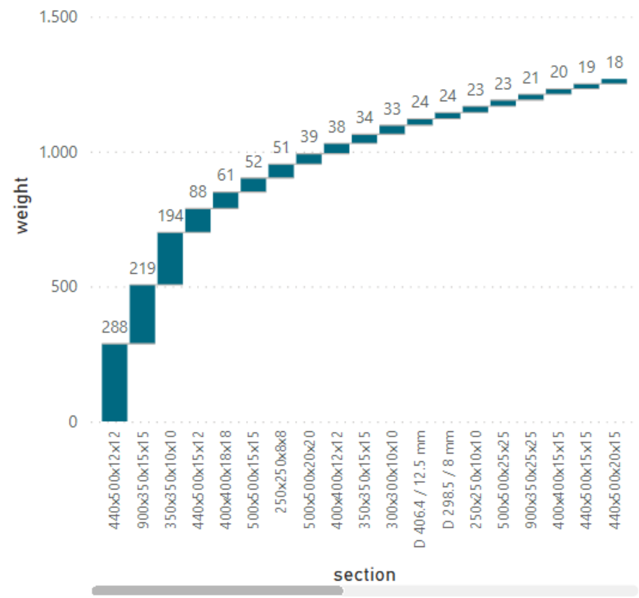


Figure 74: 03_MNG_BOQ overview

most relevant sections



BOQ TABLE

category	workset	group	section	material	custom_density	volume	weight
Structural Framing	ST-STRUCTURE	40	RHS_900x350x15x15_CS-30		7,85E-09	15,6	268,83
Structural Framing	ST-STRUCTURE	40	RHS_900x350x20x20_CS-31		7,85E-09	0,3	268,83
Structural Framing	ST-STRUCTURE	40	RHS_900x350x25x25_CS-32		7,85E-09	1,5	268,83
Structural Framing	ST-STRUCTURE	40	RHS_900x350x30x25_CS-33		7,85E-09	1,1	268,83
Structural Framing	ST-STRUCTURE	40	RHS_900x350x50x40_CS-35		7,85E-09	0,8	268,83
Structural Framing	ST-STRUCTURE	20	RHS_350x350x10x10_CS-201		7,85E-09	1,3	104,78
Structural Framing	ST-STRUCTURE	20	RHS_440x500x12x12_CS-211		7,85E-09	5,5	104,78
Structural Framing	ST-STRUCTURE	20	RHS_440x500x15x12_CS-212		7,85E-09	1,6	104,78
Structural Framing	ST-STRUCTURE	20	RHS_440x500x15x15_CS-221		7,85E-09	1,1	104,78
Structural Framing	ST-STRUCTURE	20	RHS_440x500x20x15_CS-222		7,85E-09	0,5	104,78
Structural Framing	ST-STRUCTURE	30	RHS_250x250x8x8_CS-301		7,85E-09	1,4	79,72
Structural Framing	ST-STRUCTURE	30	RHS_350x350x10x10_CS-303		7,85E-09	0,8	79,72
Structural Framing	ST-STRUCTURE	30	RHS_350x350x15x15_CS-304		7,85E-09	1,4	79,72
Structural Framing	ST-STRUCTURE	30	RHS_440x500x15x12_CS-305		7,85E-09	2,5	79,72
Structural Framing	ST-STRUCTURE	30	RHS_440x500x15x15_CS-306		7,85E-09	0,2	79,72
Structural Framing	ST-STRUCTURE	30	RHS_440x500x20x15_CS-307		7,85E-09	1,1	79,72
Structural Framing	ST-STRUCTURE	30	RHS_440x500x25x20_CS-309		7,85E-09	0,7	79,72
Structural Framing	ST-STRUCTURE	22	RHS_350x350x10x10_CS-201		7,85E-09	1,3	62,78
Structural Framing	ST-STRUCTURE	22	RHS_440x500x12x12_CS-211		7,85E-09	4,2	62,78
Structural Framing	ST-STRUCTURE	22	RHS_440x500x15x12_CS-212		7,85E-09	0,6	62,78
Structural Framing	ST-STRUCTURE	23	RHS_350x350x10x10_CS-201		7,85E-09	1,4	61,46
Structural Framing	ST-STRUCTURE	23	RHS_440x500x12x12_CS-211		7,85E-09	4,6	61,46
Structural Framing	ST-STRUCTURE	21	RHS_350x350x10x10_CS-201		7,85E-09	4,7	59,09
Total						**146,2**	**1.429,71**

1000 heaviest elements

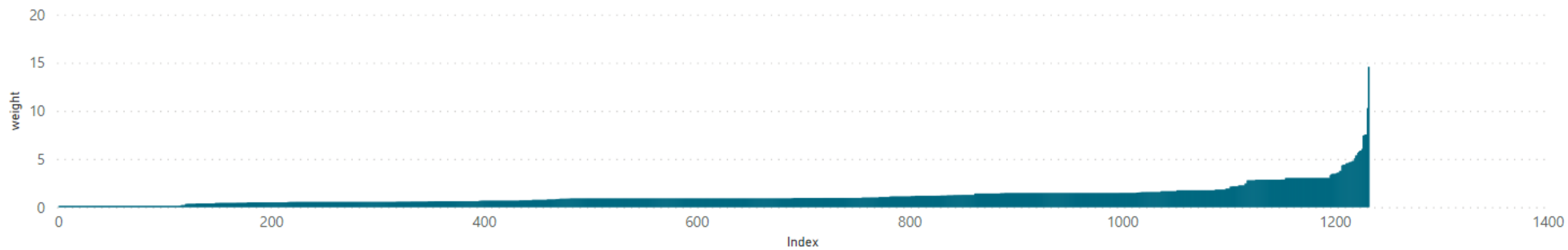


Figure 75: 04_COO_BOQ overview

5.2.3. 05_COO_BOQ

This report shows the comparison between the total BoQ from the BIM model and the FEA model. It is intended to be used by project coordinators, more specifically structural engineers, who could analyze the differences between FEA and BIM model weight extractions and report them to the project manager.

An overview is given in Figure 76. The graphs used are:

- Card - with the total number of elements;
- Card – with the total weight;
- Card – with the overall ratio;
- Card – with the number of different sections;
- Mark plot – a dynamic view of each model;
- Snapshot plot – frozen view of each model;
- Table – element_mark correspondence;
- Filters with a dropdown list – for category, workset, and section of the BIM model, and for group and section of the FEA model;
- Filter with text input – mark for BIM model and for FEA model.

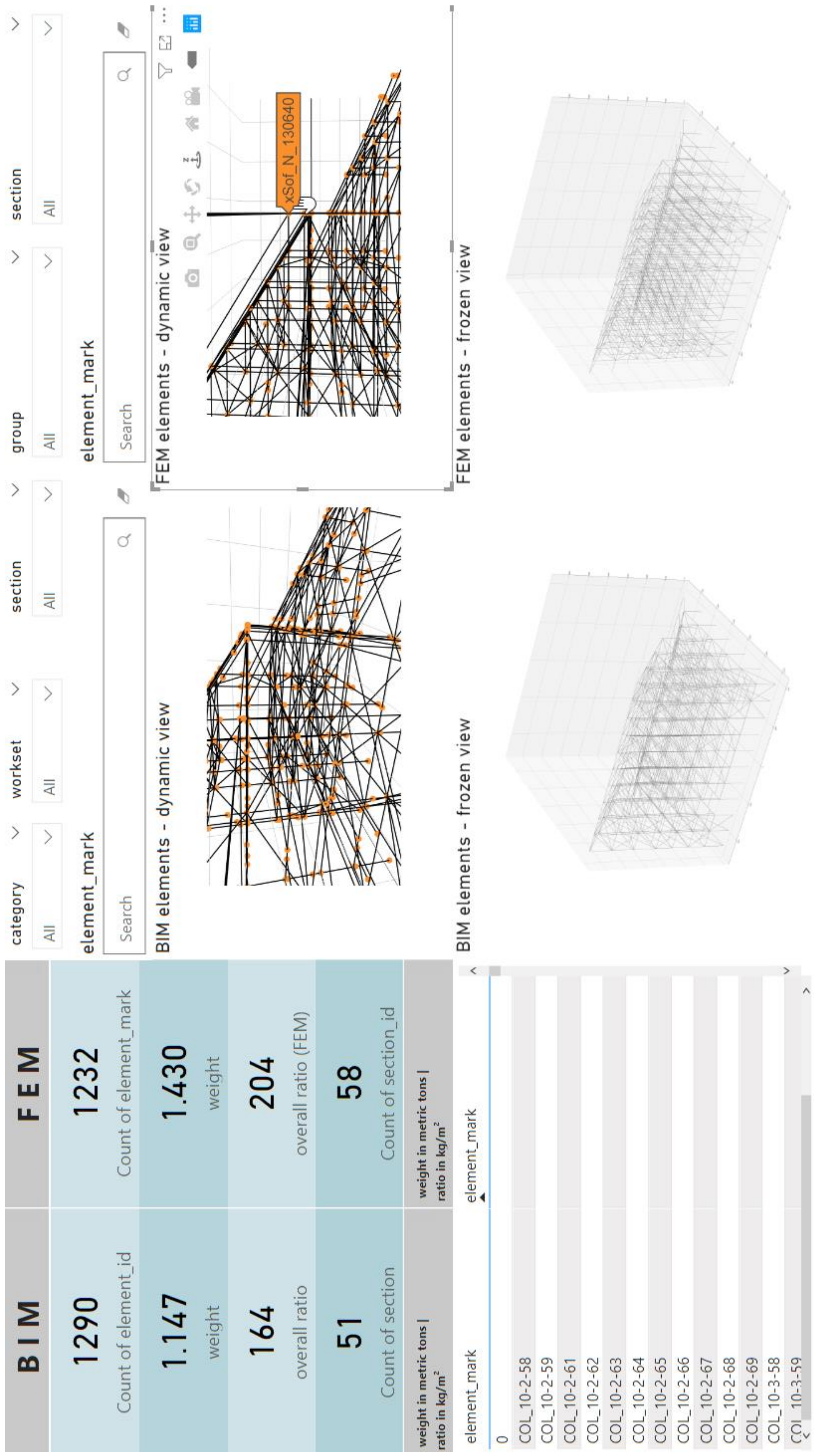


Figure 76: 05_COO_BOQ overview

5.2.4. 06_COO_COM

This report presents the data taken from a comparison between two models, aimed to be used for project coordinators, either BIM specialists or structural engineers. This uses as bases the data in the "model_comparison" output data frame. It is important to show which elements have changed and what changed in the elements. An overview is given in Figure 77. For that, the following visuals are prepared:

- Card - with the total number of elements;
- Card – with the total weight;
- Card – with the overall ratio;
- Card – with the number of different sections;
- Filters with dropdown list – for category, workset, and section of the BIM model; for group and section of the FEA model;
- Sunburst – presenting general and specific classifications of comparison output;
- Comparison plot – dynamic 3D view of model comparison results.

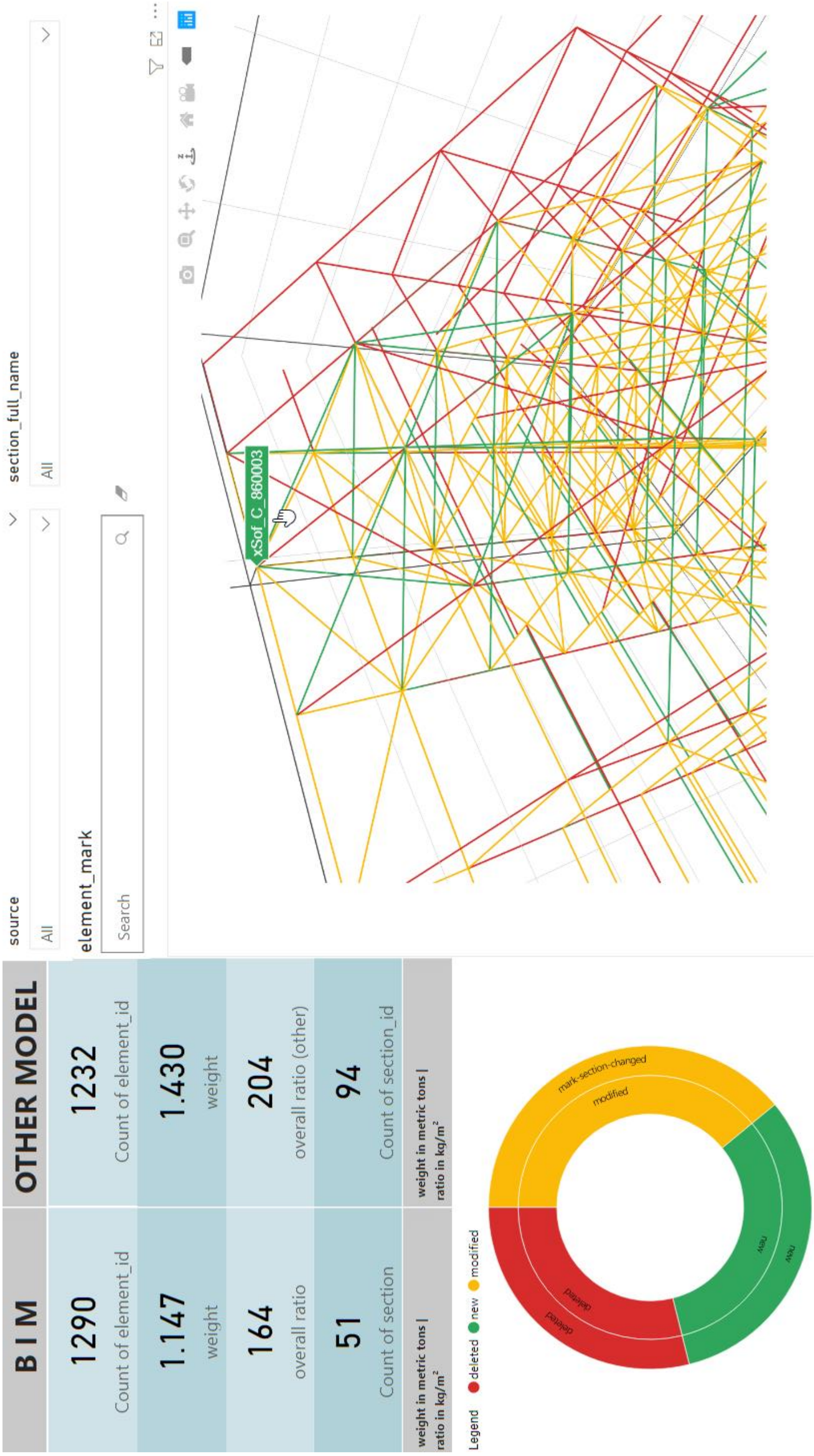


Figure 77: 06_COO_COM overview

5.3. Custom report examples

Besides those standard dashboards that would give a glimpse over the entire project, the interface is flexible enough so that the user can generate other reports to suit specific needs. The user can update standard reports to new KPIs, as described in the workflow in Figure 51, but also create completely new dashboards.

One example of a custom report that was implemented for this thesis is 100_COO_FEA, to check the internal forces of elements extracted from the FEA model. Another one is 200_COO_BIM, which presents data extracted in the advanced "BIM_element" table.

5.3.1. 100_COO_FEA

An overview of this example report is given in Figure 78. The selected graphs are:

- Filters with dropdown list – for group and section of the FEA model;
- Violin plot – showing distribution per cross-section of major axis bending My (kN.m);
- Mark plot – a dynamic view of FEA model;
- Sankey flow – showing the relation between groups and cross-sections in the FEA model.

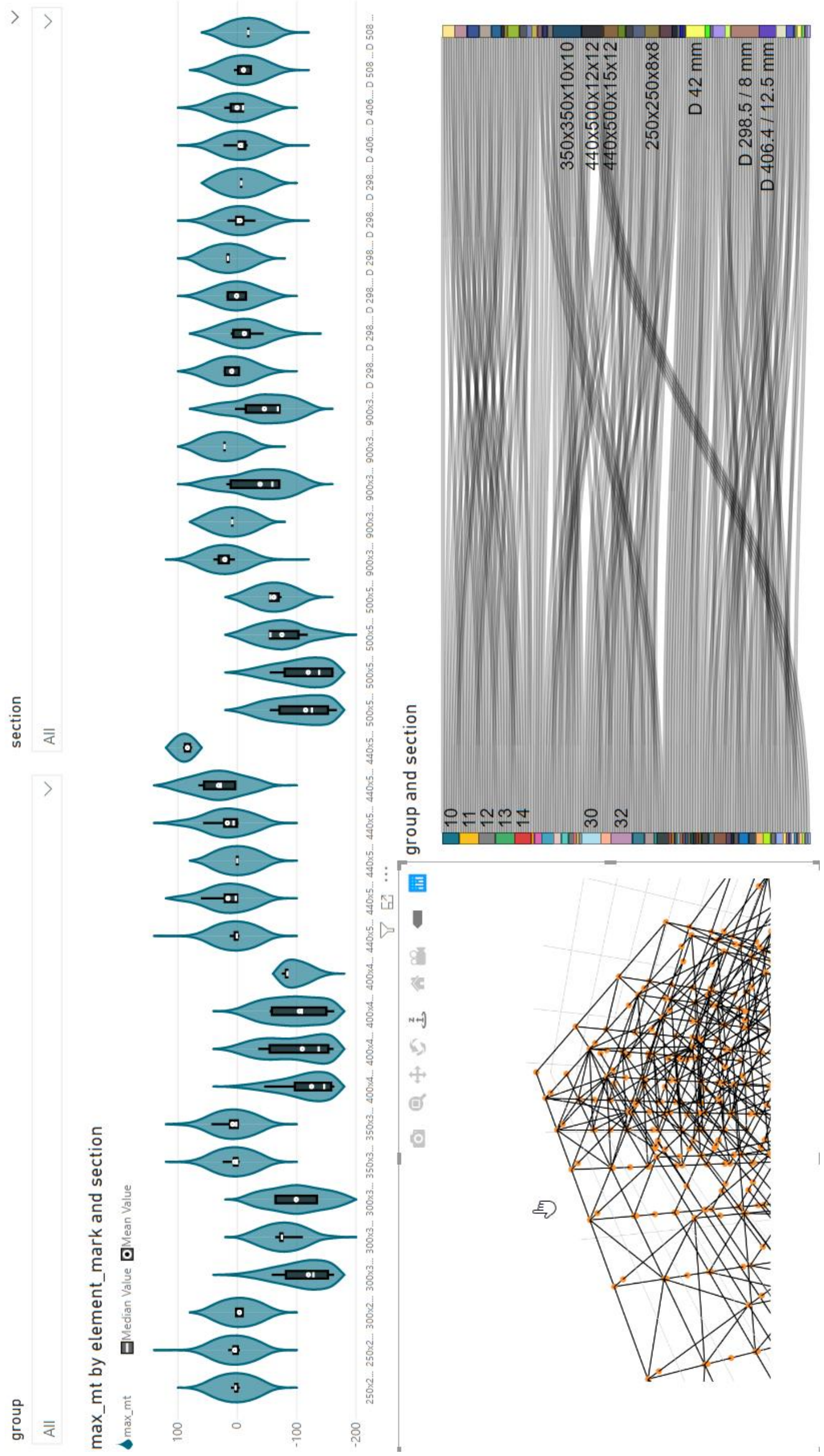


Figure 78: 100_COO_FEA overview

5.3.2. 200_COO_BIM

An overview of this example report is given in Figure 79. The selected graphs are:

- Sankey flow – showing the relation between Revit families and section names as given by the BIM_recognizer;
- Sankey flow – showing the relation between Revit types and section full names as given by the BIM_recognizer;
- Filters with a dropdown list – reference level and review comments of the BIM model;
- Card – showing overall weight in the BIM model, calculated via the "volume" parameter;
- Card – showing overall weight in the BIM model, calculated via the BIM_recognizer;
- Mark plot – a dynamic view of FEA model;
- Sunburst – with section name and section full names given by the BIM_recognizer;
- Line plot – of the sorted weight per element calculated via the "volume" parameter or the BIM_recognizer output, for comparison.

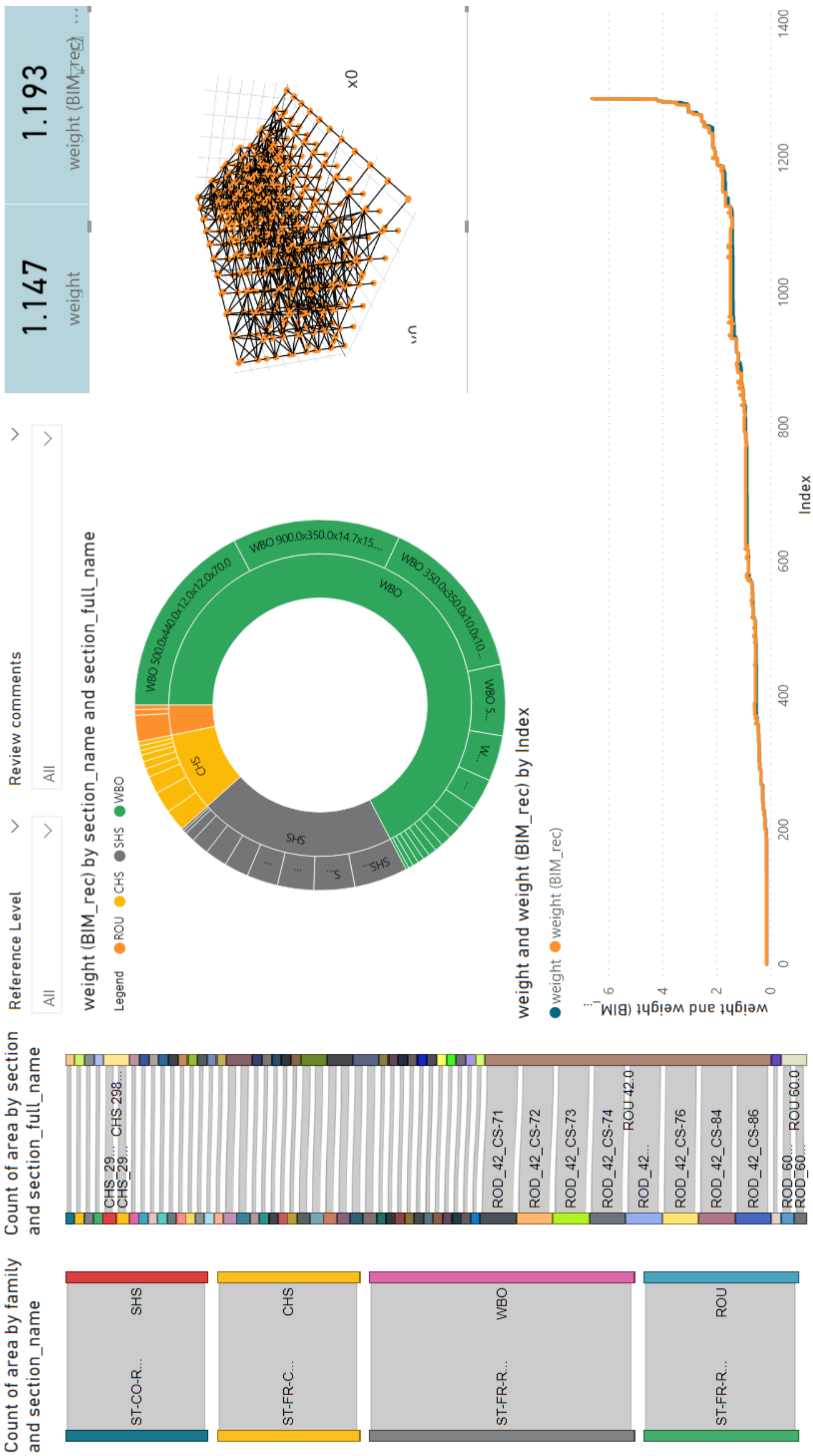


Figure 79: 200_COO_BIM overview

5.4. Interactivity

One important feature of the chosen interface is its interactivity, as highlighted multiple times in the Literature Review. Since the database is structured, the data analysis software allows that, when selecting a particular group in one of these graphs, all other graphs highlight this same group, which facilitates relating the information. This is illustrated in Figure 80 and Figure 81.

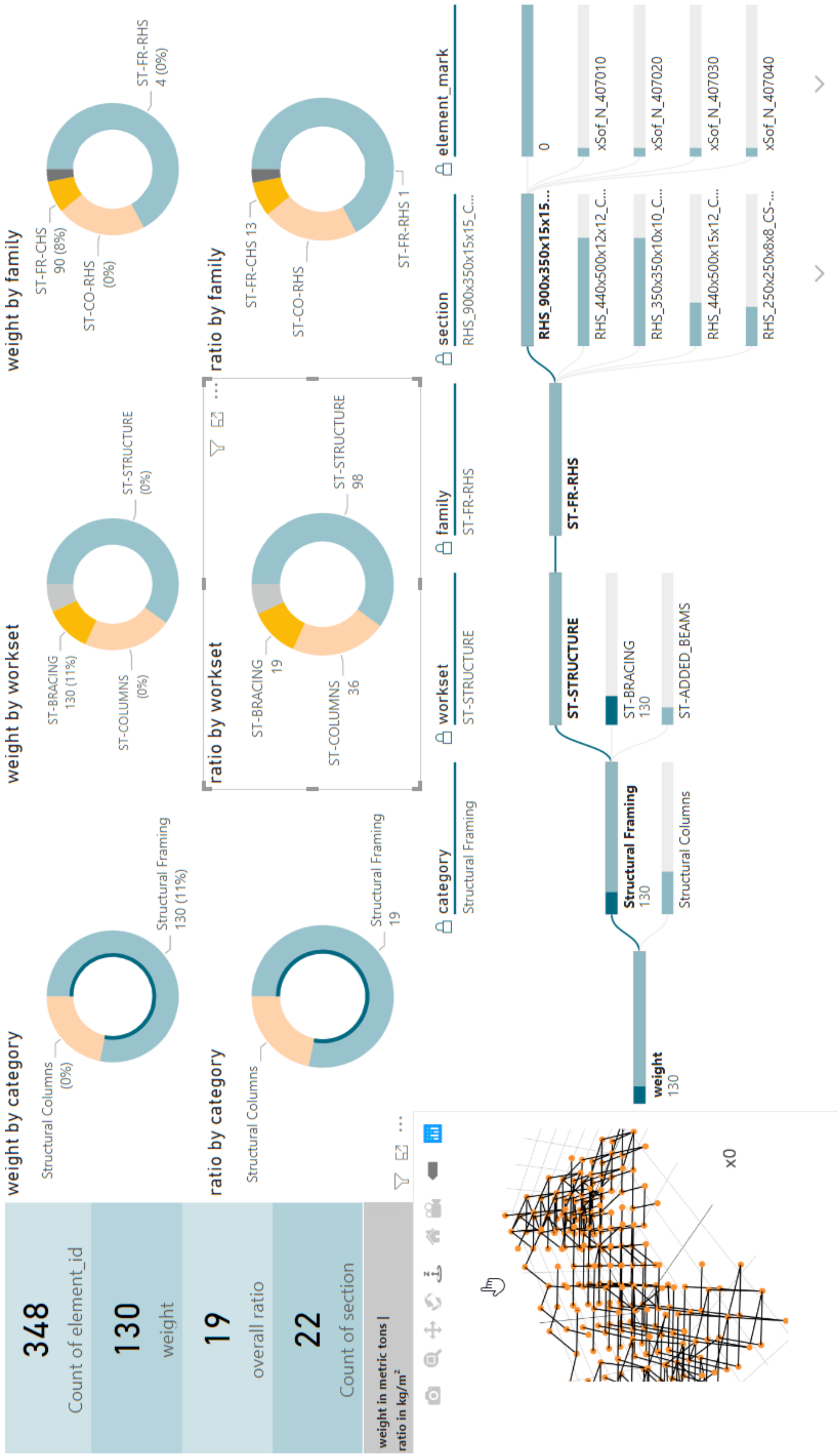


Figure 80: 01_MNG_BOQ interactivity

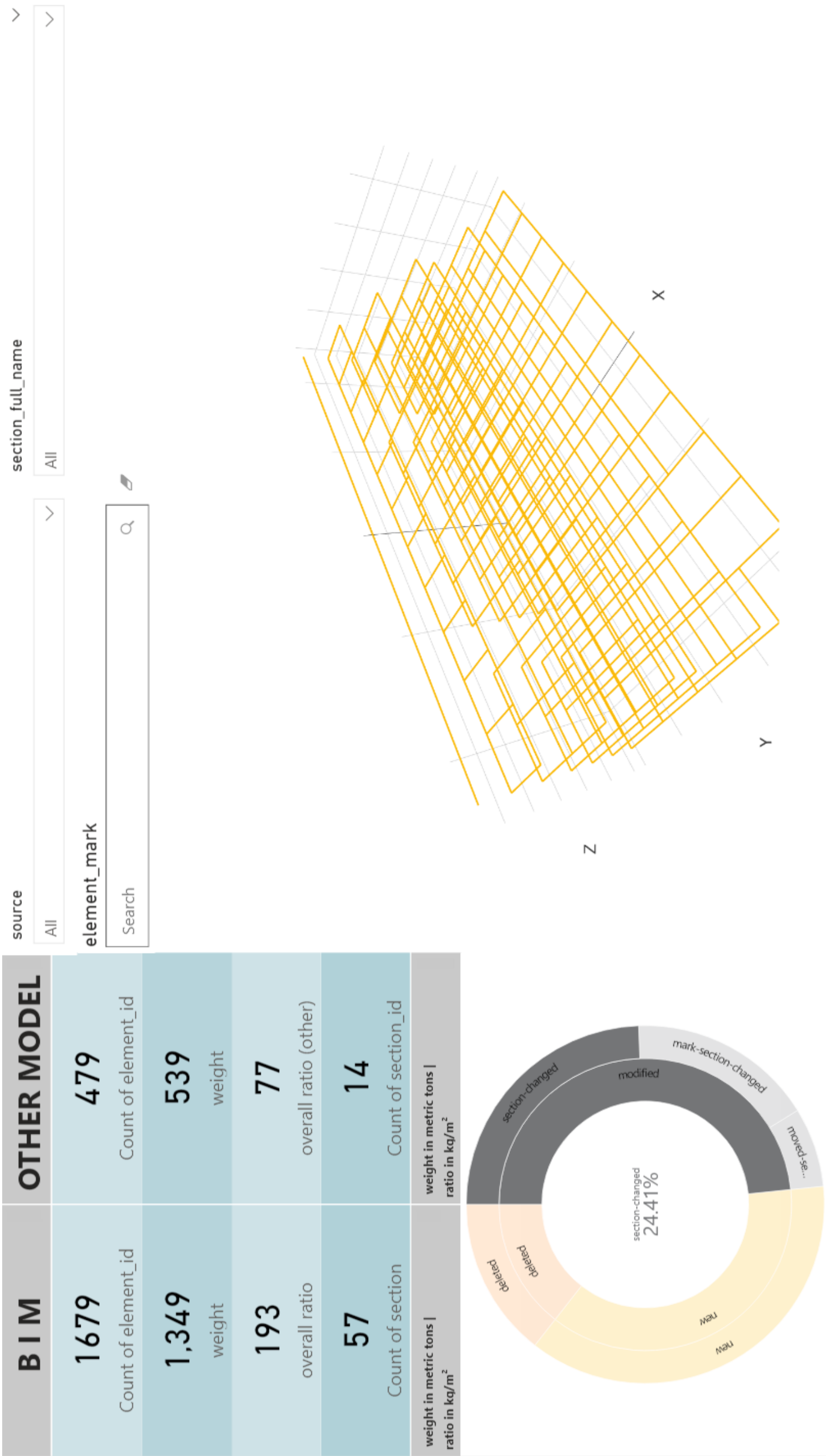


Figure 81: 06_COO_COM interactivity

6. DISCUSSION

The proposal of an augmented BIM workflow for structural design through data visualization, the proposal of a tool that enables it, and its implementation at a PoC level were executed. This augmented BIM workflow aims to enhance collaboration within the structural design. The PoC has been tested and presented to BIM specialists, structural engineers, and project managers. Its utility was validated by those professionals. The following sections discuss the results, examining the strengths and limitations of the current implemented tool that became evident during the development of this research.

6.1. Strengths of the current implementation

In the literature review, it was shown that with the advances of computation and implementation of BIM, structural engineers deal with increasingly complex projects, and generate and store a lot of data. However, the current data visualizations available for BIM and structural engineering do not address all the flexibility required for visualizing geometry, managing data, and performing statistical analysis of data within the same environment.

Furthermore, the literature also shows that interoperability between FEA and BIM models still needs improvement and that it is common for engineers to spend considerable time transferring data from one to the other. Since even software that claims to have interoperability between FEA and BIM models present issues, especially in more complex projects, it is common that companies adopt workflows in which BIM and FEA are done in two separate environments. This was the typical case in the company whose workflows based the PoC in this thesis.

The proposed "Augmented BIM workflow for structural design through data visualization" addresses both issues, proposing a tool that allows data control and geometry visualization, capturing BIM and FEA data from independent software.

It is also relevant to mention that this is done interactively. As shown in Section 5.4, the proposed interface for data visualization allows dynamic filters, which apply to all the visuals within the same report page. This facilitates considerably the understanding of information and visualization of specific elements in the geometry, as was highlighted by Solnosky (2016) and Loos et al. (2019) in the literature review.

6.2. Limitations of the current implementation

For extracting better analysis in a more efficient way, the data must be well organized. Of course, a lot of that can be adapted during the data transformation process. Nevertheless, if there is no standardized input data, which would require a set of rules defining which information should be in the model and how it should be modeled, the effort to code standard visualization tools becomes too high and is restricted to punctual use.

One example noticed, in this case, relates to the material of elements: in one of the investigated BIM models, the elements had no material assignment. They represented mostly steel but also some concrete beams. The workaround was to filter the elements in the data warehouse to show only steel elements and create a column with material densities, for being able to calculate weights from the Revit built-in volume parameters. In another model, there was a material specification in each of the structural elements, but that material had no density specified in the BIM model. Therefore, a similar workaround with a custom density column was necessary to calculate element weight.

Of course, all the “custom” steps in data transformation make it harder (although not impossible) for the workflow to be used by any project and any company. This means that for using the BoQ as it is currently implemented, one should rebuild the custom density columns accordingly in Power BI. If it was a certainty to have always the density of materials present in the BIM model, this could be an automatic step.

Another example is the mapping of FEA to BIM elements. In the present implementation, this was done through manual auxiliary input, in the *id_to_mark.xlsx* file. This is because, during the investigation of different projects, it was noted that although some projects have a clear rule of mapping (such as the correspondent FEA element id ranging from a multiplication of the BIM element mark by ten to that plus nine), others had different rules or no mathematical rule at all. This is often due to restrictions of the software and geometry definition option used. Manual input in a table was a way to overcome this lack of standardization.

A third example regards the fact that grouping of elements in existing Revit categories and worksets was not always relevant to gather similar structural members. Having a standard parameter on the BIM model to gather similar groups of elements would make the information on the dashboards more efficient for analytics. For instance, for a stadium roof, one would like to discretize the bill of quantities by "compression ring", "tension ring" and "purlins". For a gridshell, by "grid bars" and "edge beams". If there was a standard string parameter in all BIM models called "element group" for instance, this could be always shown in the standard dashboard and the relevant grouping would automatically appear in BoQs.

As in these cases, many other steps have come across balancing automation and flexibility. The choice of methods was at each time made to suit as well as possible the set of models that had been investigated.

For this balance to incline more towards automation, it is imperative to define information standards for structural engineering in BIM. This could be done within a project, causing the implementation tool to be modified at each different project. It could be done within a company, causing the workflow to be modified for each company, but keeping information that is not actually required in all projects for the sake of standardization. Alternatively, it could be for the whole industry, and then the workflow would require no major customization to be applied to any project. This seems very far from the current reality in the structural engineering area though.

From the experience gathered during the development of this PoC, it seems like having minimal standard information for the structural BIM model and for connecting it to the FEA model at a company level would lead to a reasonable balance between flexibility, automation, and difficulty of implementation. This would mean that even if this PoC evolves to a more professional, commercial implementation, it is important to make it flexible for adapting to specific company contexts.

In technical terms, some simplifications made during the PoC implementation are worth to be noted:

- As previously explained, this PoC focused on steel linear elements (beams, columns). For application to reinforced concrete structures, one should investigate how to input and extract information about rebars accordingly. This could be done by extending the extraction of parameters transferred to the common data warehouse. Additionally, as rebar drawings represent an important part of the work of the structural engineer in this type of project, it would make sense to develop further the workflow step for D&C for documentation;
- This PoC was implemented for a combination of proprietary software (Revit and SOFiSTiK) and so it is limited to the formats of those applications at the moment;
- In the Dynamo extraction script, slanted columns have not been tested;
- As the scripts retrieve start and end points, any arched or spline-like elements would be simplified to a line in the data warehouse. This influences geometry visualization and any calculation of weight that is done through start and end points only;
- For the section recognizers, as they are ruled-based, custom sections that are not specified in the data transformation section would report as “not found” sections;
- For the 3D visualization, ideally, interactivity should be almost instantaneous. This was not specifically evaluated or optimized at the current implementation given the

fact that it is a proof of concept, but it is an important aspect for the construction of an actual product in a further development phase;

- Currently, the best way to disseminate information across teams would be either via sharing screenshots of the dashboards, which would then lose interactivity, or to provide the Power BI Desktop file, which would then require that this software and all programming languages and libraries used in the dashboard are installed in the other person's computer. Microsoft also offers the Power BI Service, which could enhance the process of sharing data across a design team, allowing dashboards to be accessed and even modified through a web browser. However, this is a paid feature and it was not examined in the context of this thesis.

Lastly, a discussion regarding keeping property of knowledge versus enhanced collaboration in structural engineering also seems necessary. Having standard ways to input, extract and visualize data, of course, facilitates for engineers, especially the least experienced, to acquire parameters of comparison between projects and to create awareness of what is reasonable or not in a given structure, such as type of sections, expected material ratios, etc. It also makes it easier for this young engineer or for anyone that has access to the BIM data warehouse, to acquire this knowledge, which has been built during decades of work in a company, and to use it as a reference for designs in another company. This was a question brought up by project managers during interviews and is already mapped in the literature, as shown in the "legal and contractual" challenges by Solnosky (2013).

This point makes it clear that limitations and barriers to overcome for a more data-driven design and fully implement "Augmented BIM workflows for structural engineering through data visualization" across structural engineering offices are not only technical but also procedural and contractual.

7. CONCLUSION

This chapter summarizes the main research steps and conclusions. Through an application of the Design Science Research methodology, this thesis analyzed the relation between structural design and BIM and identified an opportunity in proposing the joining of BIM and FEA information in a data warehouse for data visualization.

A systematic literature review was carried out and showed that this is a rather recent research theme, even though the close relationship between information technology and structural engineering is a research topic since the 1950s. The review confirms that BIM is seen as a centerpiece for leading the construction industry to a more information-driven approach. Nonetheless, there are still barriers to overcome. Currently, important interoperability challenges hinder the use of the full potential of information in this specific field.

To move towards data-driven design and collaboration, new workflows are required. Research attempts in this sense have considered either direct (through proprietary file formats) or indirect (through IFC or other intermediate file formats) data exchange and have been successfully applied to specific case studies, but are not available for any company. In addition, as each office may have a different current workflow and set of used software, adapting to other specific sets of software to be able to use better interoperability may seem too risky and complicated for a discipline that implicates high technical responsibility on the outputs.

Therefore, the new workflows need to be compatible with each office's current activities to lead to better use of information. Some examples in the literature show that this use is only improved if meaningful insight can be extracted from data visualization.

In this context and based on the diagnosis of the BIM workflow in a medium-sized engineering office and interviews with the design team, an “augmented BIM workflow for structural design through data visualization” was proposed, implemented via a tool at a proof of concept level, and discussed. Its general objective is to improve collaboration within the structural design team by strengthening the use of BIM model data.

The implementation was done through a data extraction, transformation, and load process into a data warehouse. The BIM database in this case is an Autodesk Revit model, whose extraction was done through an Autodesk Dynamo interface. The FEA database is a SOFiSTiK model, whose extraction was done through a SOFiSTiK Result Viewer interface. Data transformation, load, and visualization are done within Microsoft Power BI.

This set of software was chosen for being compatible with the case study company's current workflows. The PoC was tested in five different projects during implementation to study how it could be programmed in a general way to apply to different companies and projects – with the same base software.

Feedback of potential users of the tool was collected and presented. It confirmed that such a tool would be beneficial to collaboration in projects and gave input for further levels of development. A discussion of the strengths of the current proposed workflow and tool, as well as technical and functional barriers, is given.

7.1. Future work

The tool as implemented aims at better control and use of data in structural design in BIM. There are different possibilities of future work that could improve this PoC so that it becomes a product. Some suggestions are given below:

- Provide the code to a range of different structural engineering offices to test. Collect feedback and change implementation to make sure the tool works in more cases;
- Implement data extraction and transformation for other BIM and FEA proprietary data formats;

- Implement data extraction and transformation from IFC models;
- Overcome specific technical limitations, implementing arches, spline likes beams, slanted columns, etc.;
- Implement surfaces to be able to show walls and slabs as well in the data visualization;
- Adapt custom visuals for showing 3D geometry in Power BI;
- Rearrange created custom visuals be shared openly within the Power BI visuals AppSource;
- Implement all of the modules (ETL and visualization) in a single (possibly web) interface;
- Extend implementation for multiple past projects more automatically to serve as a knowledge management tool.

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APPENDIX A – STEPS FOR INSTALLATION AND USE

Step 0: installation

The first step for the user is to install the required software and programming languages on the desired computer. The versions used in this PoC are listed below:

- Autodesk Revit (v. 2020);
- Dynamo (v. 2.1.0.7733) packages: LunchBox (v. 2016.9.30), archilab.net (v. 2020.23.13,) spring nodes (v. 204.1.0), Clockwork for Dynamo 2x (v. 2.3.0), Data-Shapes (v. 2021.1.2.91);
- Power BI desktop (v. 2.92.943.0 64-bit);
- Anaconda (v.1.10.0, Python v. 3.8.5)- on the Anaconda Prompt, write:
    - conda install pandas and wait for installation (v. 1.1.3);
    - conda install matplotlib and wait for installation (v. 3.4.1);
    - conda install numpy and wait for installation (v. 1.20.2);
    - conda install scipy and wait for installation (v. 1.6.3).
- On the Power BI Desktop options menu, enable Python Scripting and R scripting.
- If the user wants to generate other custom visuals, this will require:
    - R (v. 4.0.3) and R studio (v. 1.3.1093);
    - on the R studio console, write (compatibility of versions to be tested by the user):
        - install.packages("plotly") and wait for installation;
        - install.packages("ggplot2") and wait for installation;
        - install.packages("htmlwidgets") and wait for installation.

There are several different ways of installing those tools. The above list is one of the options.

Step 1 and 2: BIM model – Basic (mandatory) + Advanced data extraction (optional)

1. Open the desired BIM model in Revit;

2. Open Dynamo player;
3. Change the inputs:
    a. Select the desired model elements;
    b. Select the location of the standard folder;
    c. Select the name of the element parameter, which will be used as “mark”. This is supposed to be a unique identifier, used for organizing the data and comparing models. It needs to be mapped in the *id_to_mark.xlsx* file if FEA model data is to be input in the data warehouse. The “mark” can be the element “guid” in Revit if desired;
    d. Decide whether only the minimum parameters will be exported or if additional parameters for element, type, family, and section recognizer should be exported;
    e. If section recognizer information is to be exported, update the maximum dimension of cross-section, if necessary, giving an order of magnitude of the size of cross-sections in project length unities;

The user interface for this is shown in Figure 82.

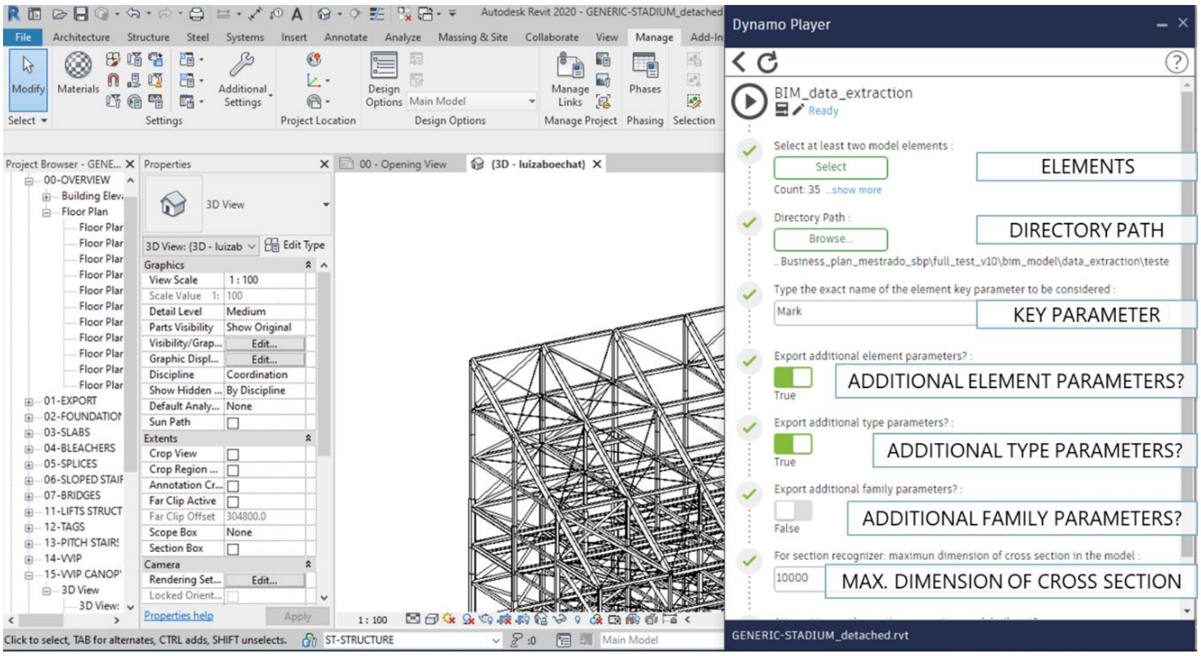


Figure 82: Selection of elements in Dynamo Player interface

4. Let it run. Depending on which extra information was selected to be exported, some user interface windows will open. The user should select which parameters on element, type, and/or family should be exported. This list has all the parameters present in at least one of the elements selected. The minimum information for the creation of a dashboard will always be exported. The time the extraction takes will depend a lot on the number of elements. For reference, when around 1000 elements were exported, this process took 1-4 minutes, with the computer capabilities as described in the Methodology section. The user interface for this step is shown in Figure 83;

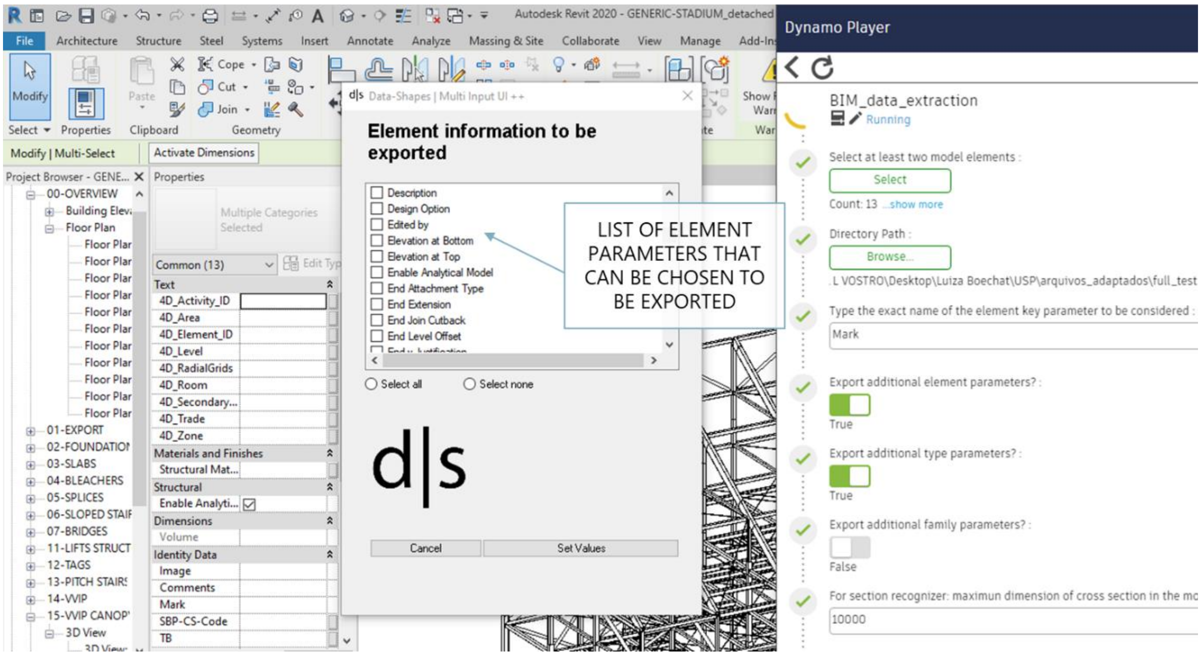


Figure 83: User interface for advanced data extraction from elements in Dynamo Player interface

5. On the project folder, five csv files are updated: *BIM_main.csv*, *BIM_element.csv* (optional), *BIM_type.csv* (optional), *BIM_family.csv* (optional), *BIM_section.csv* (optional). The files do not need to be opened but can be if the user desires to check the exported information;
6. Open the data transformation window of the report in Power BI Desktop;
7. Update the “data_folder” parameter and any desired parameters (Figure 84);

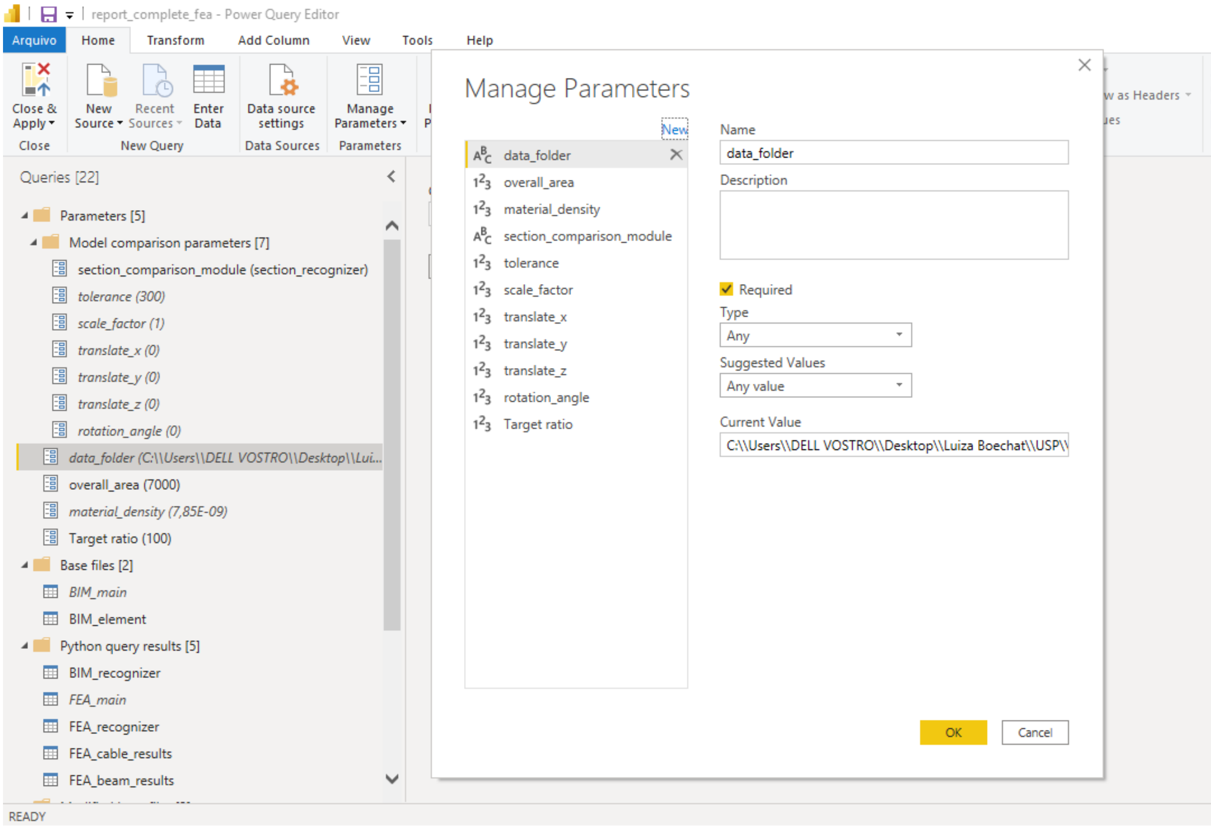


Figure 84: Power BI interface for updating project folder and other parameters

8. All queries will update automatically to the content of the new chosen standard folder. If a column name has changed in “BIM_element”, “BIM_family”, or “BIM_type” files, the user will need to delete the query and import the data source again;
9. The standard dashboards will be updated automatically with the new model data;
10. The user may create any other desired dashboards with the additional information.

<u>Step 3: BIM section recognizer (optional)</u>

In case the “BIM_recognizer” query does not update automatically, delete it and create a new one, with the following steps:

1. Create a new query with Python in the Power BI;
2. Copy the code from *BIM_section_recognize.txt* and run in Power BI;
3. It will read the geometric data from the *BIM_section.csv* file and prepare it in a format that will show up in Power BI, as shown in Figure 85.

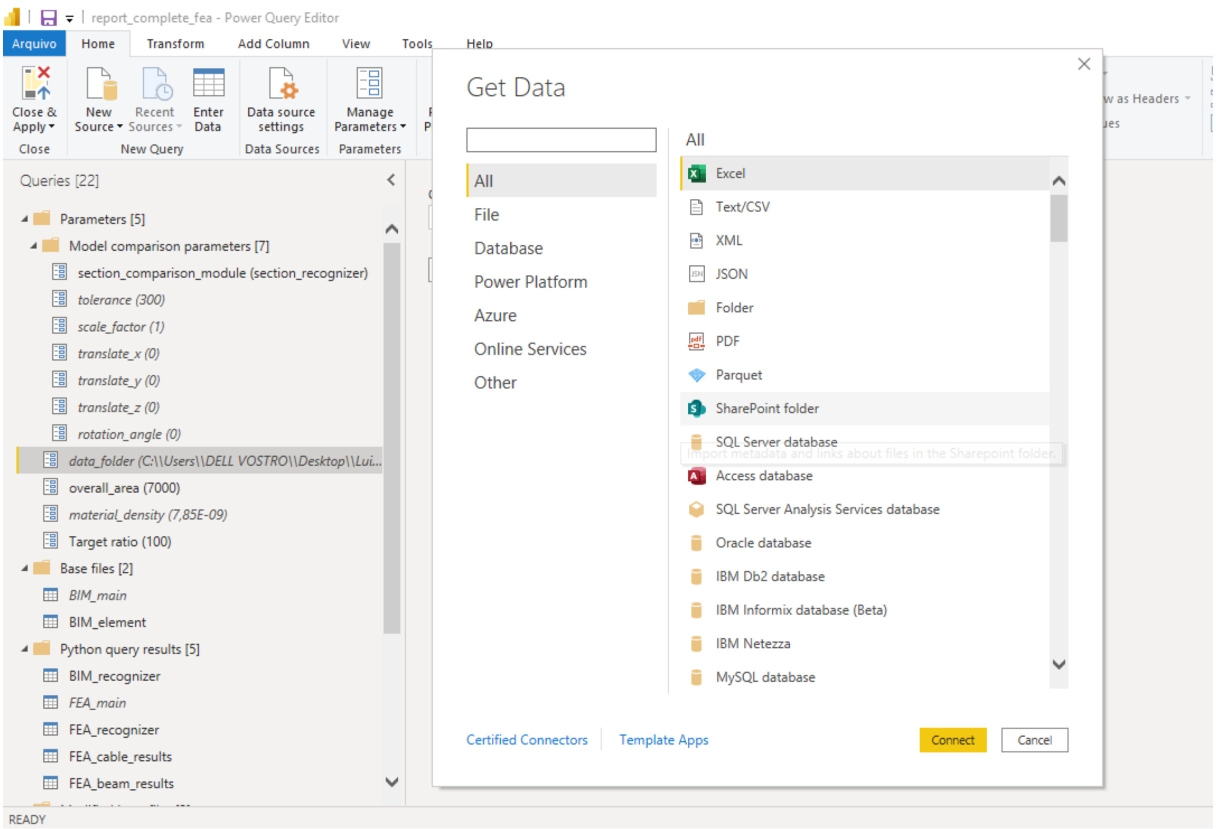


Figure 85: Power BI interface for updating BIM section recognizer – new query

Step 4 and 5: FEA model – Data Extraction – FEA Main transformation (optional)

In case the “BIM_recognizer” query does not update automatically, delete it and create a new one, with the following steps:

1. Create a new query with Python in the Power BI;
2. Copy the code from *FEA_main_transform.txt* and run in Power BI;
3. It will read the geometric data from the SOFiSTiK extraction file and prepare it in a format that will show up in Power BI, as shown in Figure 86.

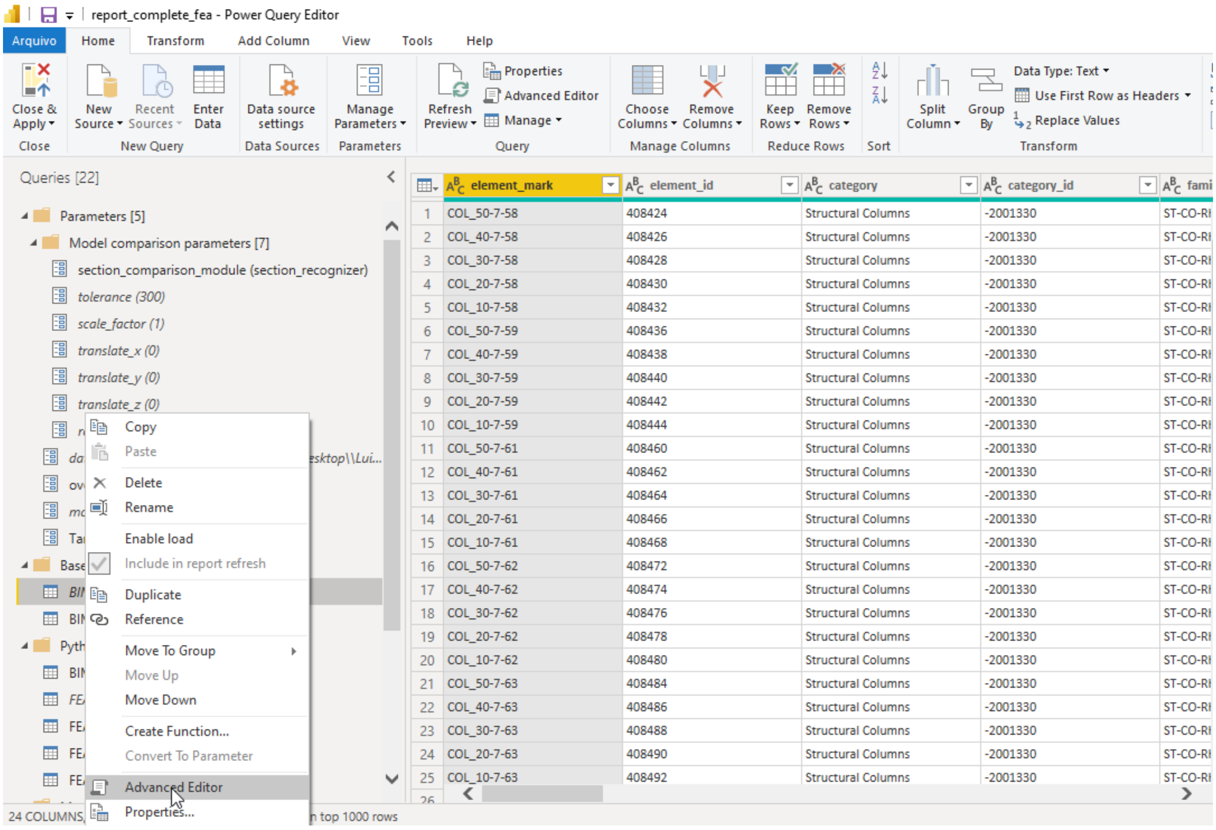


Figure 86: Power BI interface for updating FEA main – advanced editor

<u>Step 6: FEA model – Data Extraction – FEA section recognizer (optional)</u>

In case the "FEA_recognizer" query does not update automatically, delete it and create a new one, with the following steps:

1. Create a new query with Python in the Power BI;
2. Copy the code from *FEA_section_recognize.txt* and run in Power BI;
3. It will read the section data from the SOFiSTiK extraction file and prepare it in a format that will show up in Power BI, as shown in Figure 87.

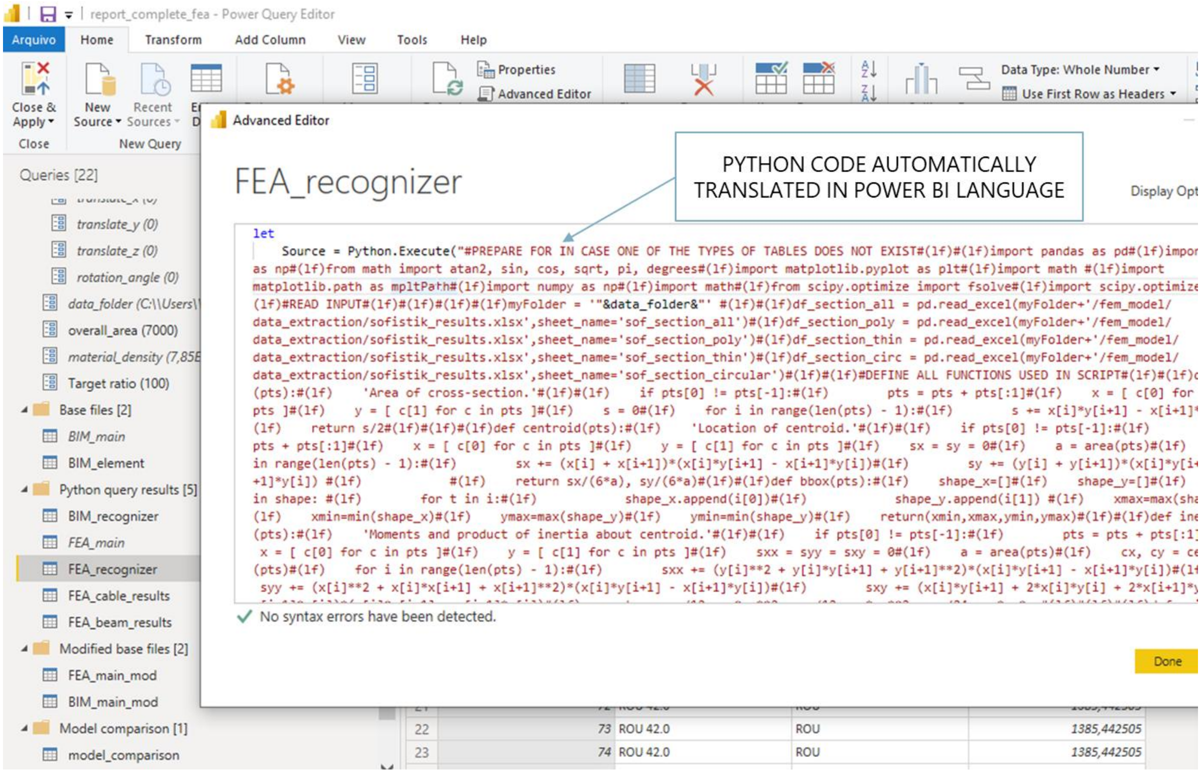


Figure 87: Power BI interface for updating FEA main - advanced editor

Step 7: FEA model – Data Extraction – FEA elements (optional)

If any other information that is not in the main file is required for a specific analysis, the user can create other queries and import, with the only requirement that the table is also organized per mark. "FEA_element" is one example of a query in this context and extracts the maximum and minimum internal forces in one element. To run that, the user must:

1. Create a new query with Python in the Power BI;
2. Copy the code from *FEA_element.txt* and run in Power BI;
3. It will read the internal forces from the SOFiSTiK extraction file and prepare it in a format that will show up in Power BI, as shown in Figure 88.

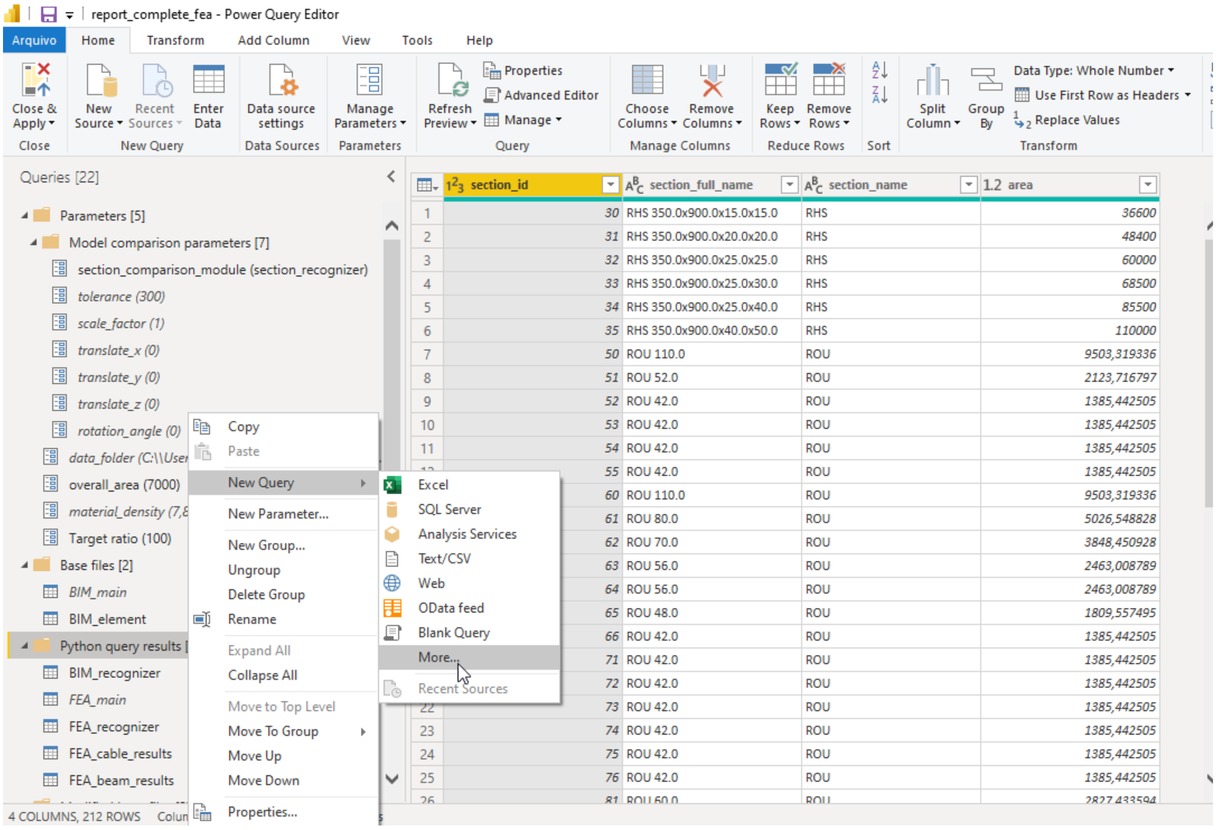


Figure 88: Power BI interface for updating FEA element - query

<u>Step 8: Model comparison (optional)</u>

For running the model comparison, the user should follow the steps below:

1. The user should copy the “main” geometry file (either a previous “BIM_main” or the “FEA_main”) to the “model_comparison” input folder;
2. The user should update the “Model comparison parameters” in Power BI, which are:
    a. “Section_comparison_module”: the choice of how the “model_comparison” will compare the cross-sections, either:
        i. “Section_recognizer”: using the output from section recognizer from both models or comparing the section. For that the *section.csv* file in the input folder should also be copied from the relevant folder (either a previous “BIM_section_output” or the “FEA_section_output”);
        ii. “Section_id_BIM”: using the type id from each BIM model which is given in the “main” table;

iii. "Section_id_FEA": using the type id from the current BIM file and the mapping of FEA section ids to BIM section ids, which should be updated, in the *sof_section_to_type.xslx* file.

This step is illustrated in Figure 89.

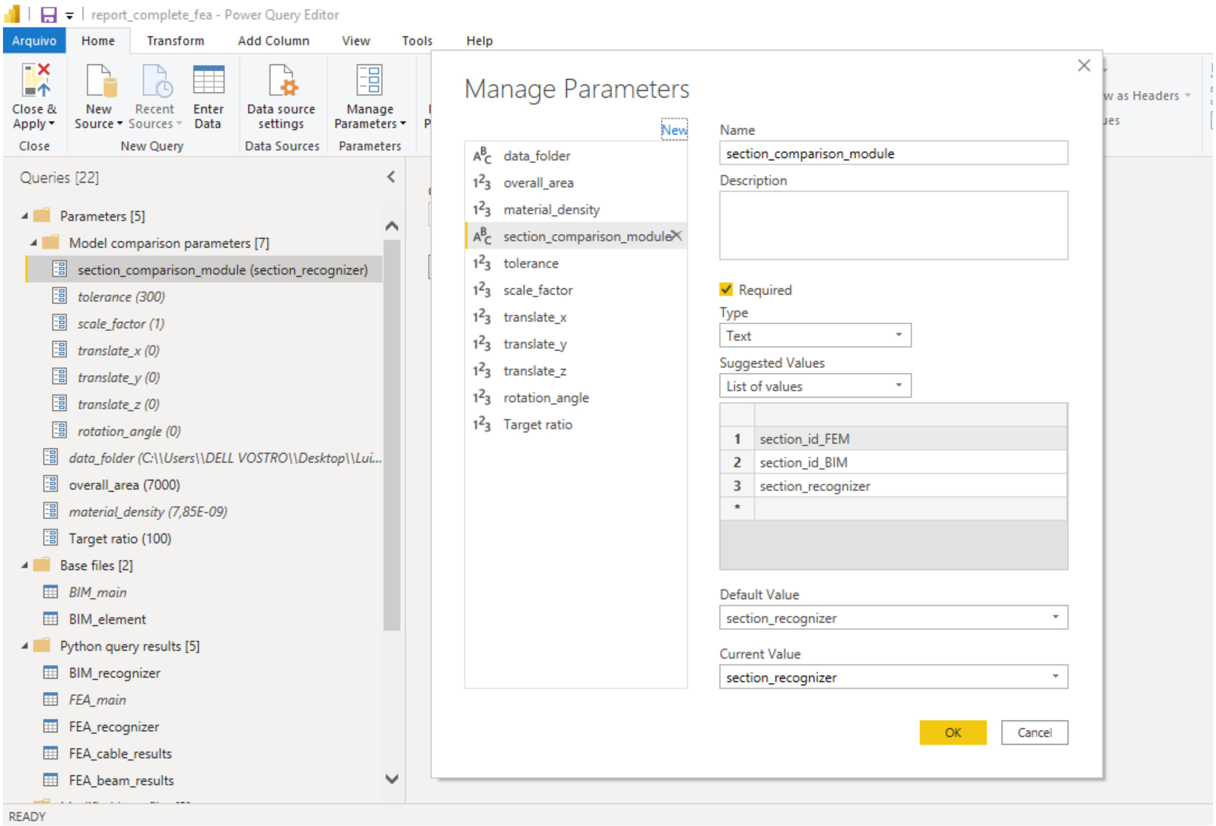


Figure 89: Power BI interface for choosing a type of model comparison

3. Create a new query with Python in the Power BI;
4. Copy the code from *model_compare.txt* and run in Power BI;
5. It will read the current BIM_main data and the main data in the folder "to_compare", the cross-section data as specified by the parameter "section_comparison_module" and prepare the output in a format that will show up in Power BI.

APPENDIX B – DATA EXTRACTION IN DETAIL

BIM model

The BIM data extraction script programmed in Dynamo follows the steps described in the following sections.

Elements information

1. Filters the selected elements:
    a. Only elements of categories "Structural framing" or "Structural columns" are considered;
2. For the main output:
    a. Retrieves the value of the parameter set as "mark" by the user for each element;
    b. Retrieves the element id, category, family, and type names and ids for each element;
    c. Retrieves element location curve in Dynamo if it is a structural framing or creates it if it is a structural column by picking the base point and the minimum bounding box z coordinate and adding the height of the column in z coordinate to find the end point. This does not work properly for slanted columns as currently implemented;
    d. Retrieves parameters of Revit length, Revit cutback length (only for structural framing), and Revit volume;
    e. Retrieves the workset of the element.
3. Export of element parameters:
    a. For each element, it will retrieve the properties as selected by the user in the user interface and export them in a table whose key is the element id. If a property is not available for one element, the correspondent cell will be blank.
4. Export of type parameters:

a. For each unique type present in the element list, it will retrieve the properties as selected by the user in the user interface and export them in a table whose key is the type id. If a property is not available for one type, the correspondent cell will be blank.

5. Export of family parameters:
    a. For each unique family present in the element list, it will retrieve the properties as selected by the user in the user interface and export them in a table whose key is the family id. If a property is not available for one family, the correspondent cell will be blank.

<u>Cross-section geometry</u>

1. Extract cross-section data for section recognizer:
    a. Finds the unique types present in the element list;
    b. Finds sample elements for those types in the Revit model;
    c. Gets each sample element geometry as solids;
    d. Finds the centroid of the correspondent solid union;
    e. Explodes the solid union to have the different surfaces that compose it;
    f. Build a vector generated by the start and end point of the location curve found as described in the extraction detailed explanation (slanted columns not implemented). Curved elements get exported as straight lines;
    g. Creates a surface from a circle whose center point is the solid centroid, normal vector is the vector described in item "f" and radius 4 times the biggest size of the section specified by the user;
    h. Intersects the surfaces from "e" and the circle, generating all the cross-section curves in the plane normal to the vector passing by the centroid of the solid, as highlighted in Figure 90;

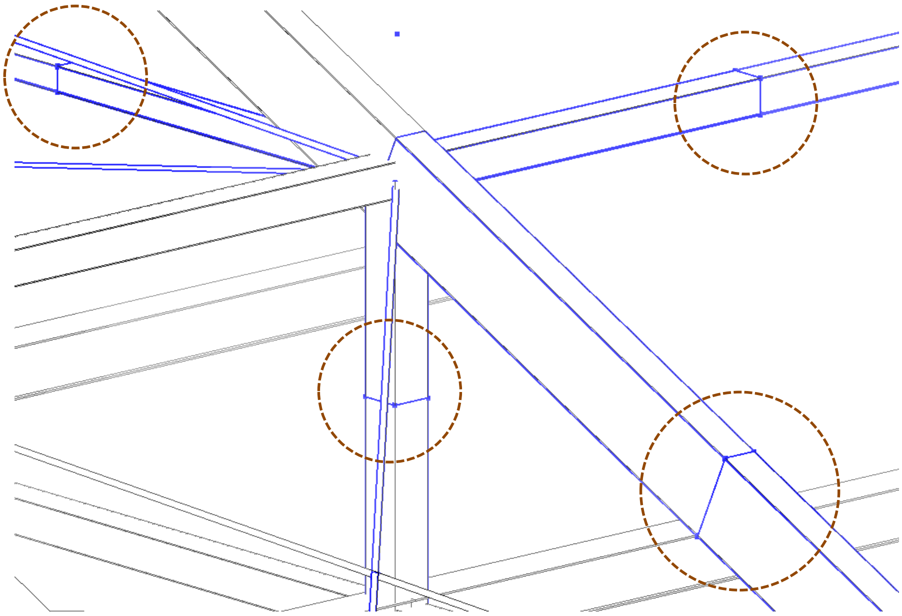


Figure 90: Structure with section lines marked in blue during section data extraction

i. If a section curve is a circle, divides it into two arcs;
j. Classifies the section curve in line (if the length is equal to the distance between the start and end point) or not;
k. Outputs per row the section curve start point, middle point, and end point, in global coordinates;
l. Adds the type id, the type name, the normal vector coordinates, and the line classification;
m. The outputs are always in project length unities, which is also output in a column, for information.

<u>FEA model</u>

Optionally, the user can import data from the FEA model. An overall view of the extracted information is shown in Figure 91. In case one type of element is not in the model, the table will simply show up with only column headers.

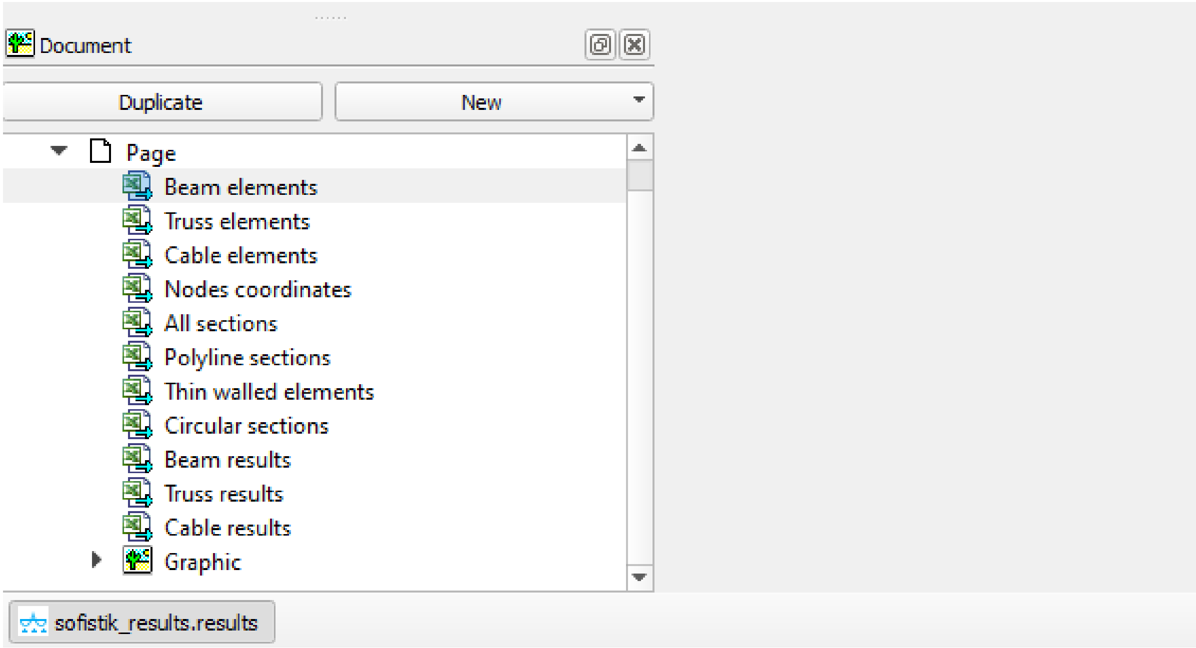


Figure 91: Tables exported from Result Viewer

Element information

The element's information is given on the pages:

- Beam elements: geometry information (number of element, number of nodes, and number of group) for elements modeled with the finite element for beams;
- Truss elements: geometry information (number of element, number of nodes, and number of group) for elements modeled with the finite element for truss (only normal forces);
- Cable elements: geometry information (number of element, number of nodes, and number of group) for elements modeled with the finite element for cables (only tension forces);
- Nodes coordinates: global x,y,z coordinates for all nodes in the model;
- Beam results: internal forces for all beam elements from the selected load cases. This information is only used if an optional advanced FEA information extraction takes place;

- Truss results: maximum and minimum internal forces for all truss elements from the selected load cases. This information is only used if an optional advanced FEA information extraction takes place;
- Cable results: maximum and minimum internal forces for all cable elements from the selected load cases. This information is only used if an optional advanced FEA information extraction takes place.

Cross-section geometry

In the chosen analysis software, the cross-section of elements may be input in different ways. The most commonly used in the studied company workflow is via text input, in a module of the software called "Teddy".

It is possible to create cross-section profiles in the following ways:

1. Specifying directly the a cross-section properties;
2. Specifying a standard cross-section from a selection of catalogs available;
3. Freely defining a thin-walled cross-section;
4. Freely defining a solid cross-section;
5. Freely defining a finite element cross-section, importing from a mesh in a separate database.

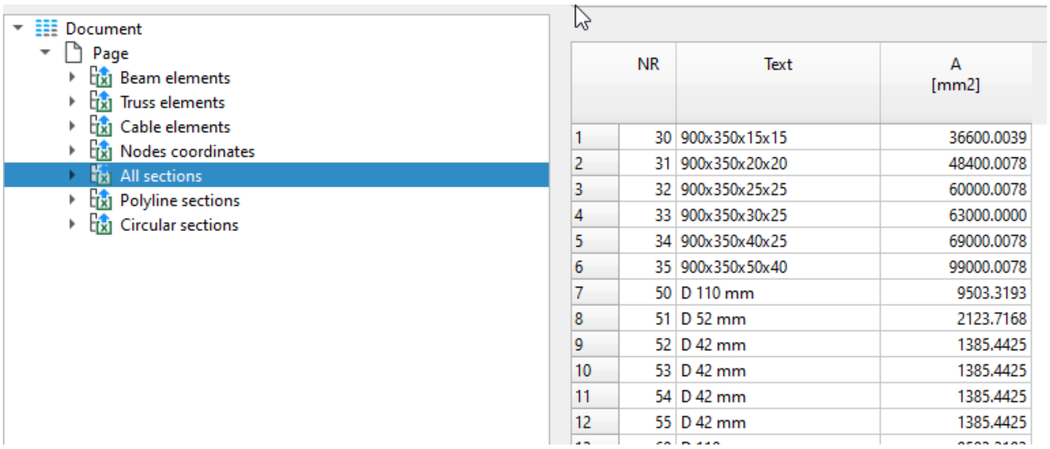
The methods used in the workflows studied and considered for the construction of the FEA recognizer are (2) and (3). In terms of how the section geometry and properties can be extracted from the database, the software provides easy export to .xlsx tool with some possibilities of data selection.

The goal of the "section recognizer" is to output any cross-section in a pre-determined format that is "understood" by the data management tool. For that, it needs to retrieve at least information to be able to:

1. Identify the section through an ID;
2. Retrieve the original name of the section in the database;

3. Determine its type according to the standard output table (CHS, RHS, SHS, I, L, T, C, U, ROU, REC, etc.)
4. Determine its main dimensions given its type.

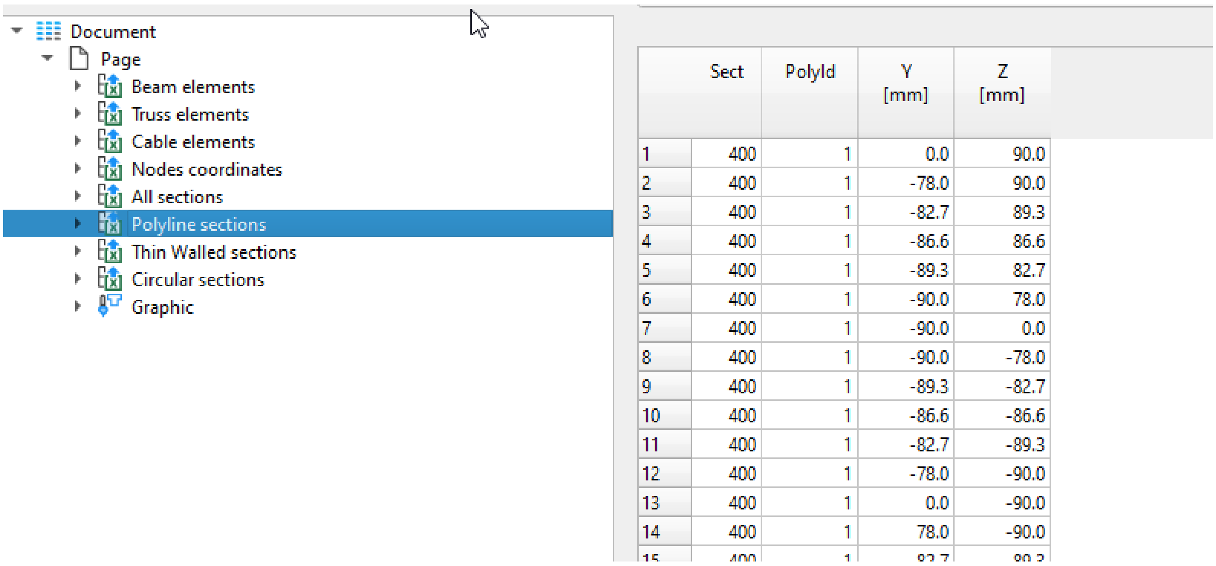
In this way, a table called "All sections" is generated containing the "NR" (id), "Text" (original name in the database), and "A [mm²]" (area in mm² which will later help in determining the dimensions), as shown in Figure 92.



	NR	Text	A [mm2]
1	30	900x350x15x15	36600.0039
2	31	900x350x20x20	48400.0078
3	32	900x350x25x25	60000.0078
4	33	900x350x30x25	63000.0000
5	34	900x350x40x25	69000.0078
6	35	900x350x50x40	99000.0078
7	50	D 110 mm	9503.3193
8	51	D 52 mm	2123.7168
9	52	D 42 mm	1385.4425
10	53	D 42 mm	1385.4425
11	54	D 42 mm	1385.4425
12	55	D 42 mm	1385.4425

Figure 92: All sections table in Result Viewer

A second table called "Polyline sections" is generated (Figure 93) and contains the geometry information of all sections whose geometry has been generated based on standard sections (Figure 94). The columns of the table are "Sect" (equivalent to NR in the former table), "PolyId" (number of polyline in which the point is, always 1 for open or general solid sections and 1 or 2 for hollow sections), "Y [mm]" (y coordinate in mm of each section point), and "Z [mm]" (z coordinate in mm of each section point).



	Sect	PolyId	Y [mm]	Z [mm]
1	400	1	0.0	90.0
2	400	1	-78.0	90.0
3	400	1	-82.7	89.3
4	400	1	-86.6	86.6
5	400	1	-89.3	82.7
6	400	1	-90.0	78.0
7	400	1	-90.0	0.0
8	400	1	-90.0	-78.0
9	400	1	-89.3	-82.7
10	400	1	-86.6	-86.6
11	400	1	-82.7	-89.3
12	400	1	-78.0	-90.0
13	400	1	0.0	-90.0
14	400	1	78.0	-90.0

Figure 93: Polyline sections table in Result Viewer

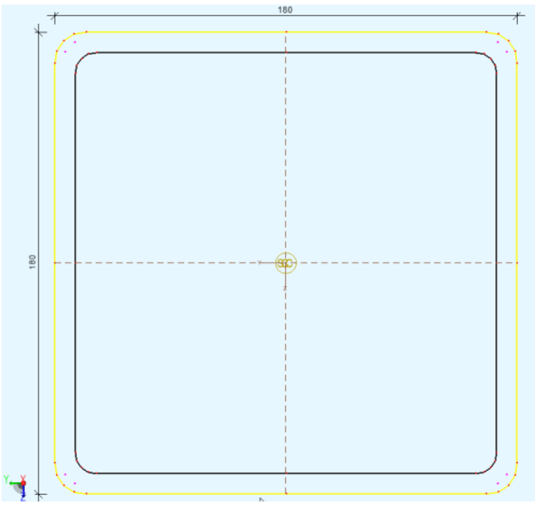
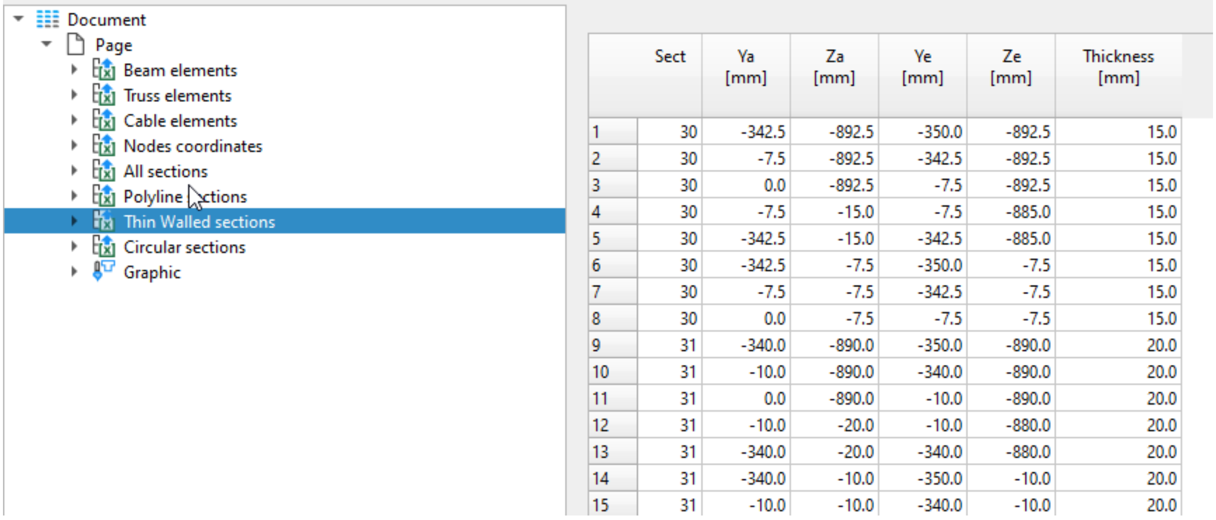


Figure 94: Example of Polyline section

A third table called “Thin walled sections” (Figure 95) is generated and contains the geometry information of all sections whose geometry has been generated based on thin-walled plates as per method (3), as the example in Figure 96. The columns of the table are “Sect “ (equivalent to NR in the first table), “Ya [mm]” (y coordinate in mm at start of plate centerline), “Za [mm]” (z coordinate in mm at start of plate centerline), “Ye [mm]” (y coordinate in mm at end of plate centerline), “Ze [mm]” (z coordinate in mm at end of plate centerline), and “Thickness [mm] (thickness of the plate in mm).



	Sect	Ya [mm]	Za [mm]	Ye [mm]	Ze [mm]	Thickness [mm]
1	30	-342.5	-892.5	-350.0	-892.5	15.0
2	30	-7.5	-892.5	-342.5	-892.5	15.0
3	30	0.0	-892.5	-7.5	-892.5	15.0
4	30	-7.5	-15.0	-7.5	-885.0	15.0
5	30	-342.5	-15.0	-342.5	-885.0	15.0
6	30	-342.5	-7.5	-350.0	-7.5	15.0
7	30	-7.5	-7.5	-342.5	-7.5	15.0
8	30	0.0	-7.5	-7.5	-7.5	15.0
9	31	-340.0	-890.0	-350.0	-890.0	20.0
10	31	-10.0	-890.0	-340.0	-890.0	20.0
11	31	0.0	-890.0	-10.0	-890.0	20.0
12	31	-10.0	-20.0	-10.0	-880.0	20.0
13	31	-340.0	-20.0	-340.0	-880.0	20.0
14	31	-340.0	-10.0	-350.0	-10.0	20.0
15	31	-10.0	-10.0	-340.0	-10.0	20.0

Figure 95: Thin walled sections table in Result Viewer

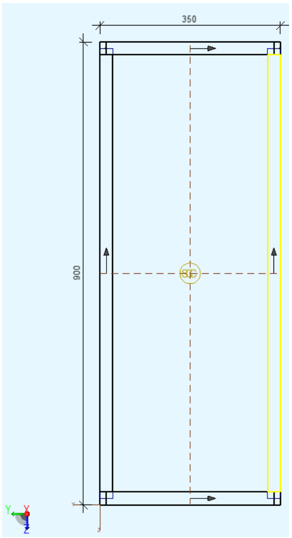
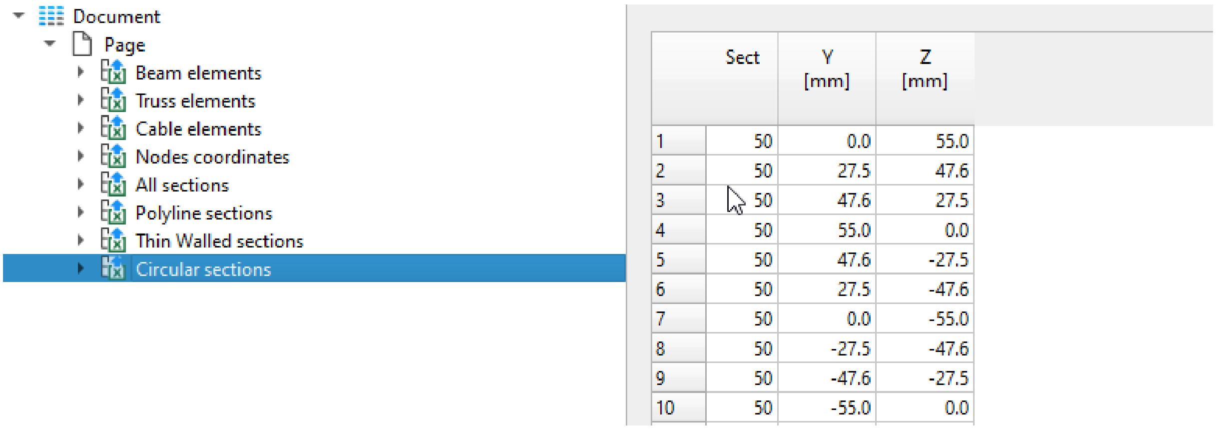


Figure 96: Example of a thin walled section

A fourth table is called “Circular sections” (Figure 97) and contains the geometry information of all sections whose geometry has been generated based on thin-walled plates as per method (3), but using circles instead of polylines, as the example in Figure 98. The columns of the table are “Sect “(equivalent to NR in the first table), “Y [mm]” (y coordinate in mm of each section point), and “Z [mm]” (z coordinate in mm of each section point). It is important to notice that only points in the outer circumference are given, so in the case of circular hollow sections, further information is required to determine the main dimensions.



	Sect	Y [mm]	Z [mm]
1	50	0.0	55.0
2	50	27.5	47.6
3	50	47.6	27.5
4	50	55.0	0.0
5	50	47.6	-27.5
6	50	27.5	-47.6
7	50	0.0	-55.0
8	50	-27.5	-47.6
9	50	-47.6	-27.5
10	50	-55.0	0.0

Figure 97: Circular sections table in Result Viewer

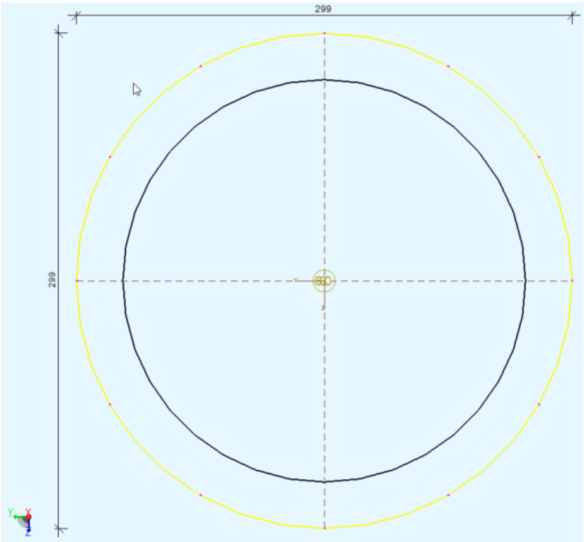


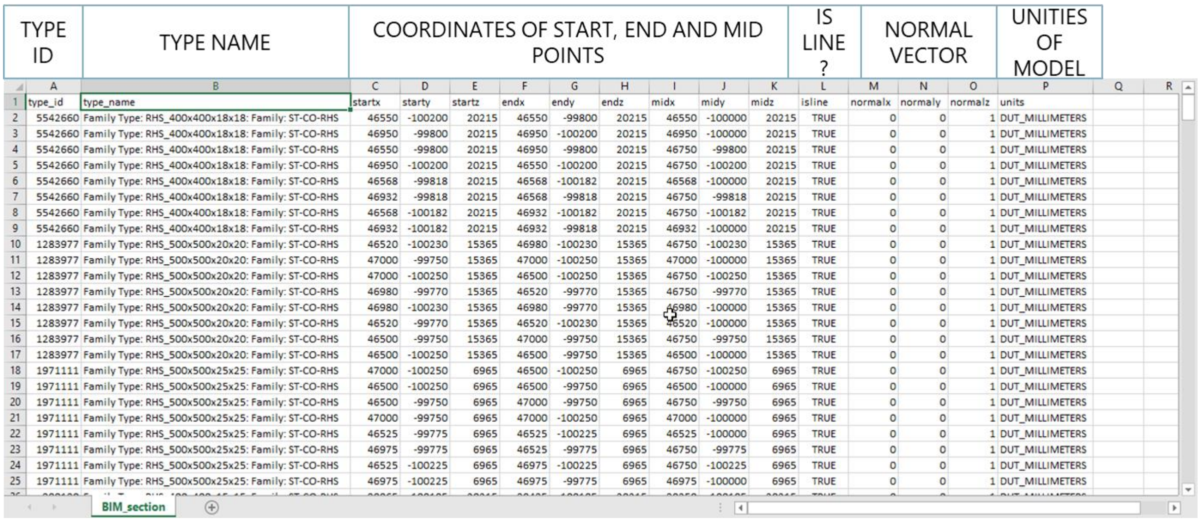
Figure 98: Example of circular section

APPENDIX C – DATA TRANSFORMATION IN DETAIL

BIM model

BIM section recognizer

When the BIM extraction is performed, it is optional to extract data to export to the file called *BIM_section.csv*. If generated, this file contains one table, as in Figure 99.



	TYPE ID	TYPE NAME	COORDINATES OF START, END AND MID POINTS									IS LINE ?	NORMAL VECTOR			UNITIES OF MODEL
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	type_id	type_name	startx	starty	startz	endx	endy	endz	midx	midy	midz	isline	normalx	normaly	normalz	units
2	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46550	-100200	20215	46550	-99800	20215	46550	-100000	20215	TRUE	0	0	1	DUT_MILLIMETERS
3	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46950	-99800	20215	46950	-100200	20215	46950	-100000	20215	TRUE	0	0	1	DUT_MILLIMETERS
4	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46550	-99800	20215	46950	-99800	20215	46750	-99800	20215	TRUE	0	0	1	DUT_MILLIMETERS
5	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46950	-100200	20215	46550	-100200	20215	46750	-100200	20215	TRUE	0	0	1	DUT_MILLIMETERS
6	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46568	-99818	20215	46568	-100182	20215	46568	-100000	20215	TRUE	0	0	1	DUT_MILLIMETERS
7	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46932	-99818	20215	46568	-99818	20215	46750	-99818	20215	TRUE	0	0	1	DUT_MILLIMETERS
8	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46568	-100182	20215	46932	-100182	20215	46750	-100182	20215	TRUE	0	0	1	DUT_MILLIMETERS
9	5542660	Family Type: RHS_400x400x18x18: Family: ST-CO-RHS	46932	-100182	20215	46932	-99818	20215	46932	-100000	20215	TRUE	0	0	1	DUT_MILLIMETERS
10	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	46520	-100230	15365	46980	-100230	15365	46750	-100230	15365	TRUE	0	0	1	DUT_MILLIMETERS
11	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	47000	-99750	15365	47000	-100250	15365	47000	-100000	15365	TRUE	0	0	1	DUT_MILLIMETERS
12	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	47000	-100250	15365	46500	-100250	15365	46750	-100250	15365	TRUE	0	0	1	DUT_MILLIMETERS
13	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	46980	-99770	15365	46520	-99770	15365	46750	-99770	15365	TRUE	0	0	1	DUT_MILLIMETERS
14	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	46980	-100230	15365	46980	-99770	15365	46980	-100000	15365	TRUE	0	0	1	DUT_MILLIMETERS
15	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	46520	-99770	15365	46520	-100230	15365	46520	-100000	15365	TRUE	0	0	1	DUT_MILLIMETERS
16	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	46500	-99750	15365	47000	-99750	15365	46750	-99750	15365	TRUE	0	0	1	DUT_MILLIMETERS
17	1283977	Family Type: RHS_500x500x20x20: Family: ST-CO-RHS	46500	-100250	15365	46500	-99750	15365	46500	-100000	15365	TRUE	0	0	1	DUT_MILLIMETERS
18	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	47000	-100250	6965	46500	-100250	6965	46750	-100250	6965	TRUE	0	0	1	DUT_MILLIMETERS
19	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	46500	-100250	6965	46500	-99750	6965	46500	-100000	6965	TRUE	0	0	1	DUT_MILLIMETERS
20	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	46500	-99750	6965	47000	-99750	6965	46750	-99750	6965	TRUE	0	0	1	DUT_MILLIMETERS
21	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	47000	-99750	6965	47000	-100250	6965	47000	-100000	6965	TRUE	0	0	1	DUT_MILLIMETERS
22	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	46525	-99775	6965	46525	-100225	6965	46525	-100000	6965	TRUE	0	0	1	DUT_MILLIMETERS
23	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	46975	-99775	6965	46525	-99775	6965	46750	-99775	6965	TRUE	0	0	1	DUT_MILLIMETERS
24	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	46525	-100225	6965	46975	-100225	6965	46750	-100225	6965	TRUE	0	0	1	DUT_MILLIMETERS
25	1971111	Family Type: RHS_500x500x25x25: Family: ST-CO-RHS	46975	-100225	6965	46975	-99775	6965	46975	-100000	6965	TRUE	0	0	1	DUT_MILLIMETERS

BIM_section

Figure 99: Data in BIM_section.csv

Each row of this table represents one curve, resultant from the intersection of an element of a given type in the Revit model and a plane perpendicular to the element alignment. For each row, there is information of the correspondent type, start, end, and middle coordinates, if it is a line or an arc, normal vector, and unities.

The "BIM section recognizer" script processes this information according to the following steps:

1. Reads the *BIM_section.csv* file;
2. Creates lists that will contain the output information: name of section, full name of section, and cross-section area;
3. Finds the unique sections in the table per id;
4. For each type id, filters the table to get only the rows for this id;

5. Rotates the start, end, and middle points to get their 2D coordinates on the plane perpendicular to the normal vector and whose origin is the centroid of the shape formed by the lines;

6. If the curve is an arch, gets the start, middle, and end point and tries to generate a circle. For the same type id stores the maximum and minimum radius found for circles;

7. After getting the radius list, it regenerates the circle (or circles, if hollow) as a polyline with 200 points;

8. For sections with arcs or lines, the order of the points is adjusted so that if we connect them in a polyline, the sense of rotation in the inner shape is opposite to the outer shape, and that they are connected by a line in case of a hollow section. Examples are shown in Figure 100;

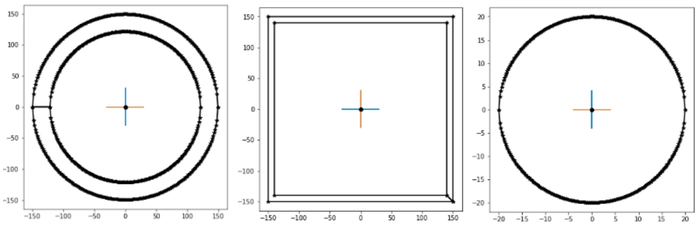


Figure 100: Example of recognized shapes

9. If more than one polyline is found, the section is classified as "hollow", otherwise its "solid_or_open";

10. Every section starts the recognizer with the label "not_recognized";

11. For open or solid sections that are not formed by arches or are defined by only four main lines, a check to find the root shape of the section is performed. This is intended to remove any welds or fillet corners from I profiles. This function selects only lines that make 90 degrees with the last one and extends them until they meet a common point. This point is added to the point list that defines the polylines. In this way only the "main segments" from a given root shape are stored;

12. Table 15 shows what are the criteria for recognizing each name of section as implemented;

SECTION ACRONYM	SECTION NAME	PROPERTIES OF POLYLINES USED FOR NAME CLASSIFICATION			
		GROUP	NUMBER OF MAIN SEGMENTS	LOCATION OF CENTROID	RATIO BETWEEN INERTIA IN PERPENDICULAR AXES
CHS	Circular hollow section	hollow	not the others	-	
RHS	Rectangular hollow section	hollow	4	-	not equal
SHS	Square hollow section	hollow	4	-	equal
WBO	Welded box section	hollow	12	-	
ROU	Round section	solid-or_open	not the others	-	
RECT	Rectangular section	solid-or_open	4	-	
I	I section	solid-or_open	12	-	
T	T section	solid-or_open	8	inside shape	
C	Channel section	solid-or_open	8	outside shape	
L	Angle section	solid-or_open	6	-	

Table 15: Criteria of BIM section recognizer to determine the section name

13. The next step is then to find the main dimensions of each section shape. If the section is not a CHS or ROU, it is rotated in a way that the longest segment is parallel to the vertical axis on the screen or if it is an I section, that it is accordingly rotated in the shape of an I and not of an H in the user's screen;

14. The adjusted rotated shape is read. Through a bounding box algorithm, the main external dimensions are found. Using the values of calculated section areas and inertia in the script, the remaining dimensions are determined. Those determinations are described per section in Table 16. They assume that only RHS, SHS, and WBO section shapes can have two different thicknesses, one for the plates parallel to the width, and another for the plates parallel to the height; all other section shapes are composed of plates with the same thickness.

SECTION ACRONYM	BOUNDING BOX	AREA	MOMENT OF INERTIA (Ixx)	MOMENT OF INERTIA (Iyy)
CHS	x	x		
RHS	x	x	x	
SHS	x	x	x	
WBO	x	x	x	x
ROU	x			
RECT	x			
I	x	x	x	
T	x	x	x	

C	x	x		
L	x	x		

Table 16: Properties of sections used for dimension determination

15. The type id, the determined shape name, the shape full name (including dimensions), and the area given by the polylines are stored in the final output. An example is shown in Figure 101.

	type_id	shape_full_name_list
0	1283977	SHS 500.0x500.0x20.0x20.0
1	1283979	SHS 500.0x500.0x15.0x25.0
2	1283987	SHS 500.0x500.0x30.0x40.0
3	1283975	SHS 500.0x500.0x15.0x20.0
4	1283985	SHS 500.0x500.0x30.0x30.0
5	1283983	SHS 500.0x500.0x25.0x30.0
6	1283971	SHS 400.0x400.0x12.0x12.0
7	380130	SHS 400.0x400.0x15.0x15.0
8	1283973	SHS 400.0x400.0x15.0x20.0
9	1283981	SHS 500.0x500.0x20.0x30.0
10	380128	SHS 500.0x500.0x15.0x15.0
11	1282726	SHS 300.0x300.0x12.0x12.0
12	1282724	SHS 300.0x300.0x10.0x10.0
13	1267439	I 260.0x260.0x17.0x10.0
14	1265876	WBO 500.0x400.0x9.8x10.2x1.6
15	1265874	WBO 700.0x500.0x9.9x17.2x1.1
16	1265870	WBO 350.0x350.0x11.8x8.2x1.5
17	1265806	ROU 50.0
18	1265804	ROU 40.0
19	1265802	ROU 25.0
20	1268003	CHS 194.0x10.0
21	1267934	CHS 140.0x6.3
22	1362302	WBO 500.0x500.0x20.0x15.0x50.0
23	1356419	WBO 500.0x500.0x15.0x15.0x50.0
24	1358379	WBO 500.0x500.0x25.0x20.0x50.0
25	1360340	WBO 500.0x500.0x30.0x25.0x50.0
26	1354460	WBO 500.0x450.0x5.4x25.3x31.6
27	1352502	WBO 350.0x350.0x10.0x10.0x1.0
28	1370160	WBO 350.0x350.0x20.0x15.0x1.0
29	1368194	WBO 350.0x350.0x10.0x10.0x1.0

Figure 101: Output of BIM section recognizer

FEA model

Main information

1. The information given on the following sheets of the SOFiSTiK results file is retrieved:

   a. “Sof_beam”;

   b. “Sof_truss”;

   c. “Sof_cable”;

   d. “Sof_nodes”;

   e. “Sof_section_all”.

2. Additionally, the filed *id_to_mark.csv* is also read.

3. The original names of the columns from the tables are standard for the software chosen. They are replaced by more meaningful values to the way the data warehouse is organized;

4. The geometry tables for beam, trusses, and cables are reorganized and properly concatenated in one single table with all elements;

5. For each element in this table, the initial and final node coordinates are retrieved from the node coordinates table;

6. Using the "id_to_mark" mapping table, a column with the element mark is added;

7. Generally, one element in the BIM model is discretized in several different elements in a FEA model. Therefore, for each unique mark, the code filters the data frame, getting lines with each of the related FEA elements that relate to one given mark;

8. From all the points on this filtered table, the code selects the one that is farthest from the origin. This is arbitrarily named the start point;

9. Then, the code finds the point on the filtered table that is the farthest from the selected start point. This is named the end point;

10. The length of the element is calculated as the distance between those selected points;

11. As each FEA element has a section number and this section number has a calculated area from inside the software, the mean of the filtered table section areas is retrieved and output as the area of the element;

12. The section name in the FEA software, for the first element on the filtered table is also retrieved;

13. The volume of the element is calculated from the calculated length and section area;

14. An output table is created containing one row per "element_mark", with the following columns:

    a. "element_mark";
    b. "element_id";

c. “group”;
d. “section_id”;
e. “section”;
f. “sx”;
g. “sy”;
h. “sz”;
i. “ex”;
j. “ey”;
k. “ez”;
l. “length”;
m. “section_area”;
n. “volume”.

<u>FEA section recognizer</u>

For each section in the “Polyline section” table, the following steps are taken:

1. Organize the polygon points coordinates in the form of an organized list of [x,y] coordinates per “PolyId” or polyline;
2. Classify the shape in “hollow” or “solid_or_open” given the number of “PolyId”s;
3. Remove any duplicate start/end points of polylines;
4. Find the “root shape” of the section, i.e. the shape of the polyline removing any chamfers or curves, by doing for each polyline:
    a. For each point, find its antecedent in the points list;
    b. Get coordinates from both points;
    c. Find the vector from the antecedent to the current point;
    d. Find what is the next couple of points on the list whose linking vector is perpendicular to the first vector;
    e. Gets the coordinates from the two points;
    f. Finds the intersection point from those two vectors by doing an intersection of lines, which are found through the four coordinate points;

g. Store this intersection point;
h. Repeats until the polyline is closed, i.e., the first point equals the last point on the list.

5. Rearrange the list order so that if it is a hollow shape, the order of coordinates is reversed in one of the two polylines;
6. Find main dimensions of shape from bounding box;
7. Find centroid, area, and area inertia of shapes according to custom building functions that read the coordinates of their boundaries;
8. Classifies the shape according to its type:
   a. If it is a "hollow" profile, and the outer polyline has four elements, it is a "RHS" if Ixx is different from Iyy or a "SHS" if they are equal;
   b. If it is a "hollow" profile, and the outer polyline has 12 elements, it is a "RHS-extended" section;
   c. If it is a "hollow" profile that does not fit "a" of "b" it is classified as a "CHS";
   d. If it is a "solid_or_open" profile, and its boundary polyline has four elements, it is a "REC";
   e. If it is a "solid_or_open" profile, and its boundary polyline has six elements, it is an "L";
   f. If it is a "solid_or_open" profile, and its boundary polyline has 12 elements, it is an "I";
   g. If it is a "solid_or_open" profile, and does not fit "d", "e" or "f", checks if the centroid of the shape is inside or outside the shape. If it is inside, it is a "T", if it is outside, it is a "U";
9. Rotate the shape so that the height is the longest element or that they are aligned according to the line that represents its typology (as an I instead of H, for instance);
10. Find main dimensions of adjusted/rotated shape;
11. Determines the dimensions of each cross-section depending on their type, using the width and height of profile as per determined in the bounding box and finding

the thickness of plates aligned with the height and the thickness of plates aligned with the width via the root of equations such as area, Ixx, and Iyy, as required;

12. Formats the name and dimensions as standard output;
13. Output results to a csv file.

For each section on the “Circular section” table:

1. Finds the outer diameter, given by the difference between the maximum and minimum Y coordinates of section points;
2. Gets the area of the section;
3. Tests if the area equals the area of a circle with the given diameter, if so, it is a ROU section, otherwise it is a CHS section, and by calculating the area, finds the thickness of the section.

For each section on the “Thin walled section” table:

1. Gets all start and end points of the midline of plates and their thickness;
2. Adds all the corner points of each plate;
3. Computes the outer shape of all the points through a mathematical algorithm called “alpha shape”;
4. From this outer shape, gets the root shape, i.e., the shape in which each line is perpendicular to the next one; welded boxes not with outstanding flanges are not implemented.
5. With the outer shape, the section name is determined in a process like the one for the BIM_recognizer;
6. The bounding box of the shape gives the outer dimensions;
7. The thickness is calculated depending on the section name, finding one plate in each main direction and reading the thickness from the initial shape;
8. The area is calculated in a formula according to each root shape.

<u>FEA element data</u>

The idea is that this is modified for each specific query on the FEA model required by the user. The following implementation is an example that retrieves the maximum internal forces for each "element_mark" in the selected load cases.

1. Reads the "beam_results", "truss_results", "cable_results";
2. Read the "id_to_mark" table;
3. For the beam results:
    a. Gets the mark for each "element_id";
    b. For each unique mark, gets the first element id and the maximum and minimum values of each internal force (normal force, shear force in each main direction, torsional moment, bending moment in each main direction);
    c. Outputs all the values in 3.b. to a final table;
4. For the truss results:
    a. Gets the mark for each "element_id";
    b. For each unique mark, gets the first element id and the maximum and minimum values of normal force;
    c. Outputs all the values in 4.b. to a final table.
5. For the cable truss results:
    a. Gets the mark for each "element_id";
    b. For each unique mark, gets the first element id and the maximum and minimum values of normal force;
    c. Outputs all the values in 5.b. to a final table.

<u>Model comparison</u>

Reads the current *BIM_main.csv* file and the *main.csv* file in the to/compare/output folder:

1. Read what is the desired type of section comparison, chosen via the correspondent Power BI parameter;

2. If section comparison is by section recognizer, reads the “BIM_section_output” file and the section file in the “to_compare”/”input” folder;
3. If section comparison is through “section_id_FEA”, reads the “sof_section_to_type” file;
4. Reads tolerance, translation, scaling, and rotation parameters;
5. Adjust the coordinates in the “to_compare” main folder accordingly;
6. For each element in the current model:
    a. Gets the mark, check if the mark is on the other model - if so value of ”mark_check” is “kept” otherwise it is “modified”;
    b. Gets the start and end point of the line, check if there is any line on the other model which has the same base line (given the tolerances, which are applied at each coordinate) - if so the value of “element_check” is “kept” otherwise it is “modified”;
7. For each element in the other model:
    a. Gets the mark, check if the mark is on the current model - if so value of ”mark_check” is “kept” otherwise it is “modified”;
    b. Gets the start and end point of the line, check if there is any line on the current model which has the same base line (given the tolerances, which are applied at each coordinate) - if so the value of “element_check” is “kept” otherwise it is “modified”
8. If the section comparison is through section recognizer:
    a. The comparison parameters are the “section_full_name” from each output table from the section recognizer;
9. If the section comparison is through “section_id_BIM”:
    a. The comparison parameters are the “section_id” from each main table;
10. If the section comparison is through “section_id_FEA”:
    a. The BIM comparison parameter is the “section_id” from the BIM_main table;

b. The FEA comparison parameter is determined by mapping the “section_id” from the “FEA_main” table to a “BIM_id”, using the auxiliary table in *sof_section_to_type.xlsx*

11. For each element in the current model:
    a. If the “mark_check” is kept, directly compares the section parameter for the elements with the same marks in each of the models;
    b. Otherwise, but if the “element_check” is kept, finds the index of the line that had a similar line, and compares the section parameter for the current element with the correspondent in the other model;
    c. Otherwise, the “section_check” is automatically set as “modified”, since there is no correspondent element;
12. The table of outputs from the other model is filtered to contain only elements that are not in the current one, i.e., with “modified” for marks and elements checks. All “section_check” tags for those elements are set as “modified”;
13. The output tables are appended and form the output table of the model comparison.

Table 17 summarizes the comparison output for each case.

SOURCE	MARK CHECK	ELEMENT CHECK	SECTION CHECK	GENERAL COMPARISON OUTPUT	SPECIFIC COMPARISON OUTPUT
Current	Kept	Kept	Kept	Kept	Kept
Current	Kept	Modified	Kept	Modified	Moved
Current	Kept	Modified	Modified	Modified	Moved_section-changed
Current	Kept	Kept	Modified	Modified	Section-changed
Current	Modified	Kept	Kept	Modified	Mark-changed
Current	Modified	Modified	-	New	New
Current	Modified	Kept	Modified	Modified	Mark-changed_section-changed
Previous	Not present	Not present	-	Deleted	Deleted

Table 17: Criteria for model comparison output