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A FRAMEWORK FOR ARCHITECTURE AND STRUCTURAL ENGINEERING COLLABORATION IN BIM PROJECTS THROUGH STRUCTURAL OPTIMIZATION

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SUMMARY: *There has been an increasingly global tendency in the adoption of Building Information Modeling (BIM) paradigm in Architectural, Engineering, and Construction (AEC) projects. At the same time, Structural Optimization (SO) has received a lot of attention in the construction industry to reduce material and to enhance structural performance. However, the lack of communication between structural engineer and architect is a well-known problem discussed in the literature. This can lead to inefficient projects, thus increasing cost and time. The purpose of this work, thus, is to understand how SO can be inserted in a BIM project, specifically analysing the information exchanges between architects and structural engineers, to mitigate the problem related to lack of communication. The investigation included a systematic literature review to comprehend the current scientific scenario in these areas. It identified that there is still a research gap related to the adoption of SO to facilitate the communication between architects and structural engineers in a BIM environment. To help answer this question, an Information Delivery Manual (IDM) structure was developed which maps the information flow to connect architects and engineers through SO in a BIM environment, aiming to optimize the information exchanges. By applying the methodology to three experiments of increasing complexity, the proposed framework proved to improve the collaboration issue beyond other project benefits, such as reduction of material consumption, improvement of sustainability indexes, and structural performance. Thus, the main finding of this study is that the connection between BIM and SO can improve the collaboration between these two players in the early design stages and, thus, it can potentially lead to a more efficient design process. More studies are still necessary to solve technological barriers related to software interoperability.*

KEYWORDS: *architecture, BIM, information exchanges, lack of communication, structural engineering, structural optimization.*

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1. INTRODUCTION

The current global economic scenario demands that the Architecture, Engineering, and Construction (AEC) industry provide better projects that use less material, produce less waste, and have better performance, as reported by the World Economic Forum (2016). At the same time, the Building Information Modeling (BIM) paradigm, which is a prominent methodology for improving design and construction, is growing worldwide. However, according to Azhar et al. (2012), there are two types of risks in the BIM implementation that can negatively impact a construction project, one is related to technological issues and the other, to processes. In fact, through literature review and a Delphi survey, Olawumi et al. (2018) identify two main barriers depending on the partitioner's perspective. The academics community considers software interoperability as an important barrier, while industry experts consider the fragmented culture between disciplines poses a very important barrier. Therefore, recent studies are being done to have a better understanding on how to improve the communication between tools and people. For instance, Delgado et al. (2020) investigated the usage of Virtual and Augmented Realities in the construction industry and found that these new technologies are able to improve "many-to-many communication capabilities", between user and/or devices. In this sense, the present study focuses on the barriers with regards to BIM dissemination related to two types of communication: digital (between software packages) and human (between players).

With regards to the digital communication, the interoperability via the IFC format is a solution that aims to integrate and guarantee communication between BIM tools. The main idea of IFC standardization is to achieve open interoperability, which positively impacts BIM by facilitating information flow throughout a building's lifecycle, avoiding redundancy and increasing the productivity coupled with efficiency (Laakso and Kiviniemi, 2012). Beyond these abstract gains, a better interoperability also implies financial savings. As indicated by the NIST report (Gallaher et al. 2004), perfect interoperability between systems could reduce construction schedule by 5 to 10 percent. In addition, according to the McGraw Hill report (Jones et al. 2008), a total of 3% of project costs can be associated with poor software interoperability. This results in reworks and manual data input, unnecessary time spent duplicating information in different platforms, and document version's checking

According to Abanda et al. (2015), the second type of communication (human), is related to policies or people and, as verified by Lu et al. (2014), a better environment for human collaboration is promoted by the BIM implementation. In fact, in accordance with Ghaffarianhoseini et al. (2017), when this occurs in the early stages of a project, it can reduce requests for information and rework, which directly impacts cost and time. Nonetheless, Suwal and Singh (2018) claim that sometimes this BIM pillar requires cognitive studies rather than technical studies, which is beyond the scope of the present work. The present work focuses on technical issues that affect people and information flow.

It is worth pointing out that the lack of communication is a well-known problem in the construction industry and that it occurs in the entire building lifecycle, i.e., from the conceptual design phase (Guest et al. 2013) to construction activities (Calvetti et al. 2020). Even in the same construction company, there can be barriers related to communication and integration between players, as highlighted by Núñez et al. (2018) during interviews with professionals. Many authors suggest that new technologies could improve the communication in the construction industry, such as BIM and Blockchain (Safa et al. 2019) and the usage of Augmented Reality to identify deviations between designed and built objects in the construction site (Chalhoub et al. 2021).

Specifically, in the interface between architects and structural engineer, the need for better communication has been highlighted by some authors for some time. For instance, Fruchter et al. (1996) proposed a framework named Interdisciplinary Communication Medium to enhance the communication between structural engineer and architect through a shared 3D graphic model. The workflow consists of four stages: design proposal from architect; interpretation; critique from structural engineer; and explanation. Exploring the same interface, Beghini et al. (2014) concluded that topology optimization could be used as "a common ground" to facilitate the communication between structural engineering and architectural disciplines.

Along these lines, the present work explores the structural optimization process that requires collaboration between architects and engineers, mainly in a BIM-enabled project. Structural optimization (SO) is often concerned with reducing weight and improving structural performance. Topology Optimization (TO), which is a type of SO, is better adopted in early stages of the design, when there are few shape restrictions (Papalambros, Wilde 2000). Compared to other types of Structural Optimization (sizing and shape optimizations), TO provides the most freedom in the design; in other words, it can produce unexpected structures, with atypical shapes and curves, from a basic conceptual volume (Deaton and Grandhi, 2014). According to these authors, since the beginning of the 21st century, TO has been the most studied area in structural multi-objective optimization.

In this research, the focus is on the early stages of the design, when there are few restrictions and only the building mass is defined. More specifically, it applies TO to produce efficient structural shapes, which consequently anticipates the collaboration between structural engineering and architecture. This goes in the direction of creating a better BIM environment and demonstrates that there is a synergy between BIM and SO. In this sense, the main objective of this work is to understand how structural optimization can be inserted into a project within the BIM framework, and what impacts it can provide. Specifically, it seeks to shed some light on how it can influence the collaboration between architects and structural engineers in the early stages of design of a building project. Thus, the specific objective of this study is to develop the initial steps towards the integration between structural engineers and architects using structural optimization processes in a BIM environment. Previous studies have already highlighted the challenges related to interoperability between architectural and structural tools (Papadopoulos et al. 2016) but they focused mostly on technology issues. Other studies are specific to people issue, such as Sotelino et al. (2020) in which a survey was developed with graduate students to understand their perceptions on how BIM changed their understanding about collaboration between different disciplines. Unlike these two studies, the present work investigates processes that uses technology and connect people and disciplines.

To support the objective, a Systematic Literature Review (SLR) is conducted to understand the current stage of development in this scientific area. Using this methodology, scientific gaps can be found and, thus, orient the study to help fill them. After that, a framework of information flow to insert structural optimization processes in a BIM project is created, using Information Delivery Manual (IDM) concepts. This structured process map to track data flow was used because it helps to understand which players' interactions produce information losses and orient the elaboration of exchanges information requirements to improve workflow and collaboration. To test the applicability of the proposed framework and the potential impact that it might have, three experiments were developed and analysed. At the end, the conclusions and discussions are presented as well as suggestion for future works.

2. LITERATURE REVIEW

2.1 Methodology

The process adopted in this literature review is the Systematic Literature Review (SLR), whose main principles are reliability and impartiality (Denyer, Tranfield 1987). Although, the systematic review requires more efforts when compared to the traditional literature review (Saieg et al. 2018), according to Kitchenham and Charters (2007), performing an SLR is important to understand current studies, identify gaps (areas not explored yet), and create the necessary background for the development of new research. In agreement with Denyer and Tranfield (1987) and Khan et al. (2003), there are five steps that compose the entire SLR process. They are: question formulation; studies localization; studies selection and evaluation; analysis and synthesis; and reports and results. It is worth pointing out that this process is cyclical, and that it may be necessary to repeat some steps.

To guide the scientific research, the following two questions were formulated following the SLR methodology proposed by Khan et al. (2003):

- How can the structural optimization process be inserted in the BIM methodology?
- What impact does the structural optimization process generate in the BIM process?

After the questions formulation, the next steps are to locate the studies and select them. Therefore, scientific databases were chosen as well as the search terms and then, appropriated filters were applied to the search results aiming to restrict the first sample with inclusion/exclusion conditions. In doing so, the sample becomes more coherent, from which conclusions can be drawn and gaps can be identified in the literature. Table 1 summarizes the search terms and main filters used in this work for the SLR.

After locating the studies, a qualitative evaluation of the results from inclusion/exclusion criteria was performed, i.e., all titles and abstracts were read and analysed. In this manner, studies that did not fit within the scope of this study, but for some reason fit in the quantitative filters, were discarded.

Table 1: Inclusion/exclusion conditions in the SLR.

Sources	**Scopus, Engineering Village, Web of Science, Science Direct, and Google Scholar**
Search terms	BIM, Architecture, Structural Optimization, and Topology Optimization
Time-period	2012 to 2020
Type	Journal papers
Language	English
Work area	AEC industry

The final step of the adopted SLR methodology is a final qualitative analysis consisting of the full reading of all chosen articles. This made it possible to investigate if the paper was relevant to the study. In this SLR step, the initial sample from all searches consisted of 76 papers and after the full reading the number of articles reduced to 43. Additionally, two additional papers were found outside the SLR search and were included in this work, totalizing 45 papers. The final set of selected articles divided by search area are given in Fig. 1.

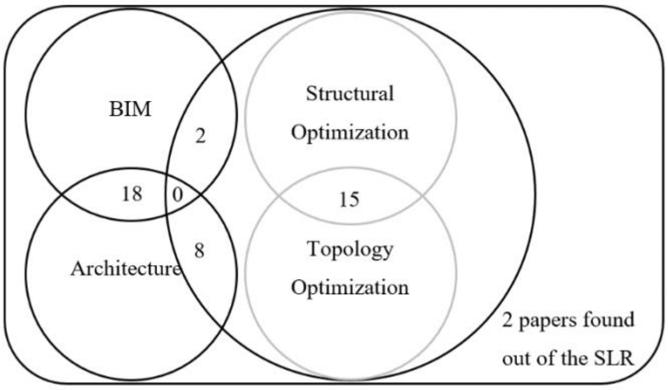

Fig. 1: Final number of papers found in the SLR, divided by search terms.

As can be seen, apparently there are few studies connecting BIM and structural or topology optimization, since only two papers discussed the subjects together. As an observation, papers that were found in citations in other papers, but not found in the SLR methodology, were incorporated in the sample when they were found to be relevant to the study. With the aim of confirming the observed scientific gap, conference papers were searched using the keywords SO and BIM. However, no satisfactory results connecting these universes were returned.

2.2 Bibliometric analysis

After the SLR, the software VOS viewer, a bibliometric analysis tool developed in the Leiden University's Centre for Science and Technology Studies (van Eck, Waltman 2006), was used to better understand the connection between the selected publications. Using this tool, it is possible to analyse the occurrence of terms in the titles or abstracts of all papers, as well as their co-occurrence. For the present study, it was set that a term must occur at least three times, in binary type (presence or absence), meaning that the term appears in at least three articles. Besides that, relevant terms were analysed, eliminating common terms such as “introduction”, “contributions”, among others.

The result of this analysis is illustrated in Fig. 2, where blue represents zero occurrences and red represents higher number of occurrences. The proximity between the terms represents the connections between them (co-occurrence); this reaffirms the initial conclusion from the SLR that BIM and structural optimization reside in separate universes with no clear connection. However, some words, such as process and conceptual design, seem to be an initial effort to integrate these areas and, thus, set the green light to keep the work in this direction.

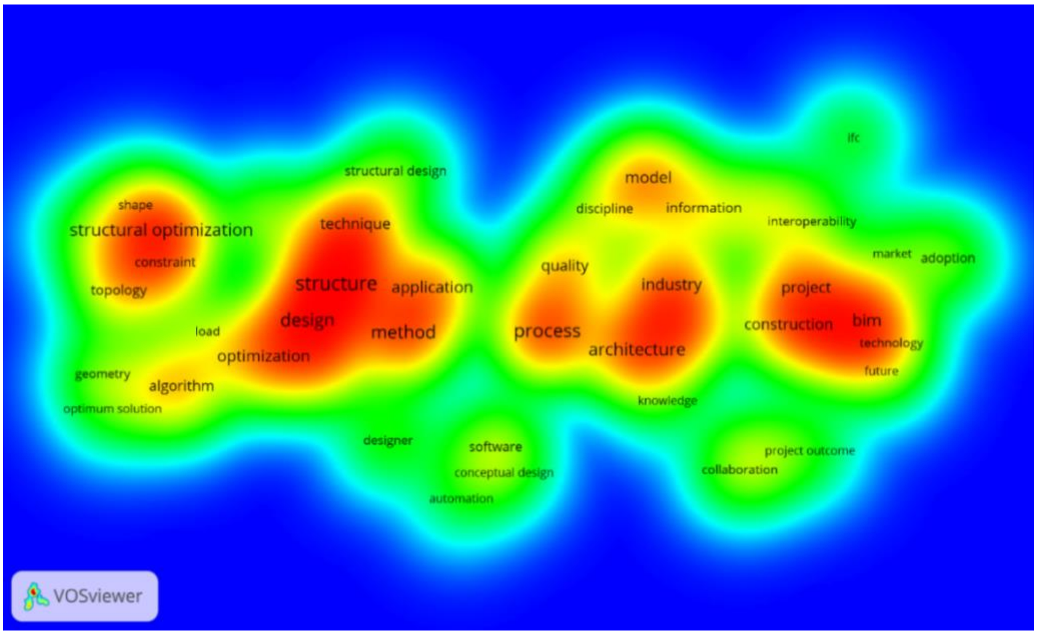

Fig. 2: Co-occurrence terms map from all selected articles.

2.3 Selected articles for review

All selected articles have some contribution to this work, but in this section, the papers that were more helpful are briefly summarized. A complete summary of the 45 selected papers can be found in Carmo (2018). The articles were divided into three groups: works related to BIM, studies related to SO in AEC industry and articles that are related to BIM and SO, and are presented next.

2.3.1 Articles related to BIM interoperability

Many papers discuss the interoperability between BIM tools, which is a major issue for the successful adoption of BIM. Three articles (Ramaji et al., 2017; Liu et al., 2016; Shin, 2017) were most relevant to this work because they highlighted the current interoperability barrier related to structural engineering and provided technical solutions that can help improve the communication between tools. Their contributions are described next.

Ramaji et al. (2017) developed an IDM framework to understand the workflow between players in the design phase of generic modular building projects. Also, the authors created an information repository named PAM to organize all data from the exchange models outlined in the IDM. After, they applied this structured workflow to some case studies, and concluded that the proposed IDM helps solve communication and information exchange problems in modular building projects. This conclusion was based on three features of the proposed framework: it supports the BIM data organization to evaluate the interoperability, it creates an example workflow to be used in other projects, and it supports software vendors to improve their solutions by providing "a holistic information management framework" that define the data required in each information exchange between players and its related modeling phase.

Similarly, Liu et al. (2016) used IFC to develop an interoperability plugin to exchange information between the physical model and structural analysis model, using IFC. They observed that it was difficult to create a direct method to achieve the desired interoperability and emphasized that their work was only a preliminary effort for interoperation between the physical model and structural analysis model.

In another study, also focused in structural engineering, Shin (2017) analysed the interoperability issue inserted in a structural engineering environment, aiming to make the best use of BIM collaborations in order to improve work efficiency and efficacy. The author used the openBIM and application-programming interface concepts, limited to an interoperability with LOD 300. Also, the author developed a case study with a construction model that contains distinct structural solutions and tested the information workflow in different ways. It was concluded that the pre-detailing design is currently the best stage to achieve satisfactory data interoperability from the structural engineering perspective.

The papers described in this section were important to this work because they showed that interoperability issues can be improved by process mapping, and also highlighted that it is important to have a greater information flow since the early stages of design. Based on this, the present work focuses on the conceptual design phase and on the development of a process mapping framework to structure the information.

2.3.2 Articles related to Structural Optimization (SO) in AEC projects

Next, some studies that apply SO to AEC applications are summarized. These articles were relevant to indicate the initial steps that have already been attempted to connect structural optimization and application in the AEC industry. Related to optimization with various objective functions, Richardson et al. (2013) developed a multi-objective TO method using genetic algorithms to optimize a bracing facade system of a museum building. This structural system was subjected mainly to wind forces. The optimization approach consisted in relocating the bracing systems until reaching the optimal solution according to structural requirements. In this case study, the SO process was applied in the early stages of the project and resulted in significant cost savings.

It is worth pointing out that usually the adoption of SO processes results in complex structures that are impractical to construct using traditional methods. Thus, in the literature, some authors connect SO with new technologies in civil construction. These papers were important to indicate the viability to adopt SO alternatives. As example, Donofrio (2016) did an extensive review on the applicability of TO focusing on its benefits to production and design using advanced materials and advanced techniques. In this study, the author concluded that TO associated with advanced manufacturing techniques (e.g., 3D printing) can result in benefits to AEC industry, especially in the development of sustainable buildings.

Two of the papers found using the SLR methodology deal with the collaboration between AEC players, a fundamental BIM principle that sometimes is more cognitive than technical, through the adoption of SO techniques. Some papers found emphasize cognitive points from SO that affect BIM principles: they deal with collaboration between AEC players. The first one, by Beghini et al. (2014), created a modified TO framework for the entire design process that connects the architecture and engineering universes. After applying this framework to experiments, they concluded that a shared parametric model establishes a natural interaction between architects and engineers by means of a common language: topology optimization.

The second one, by Kingman et al. (2014), applied TO to large-scale projects and components. With some examples, they showed that the optimization process turns the workflow slower, but they also concluded that it provides “a tool that can lead to greater collaboration between engineers and architects during the conceptual design process”. However, some challenges were highlighted, such as complex geometry in optimization solutions and shortcomings in optimization when the structural problem is nontrivial (nonlinear behaviour, member buckling, etc.).

2.3.3 Articles related to SO and BIM

Research on structural optimization within the BIM process is scarce in the literature, but some contributions that helped in the development of the present work are described next. Chi et al. (2015) analysed the growth of structural design domain associated with BIM. They concluded that some revolution in structural design is required when BIM is adopted, and structural optimization can help solve this issue, even though it can be more time consuming. The authors recommend that more research is necessary along with technological improvements to fully solve this problem.

Also related to SO and BIM, Park et al. (2012) examined the integration problem between architects and structural engineers in the initial phases of the project. They suggest that understanding the role of structural issues in the conceptual architectural design can be achieved through structural layout optimization, which can help construct this connection between architects and engineers. However, current tools are not yet ready to make this connection. Furthermore, they point out that an optimization tool should be understood as an auxiliary tool and not be treated as an isolated task.

Gomes et al. (2018) developed a methodology to connect architects and structural engineers through the optimization of thin concrete shells in early stages of the project. In their work, they integrate a multi-criteria optimization within an Integrated Project Delivery (IPD) framework. Their optimization was oriented to support the decision-making process and it was based on limiting the maximum displacement and minimizing cost. They concluded that their method results in more efficient and higher quality solutions for the pre-design stage of shell structures, satisfying both structural and architectural requirements.

As a conclusion, almost all reviewed articles focused on structural performance or space arrangement, and do not consider a combination of architectural and structural requirements. This is incompatible with the philosophy of the BIM methodology related to multidisciplinary collaboration. Thus, to be applicable within the BIM framework, it is important to conduct an optimization that considers all involved actors: architects, engineers, contractors, clients, etc. Optimization of an individual specialty does not make sense within the BIM workflow.

3. PROPOSED FRAMEWORK

Considering the SLR results and the recent scientific findings described before, an IDM is proposed to understand how structural optimization processes can be inserted in building projects in early stages within the BIM methodology. The Information Delivery Manual (IDM), standardized by the international code (ISO 29481-1:2016), is a useful approach to define the information flow and its relationship with all stakeholders involved in the project. By developing the IDM, it is possible to identify information gaps, players involved in these exchanges, and possible ways to solve the lack of interoperability.

The developed approach that supports the proposed IDM is based on reverse engineering; in other words, it is assumed that tools can handle the information exchanges between tasks. However, at the present time, BIM tools still lack the interoperability required to fully read and understand the specifications required in the information exchange. The present work intends to indicate a better way to initiate an IFC standard (or Model View Definition) specific for SO in conceptual phase.

First, in the proposed IDM, a process map is created aiming to insert structural optimization in the BIM conceptual design for building projects. The developed workflow includes all main actors involved in an AEC building project: architect, structural engineer, MEP (Mechanical, Electrical, and Plumbing) engineer, constructor, manufacturer, and client. It is worth pointing out that other entities, out of the scope of this work, can be inserted in sub-processes or in specific projects. Fig. 3 shows the proposed process map. The information workflow is described next.

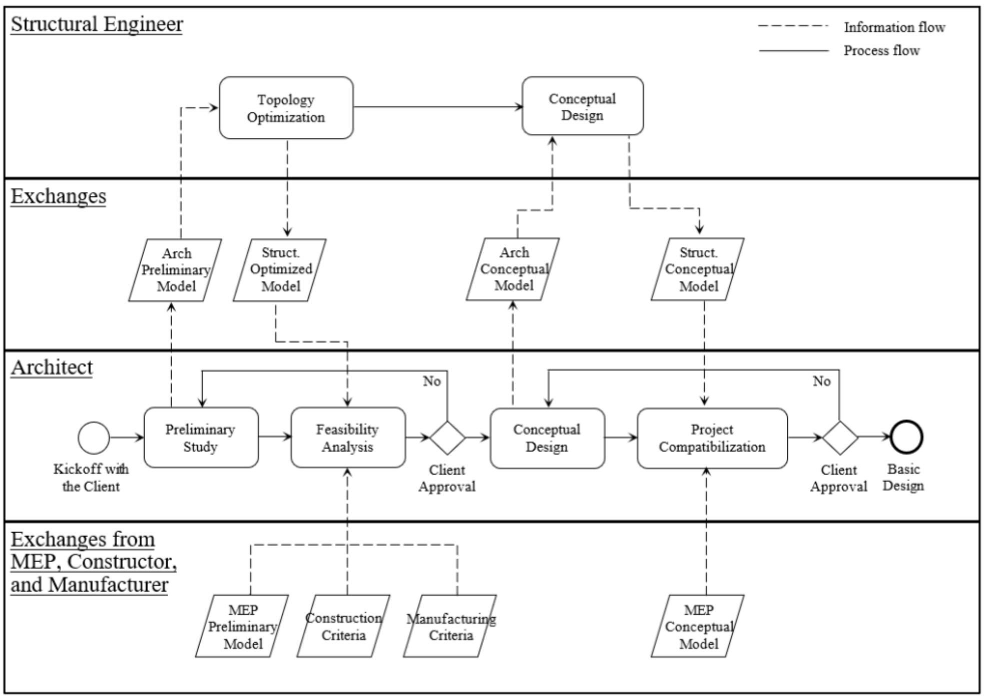

Fig. 3: Structural Optimization process inserted in the BIM methodology in the early stages for building projects.

The workflow starts with the kick-off meeting. According to the COBIM (2012), the initial modeling of a building, referred to here as architectural preliminary study, should be preceded by the owner's requirements statement, list of deliverables within a chronogram, and budget. These requirements represent the input data from the kick-off meeting with the client and can be expressed in a database table.

After the initial discussion with the client, the architect develops a volumetric model with the defined material. In this stage, the surroundings and its interaction with the new building are studied. In addition, energy related issues, such as solar and wind power, can be used by the architect to establish the orientation of the building, for example. However, at this point no specific details of the building, such as openings, internal walls, etc., are specified. These details will only be defined in the conceptual design phase.

In the proposed methodology considering SO, the preliminary model is sent to the structural engineer to start the next task. Also, following to (BuildingSmart Findland 2012), in the preliminary model, also called by initial and spatial model, the following data should be included: 2D drawings, 3D models and images, neighbouring structures volumes, measurement results from topography, preliminary space study, and energy efficiency goals.

In this study, the 3D model, containing the spatial design, is sent to the structural engineer who will import the model to an SO tool using SAT extension (only geometrical information is exchanged), because the utilized optimization tools do not read and write native or IFC format files. Thus, in this first exchange, the material definition and all other non-geometrical information are lost, because the IFC standard is not yet available in optimization tools. It is worth pointing out that the identification of the data exchanges and the necessary information are fundamental to start a creation of IFC format in this workflow. Table 2 presents the Exchange Requirements (ER) and lists the information needed in this exchange beyond that provided by SAT format and to be implemented in the IFC standardization, following the proposed IDM.

Table 2: Exchange requirements for the architectural preliminary model.

Information Needed	Required	Optional	Data Type	Units
Project				
ID	X		string	n/a
Name	X		string	n/a
Owner/Client		X	string	n/a
Model author		X	string	n/a
Description	X		string	n/a
Geographic location	X		latitude, longitude	degree, minutes, seconds
Units system	X		string	n/a
Site datum	X		coordinates	meters
Site perimeter	X		real number	meters
Site preserved areas	X		real number	square meters
Building Elements				
External volume (3D Geometry)	X		real number	cubic meters
Stories definition		X	real number	meters
Elevation	X		real number	meters
Type of occupation	X		string	n/a
True north orientation	X		real number	degrees
Openings	X		real number	square meters
Construction type		X	string	n/a
Stairs/Elevator				
Location		X	coordinates	meters
Area		X	real number	square meters
Roof				
Type		X	string	n/a
Thickness		X	real number	meters
Material				
Structural system	X		string	n/a
Roof		X	string	n/a
Façades finish		X	string	n/a
Structural Particularities				
Special loads	X		string	n/a

With the aim of connecting architects and structural engineers, the initial structural optimization is conducted to obtain the building shape with the best structural performance in terms of structural stiffness, according to the proposed workflow. Thus, using the volume and material defined previously, the structural engineer generates the "optimal" shapes for the building that can be considered or not by the architect. This initial SO should not be seen as a magical tool, returning a unique solution, but as a generative design tool that results in alternatives for design.

The structurally optimized models are defined by combining the separate optimizations and sending them to the architect as design alternatives. It is worth pointing out that in this task, the material data has to be re-entered because this information is lost in the initial exchange. This information is sent by SAT file (only geometrical information is exchanged) to the next stage, the commercial SO tools (Fusion 360, Abaqus/TOSCA, and Ansys) do not export IFC files. So, once again in this second exchange, the material definition and other non-geometrical information are lost. Table 3 represents the second ER and shows the information required to be exchanged from the structural engineer to the architect.

Table 3: Exchange requirements for the structural optimized model.

Information Needed	Required	Optional	Data Type	Units
Project				
ID	X		string	n/a
Name	X		string	n/a
Owner/Client		X	string	n/a
Model author		X	string	n/a
Units system	X		string	n/a
Optimized Structural Solutions				
Description		X	string	n/a
External volume (3D Geometry)	X		real number	cubic meters
Openings		X	real number	square meters
Construction type		X	string	n/a
URL for the optimized alternatives.	X		URL	n/a
URL for the optimization report.	X		URL	n/a
Stairs/Elevator				
Suggested location		X	coordinates	meters
Suggestion area		X	real number	square meters
Roof				
Suggested type		X	string	n/a
Suggested thickness		X	real number	meters
Material				
Structural system		X	string	n/a
Roof		X	string	n/a

Following the proposed methodology, with all the SO design alternatives, the architect can adopt more structurally optimized buildings shapes based on technical and economic studies, but this is not obligatory. The initial structural optimization works as auxiliary tool that can be discarded or improved, depending on the results from the technical and economic viability study. After the optimization processes in all SO tools are finished, the structural engineer generates alternatives for the architect. These options are not mandatory but auxiliary to the architect's inspiration and, thus, they can be discarded or one of the optimized options be adopted.

In the technical and economic viability study, other alternatives and suggestions from different disciplines can be considered to further guide the conceptual design. This step is the last opportunity to change the preliminary study before the development of the conceptual design and, thus, it is the time for all actors involved in the project to state their opinions. However, it is up to the architect, manage and organize all suggestions and to present the result to the client, who will decide whether or not to adopt them in the next task.

The project advances and the conceptual design is achieved. In this phase, specific architectural elements, such as wall, windows, among others, are defined, according to (BuildingSmart Findland 2012). In contrast to the detailed design, elements details are not modeled, such as connections in windows sill. In this stage, energy analysis can also be conducted, to optimize issues related to sustainability concerns. From this point on, the SO integration with BIM environment is concluded and the following steps are not described since they are beyond the scope of this work

As shown in Fig. 3, SO functions as a connection between engineers and architects in the early stages, aiming to anticipate this integration to improve design solutions and provide alternatives. This way architectural issues and other concerns regarding structural performance are considered since the beginning of the project. This promotes more collaboration and integration between BIM players in the initial phases of the project, which is a key concern within the BIM methodology.

As verified by Eastman et al., (2011), one of the differences between a traditional project and a BIM project is that in a BIM workflow, a greater information flow is exchanged between players. With the inclusion of SO in a BIM workflow, much more information is exchanged between architects and structural engineers, as highlighted by the

ER shown in Table 2 and Table 3. Moreover, the integration is anticipated and actors can begin their work practically at the same time; and all entities contribute to all stages, rather than being spectators.

4. CASE STUDY

In this section, with the aim of testing the proposed IDM, three experiments of different geometrical scales were developed using Structural Optimization, specifically the Topology one, in the conceptual design phase. Thus, all cases initiate with a mass model that has already taken into account owner necessities, solar and wind orientation, and other architectural issues. This is followed by a SO simulation performed "by the structural engineer and the process finalizes with the architectural conceptual design, with no pre-detailing studies, which is important in future stages.

The simulations were carried out considering building projects with distinct complexities, such as sizes and structural material. By doing so, it is possible to understand the limitations and scalability of the proposed workflow, in the way that validates or not the IFC standardization process in this area. Table 4 summarizes the information related to the three case studies.

Table 4: Cases to simulate the proposed workflow

	Case A	**Case B**	**Case C**
Project Name	Egg House	Tree Building	Bamboo Project
Building type	Low-income house	Commercial	Residential
Structural material	ABS Plastic	Steel	Concrete
Construction technique	3D printing	Modular construction	Traditional construction
Floor plan	47 sqm	475 sqm/floor	250 sqm/floor/building
Height	~ 3 meters	34 meters	18 meters

From the Architectural Preliminary Model of each case, topology optimization processes were carried out using different commercial solutions in educational or trial versions, the are: Autodesk Fusion360, ANSYS, and Abaqus/TOSCA. It is important to highlight two things. First, note that topology optimization was selected as the type of SO because according to the literature review it is more adequate for earlier stages of design when the project is still like a blank paper, with few geometric limitations. Second, the use of different software does not have the aim of comparing them, but rather to test the information exchange and different types of TO processes in terms of multi-objective optimization algorithms and objective function. The following table summarizes the parameters defined for each study as well the optimization results according to the tool used.

Some of the results provided by each optimization are shown in Fig. 4 that can be used by the Architect during the process of Conceptual Design phase. This model, as proposed in the IDM framework, can be exchanged between players using SAT format file, but ideally it should be IFC format file or similar one to avoid information loss. For instance, using the SAT format file, all the parameters defined in the optimization process and will be used in future stages of design, such as structural loads, were lost in the exchange, which would make it difficult for other players to perform their analyses.

The evolution of the tasks described previously is shown illustratively in Fig. 4, for all cases and, also, the alternatives generated by the optimization process to support the architect's structural solution choice. IAs verified in this experimentation, the main difficulty lies between the SO and modeling tools, which is focus of this work, and represents two specific information exchanges involving the architect and the structural engineer.

Structural optimization tools are not capable of reading IFC files and, thus, all non-geometrical information listed in Table 3 is lost from the architectural preliminary model. On the other hand, the same SO tools are not capable of writing IFC files and, consequently, all non-geometrical information listed in Table 4 is lost in the structural optimized model. It is worth pointing out that architectural modeling tools are capable of both writing and reading IFC files, without any restrictions to the workflow.

This lack of interoperability may hinder SO insertion in a BIM project, but it would not preclude it. With this in mind, it can be concluded that SO processes can be inserted in the conceptual design phase and may produce better projects. To be effectively inserted in the BIM methodology, however, interoperability issues must be resolved to facilitate the exchange of files.

Table 5: Optimization parameters in F360

		Egg House	**Tree Building**	**Bamboo Project**
Material		ABS Plastic $\gamma = 1{,}060\ g/cm$ $E = 2{,}24\ GPa$; $\nu = 0{,}38$ $\sigma_y = 20\ MPa$;	Steel $\gamma = 7{,}850\ g/cm$ $E = 210\ GPa$; $\nu = 0{,}3$ $\sigma_y = 207\ MPa$;	Concrete $\gamma = 2{,}406\ g/cm$ $E = 20{,}5\ GPa$; $\nu = 0{,}2$ $\sigma_{fck} = 35\ MPa$;
Structural Configuration	Boundary conditions	Fixed in Basis edges	Fixed in Foundation slab	
	Structural Loads	Self-weight ($g = 9.807\ m/s^2$)		
		Vertical pressure (20 kPa applied in the roof)	Vertical pressure (10 kPa applied in the roof)	
		Horizontal pressure (1 kPa – Wind)		
Optimization Parameters	Target Mass[1]	30 % in F360 1 % in ANSYS 10 % In Abaqus	10 % in all tools	10 % in all tools
	Objective Function	Maximize stiffness in F360 Minimize force and displacements in ANSYS Minimize strain energy of the whole model in Abaqus		
	Preserved Regions	Boundary conditions and regions of load application in F360 and ANSYS None in Abaqus (None (Load and BC regions were not frozen)		
Solution Information	Final Mass	30 % in F360 40 % in ANSYS 35 % in Abaqus	10 % in F360 14 % in ANSYS 23 % in Abaqus	10 % in F360 20 % in ANSYS 25 % in Abaqus
	Average Number of Iterations to convergence	18	37	39

[1] defined aiming do not generate optimization problems, like the checkerboard pattern.

Where,
γ is the specific weight;
E is the Young's modulus;
ν is the Poisson's ratio;
σ_y is the yield stress;
σ_{fck} is the compressive stress;
g is the Earth's gravity.

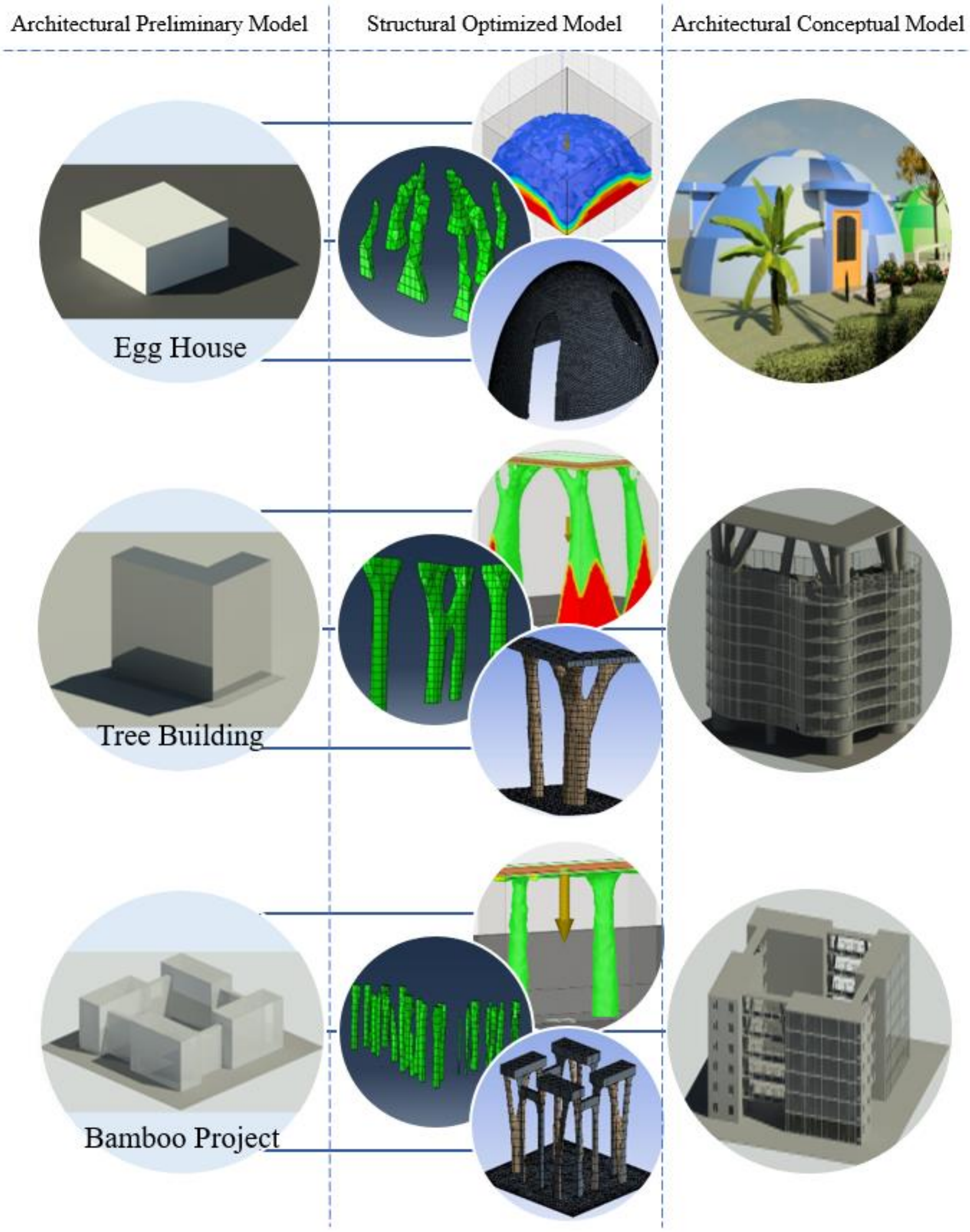

Fig. 4 – Tasks evolution for all cases

The IDM proposed in this work is the first step towards achieving this improvement in SO interoperability. In this work, a process map was developed that worked properly in all three case studies and an Exchange Requirements to orient next studies to improve interoperability in this area, tracking all information needed in each flow. This issue can only be resolved when software providers apply it in a Model View Definition (MVD) to run in their tools and, thus, a IFC format can be launched specifically to that area.

Beyond the process, it is important to highlight the applicability of this integration for the structural domain. In a more collaborative way, the solutions provided by the SO processes, if selected by the architect, can generate a better stress distribution in structural components and at the same time produce more organic shapes, which could shorten this design stage. The Fig. 5 shows an example of structural design in advanced stages derived by the SO solutions to analyse the buckling modes of a structural column in case B. It refers to a hollow metal column with wall thickness equals to 25 mm and external diameter equals to 300 cm. The buckling mode with lower critical factor represents the critical mode, which is the first buckling mode in this column.

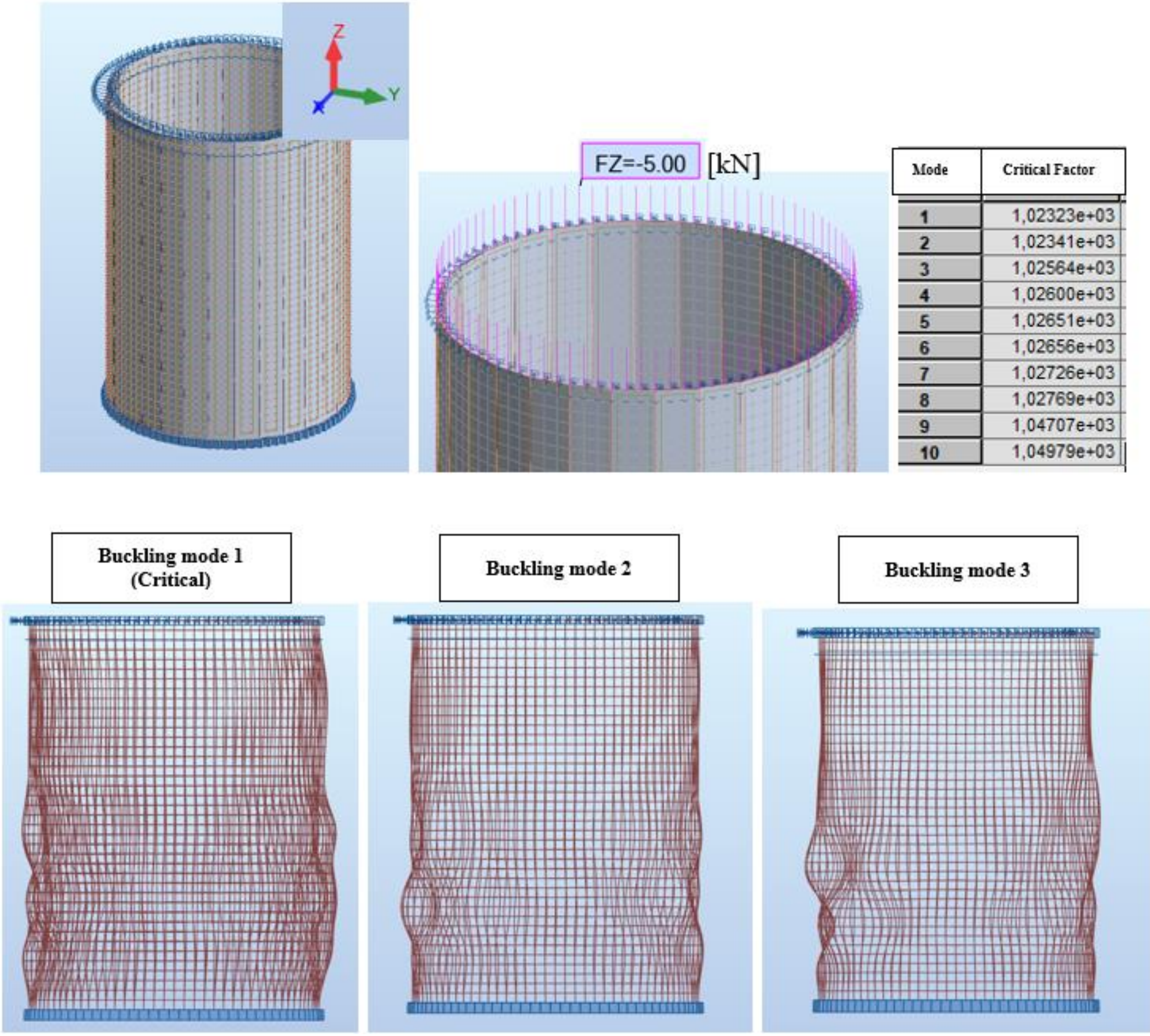

Fig. 5 – Structural model for buckling analysis in case B

5. CONCLUSION

Through a Systematic Literature Review combined with a bibliometric analysis, it was verified that there is a scientific research gap between Structural Optimization and BIM areas, since few studies were carried out that integrate both topics. However, in each separated area, there is a significant number of published works. Moreover, two research questions, that were defined to guide the SLR, did not appear to have not been completely answered yet by the scientific community. The questions are: how can the structural optimization process be inserted in the BIM methodology; and what impact does the structural optimization process generate in the BIM process. Taking this into account, the scientific value of this work consists of partially filling this gap by answering these questions with an IDM framework and three hypothetical case studies.

First, an IDM structure was developed as an initial effort to create a IFC standardization in this area to improve interoperability issues in a BIM environment. It is worth pointing out that the focus was on the conceptual stage of a building project. The process map and the exchange requirements together showed that to have a satisfactory level of interoperability to carry out SO processes, it is necessary that at least the mass volume and material be specified in the IFC file or similar format. By using SAT format, it is only possible to maintain the geometrical information.

After that, to test the proposed IDM three examples were developed. In all cases, SO was used as an initial idea for an architectural conceptual model, generating design options for the architect's consideration as indicated by the IDM structure, but not as an imposition. The SO processes involved different types of materials and buildings, and required geometrical information related to mass volume and non-geometrical information related to material properties, structural loads, and boundary conditions. With the objective function defined to minimize the mass volume (10% for cases B and C, 30% for case A), an average number of 31 iterations was necessary for the optimization convergence without encountering benchmarking problems, such as the checkboard pattern. Then, to validate that the structural viability of the optimized models, a basic structural analysis was carried out confirming that the models perform satisfactorily if the Architect were to select them.

This collaboration between structural engineer and architect is intended to improve and to be improved by the BIM environment. In other words, by anticipating the team's integration and collaboration, BIM implementation could be facilitated. On the other hand, by implementing the BIM methodology this collaboration is also improved. Moreover, it can be concluded that without interfering in the architectural creative process and with the collaboration spirit intrinsic to the BIM methodology, optimization issues can be inserted earlier in the process.

Therefore, aligned with the root problem that guided this work, it is possible to conclude that the proposed framework improves the relation between architect and structural engineering from the beginning of the project, in both types of communication (digital and human). Complementing the work developed by Beghini et al. (2014), the present contribution is to provide a structure for the communication bridge using BPMN and process map, in order to enable practical workflow in the AEC industry.

For all the studied cases, it was found that the commercial software packages adopted in this work (Fusion 360, Abaqus/TOSCA, and Ansys) are not interoperable with BIM modeling packages. The information flow was only possible using SAT format which contains only geometrical information. With this in mind, it can be concluded that the conceptual design phase is appropriated for the insertion of SO processes because at this stage the files contain only geometrical and material information. To be effectively inserted in the BIM methodology, however, interoperability issues must be resolved to facilitate the exchange of files. This could be achieved using, for example, the IFC format.

There are two main findings in the present work. First, by structuring the processes and mapping the information, it was possible to conclude that SO processes can be inserted in early stages of design. Second, the integration between architect and structural engineer, not only promotes a better structural solution for the project, but also improves the collaboration between these two players, which is the core value of BIM implementation. However, it is necessary that more studies be carried out to understand the Model View Definition necessary to implement this kind of interoperability in a software package, such as those provided by Autodesk.

The IDM proposed in this work is the first step towards achieving this improvement in SO interoperability, tracking information needed in each flow. In doing so, the first question was answered: SO can be inserted in a BIM project as an auxiliary tool that supports architect decisions as long as the shortcomings in interoperability issues are resolved. The second question about the impacts of this insertion is probably the most difficult question to answer without a real project, but some speculative conclusions were drawn.

Related to real projects, it is worth pointing out that the structural conceptual project resulted from SO processes may not be acceptable, depending on the construction technique adopted. For example, the project may be feasible using modern techniques (e.g., modular construction, 3D printing), since they can handle complicated forms. However traditional techniques generally cannot easily handle complex shapes, and this will require more time and higher cost, which can make the project unfeasible. For this reason, more studies should be directed towards analysing cost comparison between different construction techniques and SO, taking into account project quality, Man Hour (MH) consumption, material usage, construction time, project time, etc.

In this sense, as technology advances, mainly related to IFC development, the lack of software interoperability will be solved and, thus, the structural optimization process will be more easily adopted in actual building projects. However, with the current technology, architects and structural engineers can already experiment with the use of SO at early stages of design, and together with the BIM methodology, it can improve and anticipate collaboration between these two players.

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