OSD: A framework for the early stage parametric Optimisation of the Structural Design in BIM-based platform

A R T I C L E I N F O

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Abstract

The paper aims to demonstrate a state-of-the-art framework, which uses the architectural model and relevant parametric data to design and analysis different parametric structural models through an automatic process. This process helps to reduce the iterative structural design process and improves the collaboration between the structural engineers and architects through automation in BIM platform. The study aims to leverage the importance of using automation in the structural design process and collaboration between structural engineers and other disciplines specially architects. The paper includes an exploratory objective to use a comprehensive literature review including bibliometric and content analysis followed by a mixed-method online survey to discover the current process of the structural design and analysis, existing gaps and potential solutions to solve the problems. The online questionnaire was distributed between 354 professionally accredited structural engineers of the Institution of Structural Engineers (IStructE), Institution of Civil Engineers (ICE) and the American Society of Civil Engineers (ASCE) in the UK. The paper provides the results of the quantitative and qualitative data analysis of the responses to the online questionnaire. According to the results received from the data analysis of the online questionnaire, the Optimisation Structural Design (OSD) Framework is developed to automatically linked and interoperated with the architectural model in BIM platform and generate alternative structural models. A proof of concept prototype was developed to demonstrate the workability of the framework. The proposed framework and prototype can be utilised for a wide range of structural design scenarios, i.e. residential, commercial, and even bridges.

1 Introduction

The recent development in computational design as well as growing theoretical framework of parametric design introduced a new insight for the Architecture, Engineering, and Construction (AEC) industry (Bianconi et al., 2019). Extant literature indicates the use of automation in different areas of AEC resulted in developing new ideas such as design rule check (Eastman et al., 2009), smart manufacturing (Davis et al., 2012), Virtual project development (Li et al., 2008; Popov et al., 2010) and Mass-customization (Bianconi et al., 2019). In this projects, new technologies such as Computational Design (Andreani et al., 2016; Gilbert et al., 2017; Mirjalili et al., 2018) and Building Information Modelling (BIM) provided a great support. The capability to automate the collaboration between architects and structural engineers and structural design and analysis process by using visual programming tools and the possibility to handle a significant amount of information to compare between different structural models highlights the importance of integration of Information Technology in the Building Industry (Paoletti, 2017). In this scenario, BIM provides the opportunity of electronically modelling and managing a considerable amount of data embedded in a building project, from the conceptual stage to end-of-life (Oti and Tizani, 2015). The extant literature indicates a considerable effort to expand the use of the Information Technology in the Building Industry to design complex buildings. Therefore, these complex designs require decision support tools to assist with the assessment of the stability and cost efficiency of the design solutions. Such tools would be most practical at the early design stage because according to the design stages designers are capable of influence the performance and cost of the whole life cycle of the building. This influence highlights the importance of targeting the early design stage for the design optimisation.

Beside the challenges associated with the iterative process of structural design and collaboration between architects and engineers, the optimisation decision support tools for helping engineers at the early stages have not been sufficiently explored. This research uses the digital tools including Revit (Autodesk, 2019a), Robot Structural Analysis Professional (Autodesk, 2019b) and Dynamo (Dynamo BIM, 2019) during the design process, by making use of them, not only for design and analysis, but also as optimisation and generative design tools. This paper proposes a prototype that provide a wide range of alternative Optimised Structural Designs (OSD) for the same architectural model. Moreover, the OSD prototype presents a new approach for the comparison, evaluation, and optimisation of the generated alternative structural designs at the early stages. Introducing automation to the early stage of structural design enables the engineers/designers to evaluate a larger number of alternative designs and decide the optimum solution. Moreover, the generated models using the OSD prototype are integrated into the architectural BIM model, therefore, any change in the architectural model parameters, will be identified/applied in the structural model through an automatic and predefined process. Introducing automation to the tedious processes can help to reduce the risk of expensive design changes made at a later stage, and provide a more precise overall cost estimation.

In order to limit this research and provide a proof of concept prototype to demonstrate the performance and workability of the proposed framework, this paper focuses on the steel structures. The OSD framework is developed based on the extant literature and similar works and validated through online questionnaires distributed between the professionally accredited structural engineers in the IStructE and ICE (UK). Based on the feedback received from the questionnaire and the validated framework, a conceptual prototype has been developed to demonstrate the workability of the framework.

2 Methodology

This study begins with analyses and categorizes the existing research on automation for structural design in BIM since 2011 until 2020 by conducting a quantitative and qualitative research analysis. In order to achieve a comprehensive literature review a bibliometric and content analysis is conducted on the extant literature on Scopus database. In this study, bibliometric analysis aims to generate a quantitative data by performing statistical methods to highlight the trend of academic publications to justify the research performance. According to figure 2, the bibliometric analysis in this study includes 4 steps:

1) keywords search in Scopus database
2) filter the results to include specific criteria
3) select the most relevant articles through content analysis
4) classify the articles in four clusters through thematic analysis

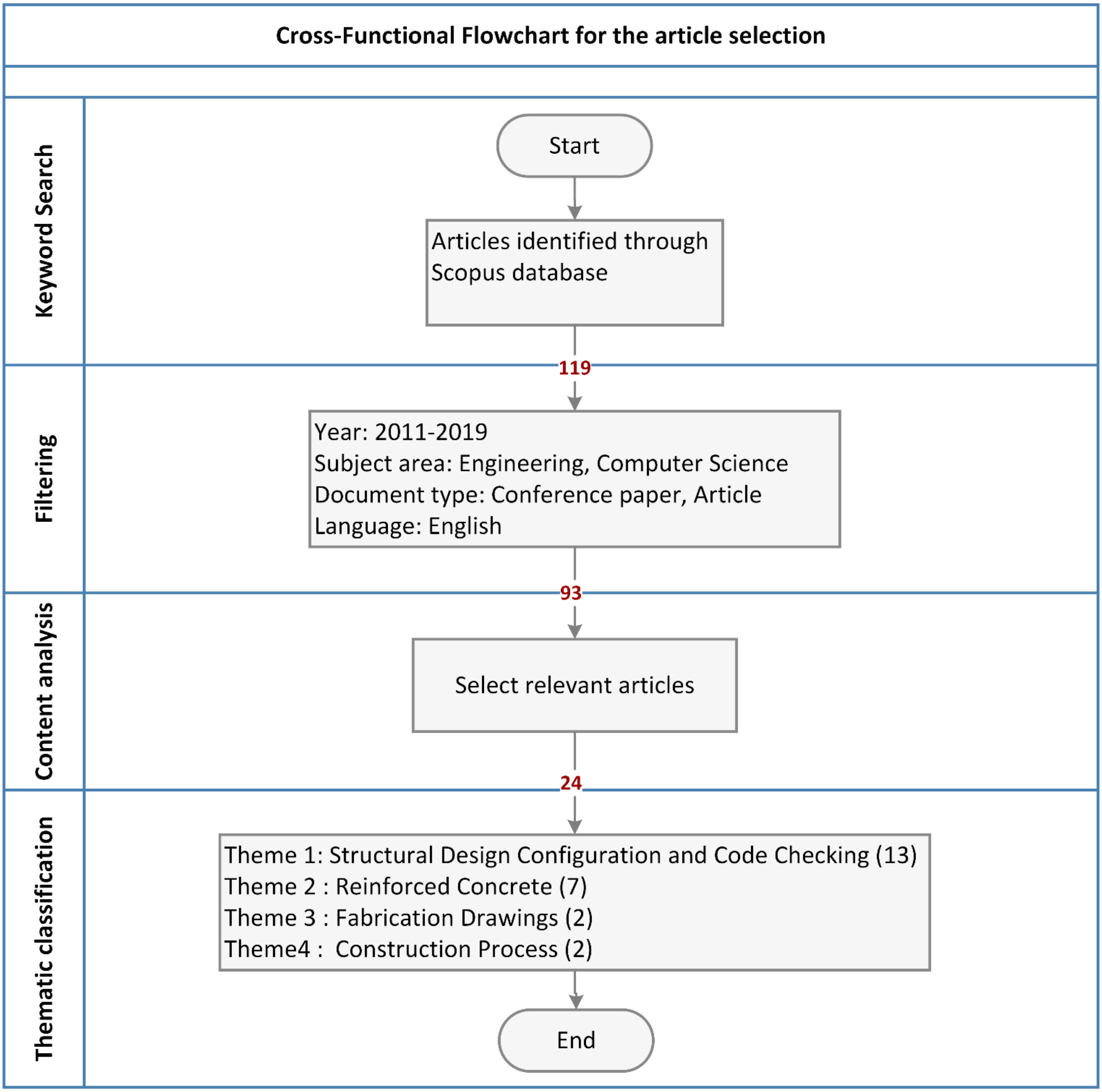

Figure 1: Flow diagram of selection of articles for bibliometric, content and thematic analysis

The bibliometric study begins with two key word searches in Scopus database: keyword search 1) "Structural Design" AND (Automation OR Automatic) keyword search 2) "Structural design" AND (Automation OR Automatic) AND BIM, which resulted in 2165 and d 119 respectively. Thereafter, the result of each list was filtered to limit the documents to only conference papers and articles in engineering and computer science, which were published in English language from 2011 until 2020. The results of the filtering reduced the number of documents to 787 and 93 for keyword search 1 and keyword search 2 respectively (figure 2). This shows that the use of automation in structural design in BIM platform is limited and body of knowledge requires more focus on this area. However, this study focused on the automatic optimisation of the structural design in BIM platform hence, only the second keyword search is considered for the bibliometric, content and thematic research analysis. In this scenario, the second list of keyword search (93 documents) was used for content review and manual article selection to find the most relevant articles and conduct thematic analysis. In total 24 articles were classified in four themes 1) Structural Design Configuration and Code Checking 2) Reinforced Concrete 3) Fabrication Drawings 4) Construction Process. Section 3 and 4 details the results of the bibliometric, content and thematic analysis.

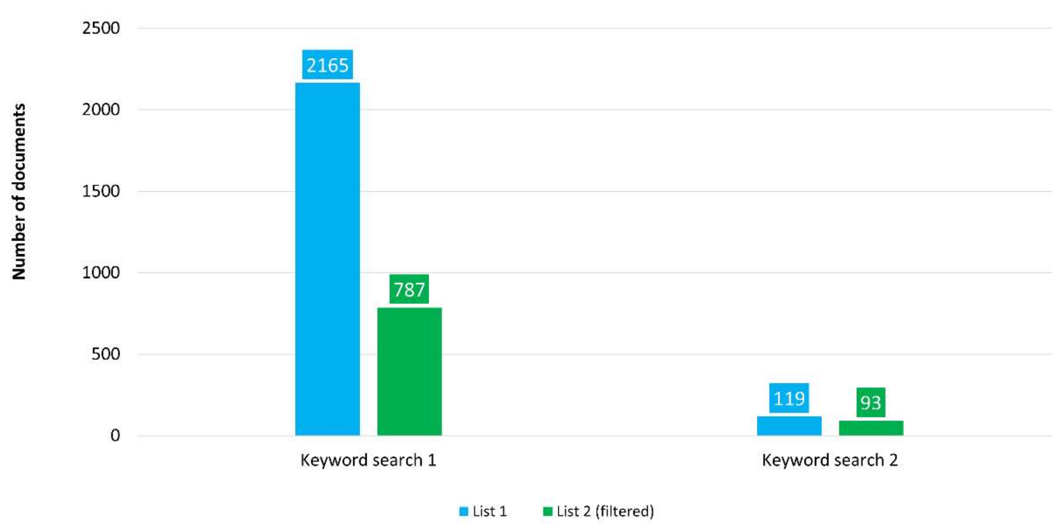

Figure 2: Lack of research on the automatic structural design in BIM

Although, the literature presents neither a clear justification of the existing issues in optimisation of structural design at the early design stages (and a potential solution), nor a great deal of research into the optimisation of structural design in BIM. Therefore, as a part of the exploratory phase of the research, survey by questionnaire was adopted to deepen the researcher understanding of the research issues. The main purpose of the questionnaire was to explore the existing issues related to the current structural design, analysis and optimisation process and provide the potential solution to solve them. Therefore, this paper presents the information collected from an online questionnaire survey to find the existing challenges in the structural design and analysis process and collaboration between structural engineers and architects during the early stages in BIM. Moreover, this survey asked participants in the research to provide potential solutions to the existing challenges. Therefore, this questionnaire helped to achieve valuable information about the existing challenges and potential solutions that justifies the research knowledge gap and helped to purposefully develop the framework.

3 Bibliometric analysis results

The bibliometric analysis indicates a considerable increase in the number of publications on automation in structural design in BIM platform, from 2011 until 2020 (figure 3 and table 1). According to figure 3 automation in structural design in BIM platform becoming an interesting research area especially during 2018 and 2019. According to the article selection criteria and as table 1 demonstrates, “Automation in construction” with 10 documents includes the highest number of publication in the field of automation in structural design in BIM platform. This was followed by “Procedia Engineering” and “Isarc 2018 35th International Symposium On Automation And Robotics In Construction And International Aec/Fm Hackathon: The Future Of Building Things” with 9 and 7 documents respectively. Moreover, the bibliometric analysis highlighted that three of the five most cited articles were published in “Automation in construction” (Table 1). Figure 4 demonstrates the top seven journals, which in total published 48% of the reviewed documents and mainly from 2015; they started to focus more on this area. The remaining journals’ publication rate varied from one to two articles from 2011 until 2019.

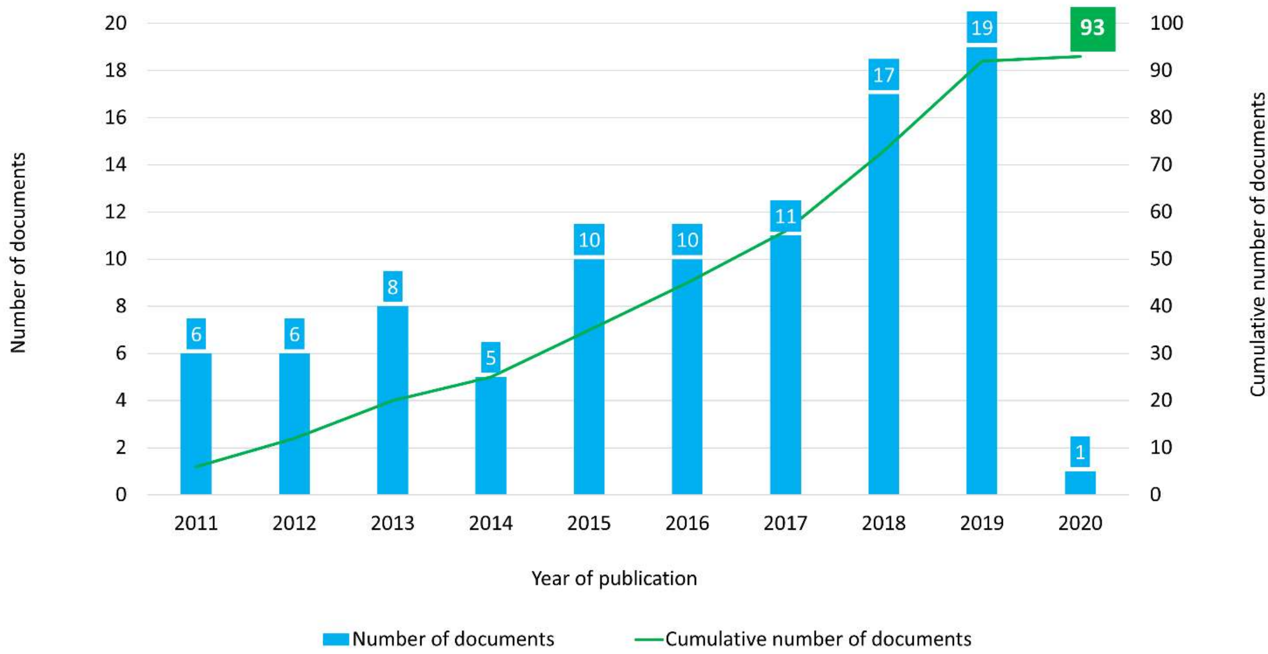

Figure 3: Automation for structural design in BIM articles published during 2011-2020.

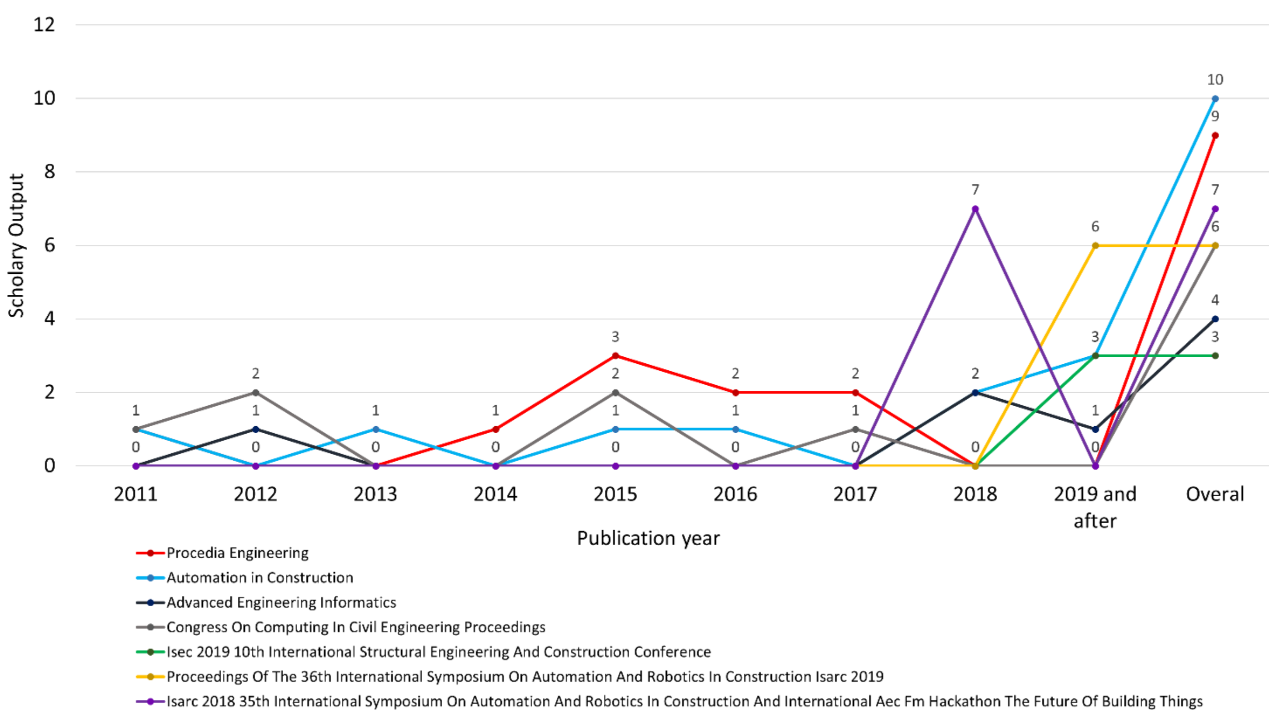

Figure 4: Benchmarking the Publication Year and Scholarly Output of the top seven journals

	2011	2012	2013	2014	2015	2016	2017	2018	2019	>2019	Overall
Automation in Construction	1	0	1	0	1	1	0	2	3	1	10
Procedia Engineering	1	0	0	1	3	2	2	0	0	0	9
Isarc 2018 35th International Symposium On Automation And Robotics In Construction And International Aec Fm Hackathon The Future Of Building Things	0	0	0	0	0	0	0	7	0	0	7
Congress On Computing In Civil Engineering Proceedings	1	2	0	0	2	0	1	0	0	0	6
Proceedings Of The 36th International Symposium On Automation And Robotics In Construction Isarc 2019	0	0	0	0	0	0	0	0	6	0	6
Advanced Engineering Informatics	0	1	0	0	0	0	0	2	1	0	4
Isec 2019 10th International Structural Engineering And Construction Conference	0	0	0	0	0	0	0	0	3	0	3
20th Congress Of IABSE New York City 2019 The Evolving Metropolis Report	0	0	0	0	0	0	0	0	2	0	2
32nd International Symposium On Automation And Robotics In Construction And Mining Connected To The Future Proceedings	0	0	0	0	2	0	0	0	0	0	2
Construction Research Congress 2012 Construction Challenges In A Flat World Proceedings Of The 2012 Construction Research Congress	0	2	0	0	0	0	0	0	0	0	2
Construction Research Congress 2018 Construction Information Technology Selected Papers From The Construction Research Congress 2018	0	0	0	0	0	0	0	2	0	0	2
Design And Decision Support Systems In Architecture And Urban Planning 13th International Conference On Design And Decision Support Systems In Architecture And Urban Planning Ddss 2016	0	0	0	0	0	2	0	0	0	0	2
Isarc 2017 Proceedings Of The 34th International Symposium On Automation And Robotics In Construction	0	0	0	0	0	0	2	0	0	0	2
Journal Of Computing In Civil Engineering	0	0	1	0	0	1	0	0	0	0	2
Proceedings Of The 13th East Asia Pacific Conference On Structural Engineering And Construction Easec 2013	0	0	2	0	0	0	0	0	0	0	2
2014 ASHRAE Ibpsa Usa Building Simulation Conference	0	0	0	1	0	0	0	0	0	0	1
6th Csce CRC International Construction Specialty Conference 2017 Held As Part Of The Canadian Society For Civil Engineering Annual Conference And General Meeting 2017	0	0	0	0	0	0	1	0	0	0	1
Aei 2017 Resilience Of The Integrated Building Proceedings Of The Architectural Engineering National Conference 2017	0	0	0	0	0	0	1	0	0	0	1
AES Atema International Conference Series Advances And Trends In Engineering Materials And Their Applications	1	0	0	0	0	0	0	0	0	0	1
Agro Food Industry Hi Tech	0	0	0	0	0	0	1	0	0	0	1
Caadria 2018 23rd International Conference On Computer Aided Architectural Design Research In Asia Learning Prototyping And Adapting	0	0	0	0	0	0	0	1	0	0	1
Civil Comp Proceedings	0	0	0	0	0	1	0	0	0	0	1
Computer Aided Civil And Infrastructure Engineering	0	0	0	1	0	0	0	0	0	0	1
Eg ICE 2015 22nd Workshop Of The European Group Of Intelligent Computing In Engineering	0	0	0	0	1	0	0	0	0	0	1
Energy And Buildings	0	0	0	0	0	0	1	0	0	0	1
European Group For Intelligent Computing In Engineering Eg ICE 2013 20th International Workshop Intelligent Computing In Engineering	0	0	1	0	0	0	0	0	0	0	1
IABSE Conference Bath 2017 Creativity And Collaboration Report	0	0	0	0	0	0	1	0	0	0	1
IEEE Access	0	0	0	0	0	0	0	0	1	0	1
Iop Conference Series Materials Science And Engineering	0	0	0	0	0	0	0	1	0	0	1
Isarc 2016 33rd International Symposium On Automation And Robotics In Construction	0	0	0	0	0	1	0	0	0	0	1
Isec 2013 7th International Structural Engineering And Construction Conference New Developments In Structural Engineering And Construction	0	0	1	0	0	0	0	0	0	0	1
Journal Of Architectural Engineering	0	0	0	0	0	1	0	0	0	0	1
Journal Of Building Engineering	0	0	0	0	0	0	0	1	0	0	1
Journal Of Cleaner Production	0	0	0	0	0	0	0	0	1	0	1
Journal Of Construction Engineering And Management	0	0	0	1	0	0	0	0	0	0	1
Journal Of Management In Engineering	0	0	0	1	0	0	0	0	0	0	1
Journal Of Transportation Engineering	1	0	0	0	0	0	0	0	0	0	1
Ksce Journal Of Civil Engineering	0	0	0	0	0	0	0	0	1	0	1
Procedia CIRP	0	0	0	0	0	0	0	1	0	0	1
Proceedings 2017 IEEE ACM 2nd International Conference On Internet Of Things Design And Implementation Iotdi 2017 Part Of Cps Week	0	0	0	0	0	0	1	0	0	0	1
Proceedings Of The 28th International Symposium On Automation And Robotics In Construction Isarc 2011	1	0	0	0	0	0	0	0	0	0	1
Proceedings Of The Fib Symposium 2019 Concrete Innovations In Materials Design And Structures	0	0	0	0	0	0	0	0	1	0	1
Research And Applications In Structural Engineering Mechanics And Computation Proceedings Of The 5th International Conference On Structural Engineering Mechanics And Computation Semc 2013	0	0	1	0	0	0	0	0	0	0	1
Safety Science	0	0	0	0	1	0	0	0	0	0	1
Structures Congress 2012 Proceedings Of The 2012 Structures Congress	0	1	0	0	0	0	0	0	0	0	1
Structures Congress 2013 Bridging Your Passion With Your Profession Proceedings Of The 2013 Structures Congress	0	0	1	0	0	0	0	0	0	0	1
Wcte 2016 World Conference On Timber Engineering	0	0	0	0	0	1	0	0	0	0	1
Overall	6	6	8	5	10	10	11	17	19	1	**93**

Table 1: Review sources of 93 reviewed academic articles

Figure 5 indicates the results of the bibliometric analysis on the countries with the largest number of journal publications during 2011-2020. According to this figure, the USA with 33 articles has the largest number of publications, which is followed by Canada (13), South Korea (10), United Kingdom (9) and China (8). Interestingly these top five countries published 78% of the articles.

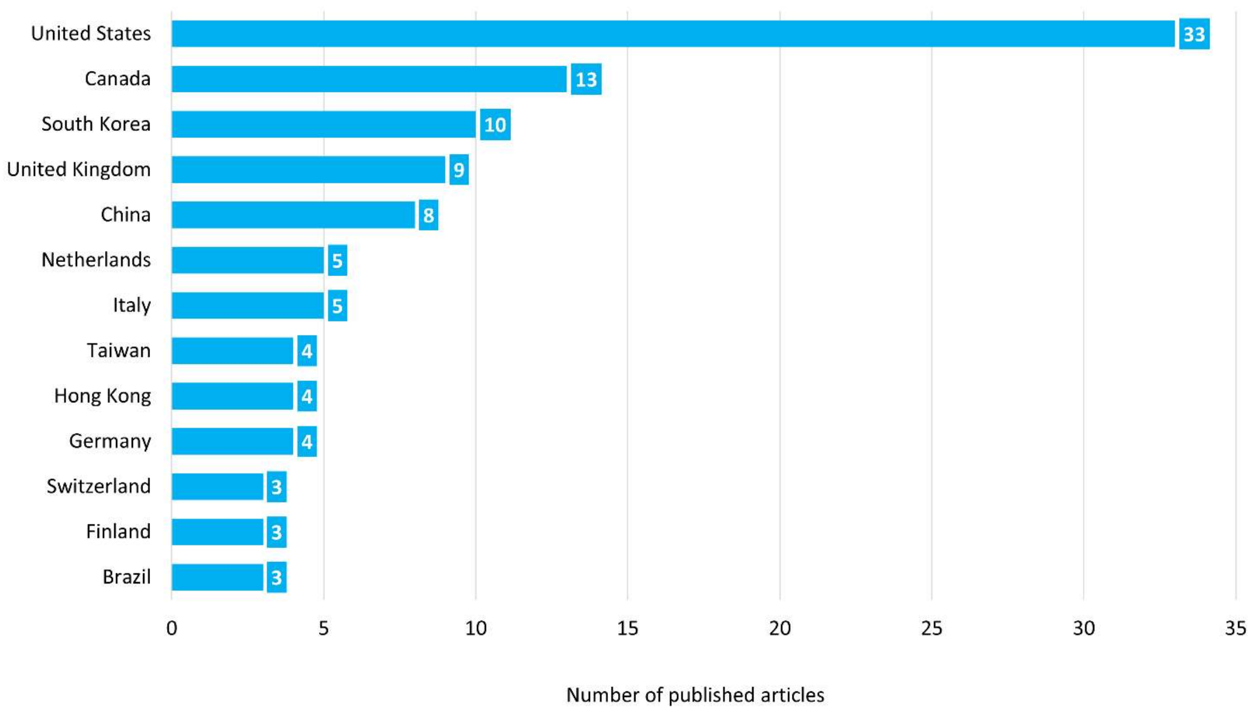

Figure 5: Published articles by country

In order to conduct keyword frequency VOSViewer ("VOSviewer - Visualizing scientific landscapes", 2019) is used to combine the keywords (803 keyword) and find the keywords with more than 10 times of occurrence. In this scenario, 19 keywords met the criteria and they were clustered as follows (figure 6): cluster 1 (9 items): architectural design, automation, building information model-bim, building information modelling, computer aided design, design, information theory, reinforced concrete, structural design; cluster 2 (5 items): buildings, decision making, information management, life cycle, sustainable development; cluster 3 (4 items): construction, construction industry, project management, robotics; cluster 4 (1 items): model checking. The bibliometric analysis indicates that structural design, architectural design, building information modelling, are the most frequently used keywords (figure 6). It is interesting that the architectural design keyword is emerged in the keyword clustering; however, it was not included in the keyword search criteria. This highlight that the main focus of the automation and BIM is on the architectural area. Moreover, the clustering of the keywords indicated that the majority of the selected documents are under the first cluster. Keyword analysis is a practical method to map the reviewed literature, although is not sufficient for the new topics like automation, computational design and generative design. Therefore, a content analysis is performed to develop themes and patterns of the reviewed articles, based on the articles' focused area and contributions.

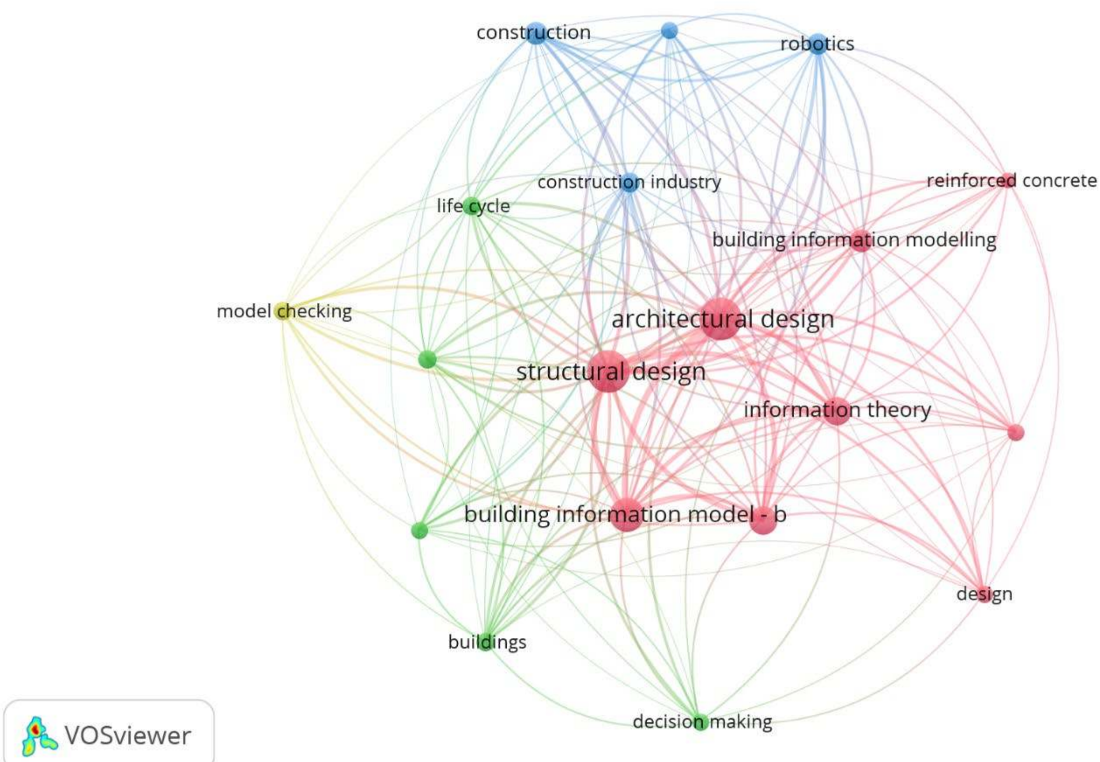

Figure 6: keyword clustering

4 Content analysis results

In order to develop a more qualitative literature analysis of the collected articles and generate a thematic analysis to propose a future work. Table 2 demonstrates the results of the content analysis and thematic analysis. Structural design configuration and code checking has the highest number of articles (13) followed by reinforced concrete (7), fabrication drawings (2) and construction process (2). Owning to the complicated structural engineering rules and regulations, the manual review has become a difficult and time-consuming process, leading to many errors and omissions (Lee et al., 2019). In this process, the structural engineers often use a manual trial and error approach to find a sufficiently safe and economical structural solution (Eleftheriadis et al., 2018). However, trial and error is an iterative and time consuming process (Mangal and Cheng, 2018) and most of the structural engineering process could be formulated and solved in an automatic process (Bennage and Dhingra, 1995).

Theme	Aims	Contribution to knowledge	References
Structural Design Configuration and Code Checking	These papers examine Automated Code Compliance (ACC) checking systems that assess building designs according to various structural code provisions	The papers proposed new frameworks for development of automated rule checking systems to verify structural design against code provisions	(Lee et al., 2019) (Patlakas et al., 2018)(Barg et al., 2018)(Nawari and Alsaffar, 2017)(Livingstone et al., 2016)(Nawari, 2013)(Chung et al., 2013)(Nawari, 2012)(Nawari, 2011)
Reinforced Concrete	These papers proposed frameworks for automatic reinforcement design system to save time and cost and ensure quality and safety during the construction process	The results demonstrate the efficiency of the automated specification procedure and propose a novel, yet technically sound, basis for further application of BIM in structural engineering	(Sheikhkhoshkar et al., 2019)(Eleftheriadis et al., 2018)(Hyun et al., 2018)(Mobasher et al., 2016)(Jiang et al., 2015)(Cho et al., 2014)(Cho et al., 2011)
Fabrication Drawings	These papers propose automatic frameworks to generate fabrication drawings for building façade structural components, including mullions and transoms	incorporates BIM technology based on CAD parametric modelling and manufacturing requirements in a 3D-model, in order to generate sets of shop and fabrication drawings	(Deng et al., 2019)(Alwisy et al., 2012)
Construction Process	These papers proposed frameworks for automatic design process	The preliminary results show that the proposed system could support more effective and efficient	(Romanovskyi et al., 2019)(Zhang and El-Gohary, 2017)

Table 2: Thematic analysis of the reviewed articles

Extant literature highlights the evaluation of the design performance by using automation in code checking and decision making at the early stage of the building construction and performance, i.e. structural behaviour and economical aspect (Likhitruangsilp et al., 2019; Hyun et al., 2018; Eleftheriadis et al., 2017), energy consumption (Asl et al., 2015; Nguyen et al., 2016), and façade generation (Datta et al., 2016) are examples of previous work covering the early stage decision making process. These projects mainly aim to facilitate the design evaluation performance and lead to a more in-depth exploration of a design space and reduce the computational time for the optimisation process, hence reducing the risk of possible expensive changes in the later stages (Barg et al., 2018).

Despite remarkable progress in the integration of several tools and methods in the goal-oriented design optimisation, shortcomings persist in the interoperability between the architectural model and structural design optimisation process. In this scenario, any change in the architectural model requires the whole structural model to be re-designed/ re-analysed/re-scheduled.

This paper uncovers a novel structural design optimisation process framework automatically linked and interoperated with the architectural model. In this scenario, architectural model parameters are synchronised in a visual programming tool (Dynamo) and structural models are generated based on these parameters. Hence, any change in the architectural model parameters will result in the generation of new structural designs. The proposed framework and prototype can be utilised for a wide range of structural design scenarios, i.e. residential, commercial, and even bridges.

5 Questionnaire results

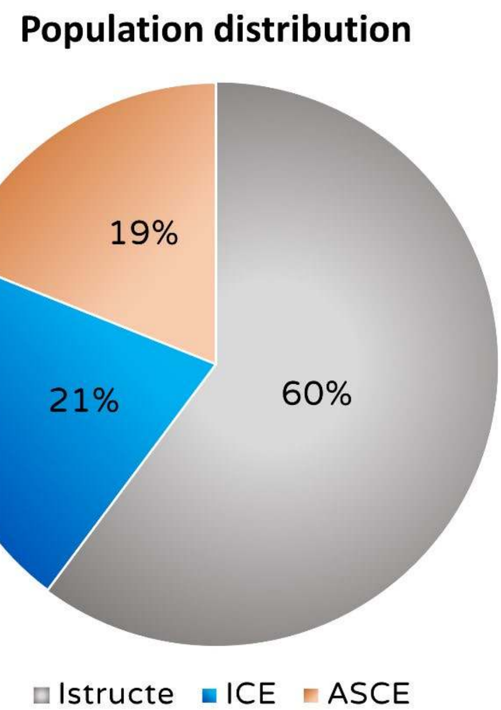

Figure 7: Survey participants

An online questionnaire were distributed between professionally accredited structural engineers of the Institution of Structural Engineers (IStructE), Institution of Civil Engineers (ICE) and the American Society of Civil Engineers (ASCE) in the UK. Figure 3 demonstrates the distribution of the participants, in which IStructE members with 60% of the total responses make up the main participants of the survey, followed by ICE and ASCE (with 21% and 19% respectively). A total number of 354 questionnaires were distributed between the research population and 105 responses were received. All questionnaires were emailed or sent on LinkedIn and follow-ups were processed for all the non-respondents every two weeks during two month.

5.1 Sampling

Contact details of the respondents were collected from three main sources IStructE, LinkedIn and relevant publications working on the similar projects. The Institution of Structural Engineers (IStructE) has 33 Regional Groups active around the world operating in over 100 countries and offering a great range of technical talks, site visits, exam preparation courses and unique networking opportunities. This research has focused on the UK and Ireland region which involves 21 regional groups with a panel of structural engineers in each region as the main research population. The quota sample were contacted via professional groups on LinkedIn and included: the BIM community, Revit structural users, BIM Experts, Structural engineers etc. Additionally, LinkedIn was used to communicate and share information with experts with relevant experience and expand the research information. Moreover, snowball sampling was used to expand the research between targeted population and approach more chartered engineer. Furthermore, a pilot survey was carried out in two stages among the PhD students and lecturers of the school of Civil Engineering and Surveying (SCES) at the University of Portsmouth. Initially, the questionnaire was piloted between 14 PhD student and after amendments; the improved version of the questionnaire was piloted between 10 lecturers of the structural engineering and BIM. Consequently, the pilot study provide the opportunity to improve the questionnaire and determine the time required to complete it (15-20 minutes). Results of the demographic analysis demonstrates that a considerable number of respondents are structural engineers (85) with more than 10 years of experience in different areas including residential buildings, high-rise buildings, industrial structures, bridges and tunnel (figure 8).

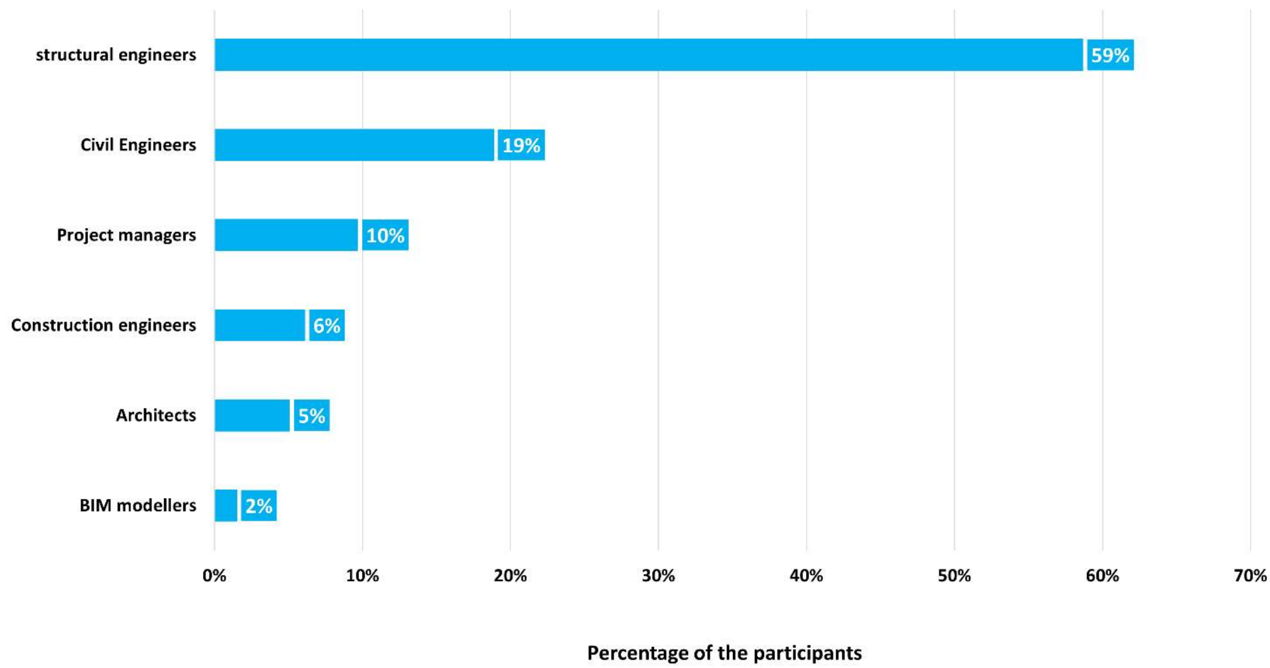

Figure 8: participants from different areas.

5.2 Quantitative Results

One of the main purposes of the survey was to highlight the main issues and challenges during the structural design and analysis process reported by the engineers who participated in the survey. Moreover, this survey asked the participants to provide the potential solution to the issues. In this scenario, quantitative and qualitative questions were asked to explore wider areas and achieve more information from the participants. Figure 9, demonstrates the results of the quantitative analysis where structural design automation (21%), interoperability with other disciplines (21%) and structural design optimisation (20%) conceptual structural design (18%) structural design detailing (11%) and structural analysis (7%) were reported as the most challenging areas, in which, would benefit the most from further improvement.

Structural Design Automation	Interoperability with other Disciplines	Structural Design Optimisation	Conceptual Structural Design	Detailed Structural Design	Structural Analysis	Other
21%	21%	20%	18%	11%	7%	2%

Figure 9: Results of the quantitative data analysis

Figure 6 shows the importance of automation, generative design and BIM in structural design and analysis. This figure demonstrates the analysis of three different quantitative questions. In this figure, more than 61% of the respondents believe that automation in the structural design and analysis process can help to improve designers' and engineers' capabilities. This rate was increased to 69% in response to the question of whether automation in the structural design and analysis within the BIM environment can improve designers' capabilities during the early stage.

This result shows the potential of the automation and generative design methods to enhance the structural design and analysis process. Although, results of the analysis demonstrated that level of awareness of the concept of generative design was considerably low, further analysis carried out and the results highlighted that 43% of the respondents had no knowledge of the concept of generative design, 31% were aware of GD but do not use it, 20% were aware of GD and are currently using it and only 6% of the respondents considered themselves to be expert in this area. Therefore, to analyse the response rate to the question of whether integration of Generative Design (GD) and BIM at the early stage of structural design can improve designers' capabilities, only respondents with knowledge of generative design were considered, because a considerable number of respondents were not familiar with the concept of generative design. In this case, results of the analysis show zero negative response to the question of whether the integration of GD and BIM at the early stage of structural design can improve designers' capabilities. Therefore, this paper presents a state of the art framework to demonstrate how to leverage GD technology in the current structural design and analysis process to effectively enhance the interoperability between engineers and architects and to reduce the considerable amount of time and cost during the iterative process of the structural design and analysis.

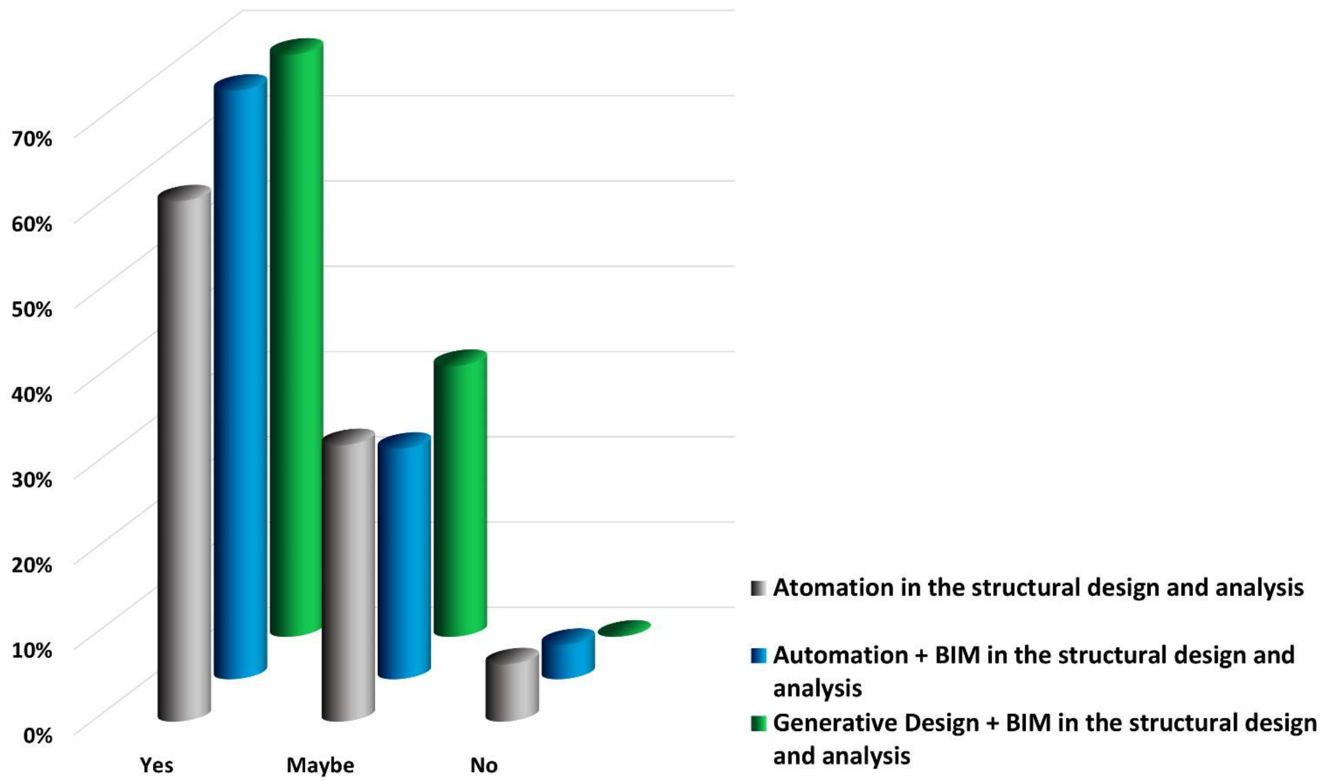

Figure 10: Importance of automation and generative design in structural design and analysis

5.3 Qualitative results

Qualitative questions were used in this survey to explore more information about the current process of the structural design and analysis process. In this questionnaire the respondent were asked to list and explain the existing challenges in structural design, analysis, optimisation and collaboration with other areas (specially architects). This question was followed by other qualitative question asking the respondents to list and explain any potential solutions that helps to solve the issues. Table 3, demonstrates the results of the qualitative data analysis. In this table, the first and second column show the current challenges and potential solution suggested by the respondents to the questionnaire and the third column shows how OSD framework/prototype tackles this issue.

Reported issues	Suggested solutions	OSD methodology

Misinterpretation of **other disciplines input**, automation without supervision brings out wrong data.	**collaboration** between disciplines right from the start (**BIM** will effectively help this process to start)	OSD is a BIM-based framework for the early stage of the structural design. This framework starts from the architectural model in Revit (Autodesk, 2019a) which is synced into Dynamo (Dynamo BIM, 2019) and explores all the possible structural models designed and analysed in Robot Structural Analysis Professional (RSAP) (Autodesk, 2019b) and saved in a directory path file defined in Dynamo. Preliminary calculations (self-weight, live load and dead load) apply on individual model in an automatic process and the results will be used for further evaluation and optimisation. In order to achieve the lightest and cheapest structural model at the conceptual stage; penalty function was considered to prevent over designed and over stressed models and generate more stable (safe) and economic models.
Conceptual design requires more **coordination** between architect, structural and civil engineers, conceptual design could always form the basis for better final outcome.	Choosing the **best conceptual design** should rely on more detailed data and may occasionally need **preliminary calculations** to avoid major changes throughout design process.	
Details can always developed at the final stage but good design and analysis will not replace the flaws in concepts		
Lack of **creativity** and suitable software for support during **concept** and **preliminary design**. **Too much time** spent on repetitive calculations, **Overdesigned** structures, Discrepancies and **mistakes in hand calculations**	Developers need to understand the requirements of designers; **they do not speak the same language**. Develop a tool to explore your creativity **without limits. Automated design procedures**	
Optimisation of the structural design should be fairly straightforward. The difficult/creative part is in **choosing the best solution to take forward to detailed design**.	Software should be normally configured to provide an **economic solution** rather than just analysing a proposed solution	
Shortage of pervious data to made some part of optimization automatic according to pervious successful designed projects data!	It seems we should use data science, machine learning, and uncertainty principles to improve design software's optimisation methods with other available successfully optimised structures.	

Table 3: Results of the qualitative data analysis

6 Prototype

The Optimisation of Structural Design (OSD) prototype is developed to demonstrate the workability of the proposed framework (figure 11). The proposed prototype links the structural and architectural model and enables the engineers to generate structural designs based on the parametric data obtained from the architectural model, i.e. boundaries within the architectural model, such as location, width/length, and height of the walls. Thereafter, OSD analyses all the generated models and optimises them in order to provide the structural designers/engineers with the generated solutions (designs) for further (manual) optimisation and detailed design.

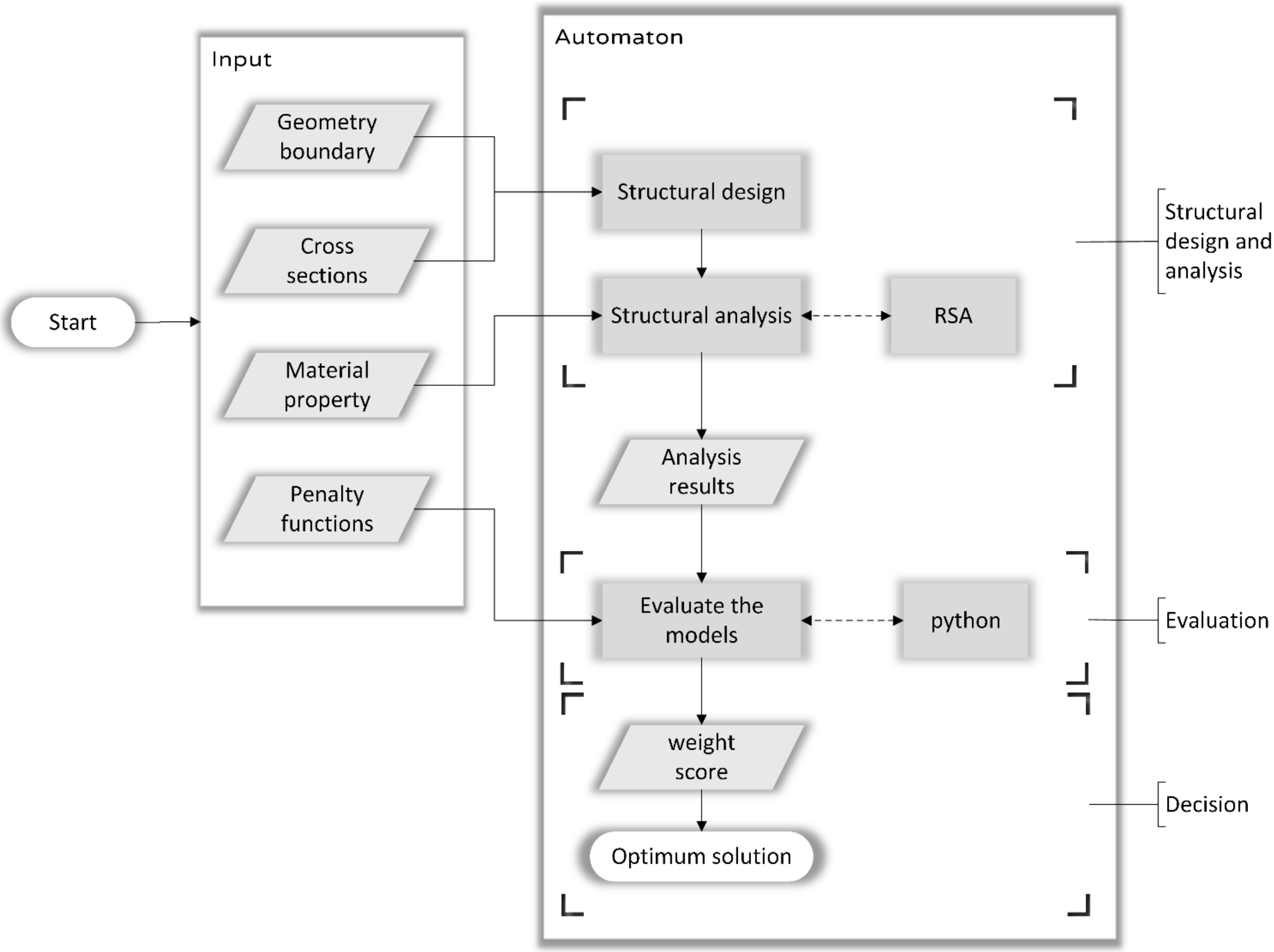

Figure 11: Schematic flowchart of the Optimisation of Structural Design (OSD) framework/prototype

Autodesk Revit is one of the most commonly used BIM tools and it is widely used for architects, structural engineers MEP engineers, designers and contractors (Autodesk, 2019a). In order to solve the issue of the interoperability and integration between architects and structural engineers, Dynamo (Dynamo BIM, 2019) was used to synchronise the required information automatically from Revit into Dynamo. These parametric data are used to perform the structural design and analysis in Robot Structural Analysis professional (RSAP). RSAP software provides structural engineers with advanced building simulation and analysis capabilities for different types of structures (Autodesk, 2019b). Moreover, RSAP provides a smoother, collaborative workflow and interoperability with 3D bidirectional links to Autodesk companion tools such as Revit and Dynamo. In OSD prototype, Dynamo is used to integrate the input information in an automatic process of generation, analysis (calculation) and evaluation of different alternative structural models. Dynamo is an open source visual programming tool that can interact with Autodesk Revit and Robot Structural Analysis Professional (RSAP) through the Application Programming Interface (API). On the other word, Revit-API and RSAP-API enabled the automatic integration between Autodesk Revit and RSAP in Dynamo. Therefore, any further change in the architectural model in Revit will be updated through an automatic process in Dynamo and new optimised structural designs will be generated in RSAP. This method solved the problem of coordination and repetitive redesign and update of the structural model followed by any possible changes by other disciplines (i.e. architects) in the design. Dynamo enables the users to create custom packages for specific purposes by using scripting language. This framework uses Structural Analysis package for Dynamo to create structural model inside Robot Structural Analysis software using Dynamo software workflows, and set up the calculations model using specific nodes and run the computation (Weyermann, 2018). Therefore, each structural model will be generated in RSAP and the required loading will be defined automatically from Dynamo and the analysis results will be created for every generated model in RSAP. Thereafter the calculation results will be send back to Dynamo to be used for comparison and decision making process by using Python scripts.

This platform uses architectural information, such as location of the walls (centre lines), length of the walls and location of the openings. Thereafter, location of the lines (centre lines) will be used to specify the structural columns grids. Hence, based on the length of the walls, different number of structural columns will be designed. The advantage of this method is that all the columns will be placed on the centreline of the walls (inside the walls), and under the slab, to transfer the weight of the building received from the slab and beam to the foundation, and also keep the aesthetic aspect of the architectural model. These decisions are pre-defined in Dynamo and the models are designed in Robot Structural Analysis professional (RSAP) based on the architectural model information synced from Revit in Dynamo.

A list of cross sections for columns and beams will be provided to design alternative structural models. In this process, each cross section receives a specific ID (index) in Dynamo to be identified. All this IDs (cross sections) are connected to a combiner engine in Dynamo to combine this IDs and generate alternative structural models with various cross section type and sizes.

All the structural models will be analysed and saved in a directory file path defined in Dynamo and all of them are viewable for further optimisation and detailed design. The optimisation process in the OSD framework is based on the structural analysis results received from each model from RSAP. This information will be used to evaluate and classify the structure in terms of over-designed and under-designed structure. The over-designed or under-designed structures will receive specific penalty function which is added to the weight of the structure and which will then receive a higher weight score. The aim of this framework is to find the best structural model which is the most stable and light structure. Hence, the objective is to find the structural model with the lowest weight-score because less weight score represents a structural model with less weight and less penalty function (not over stressed or over designed).

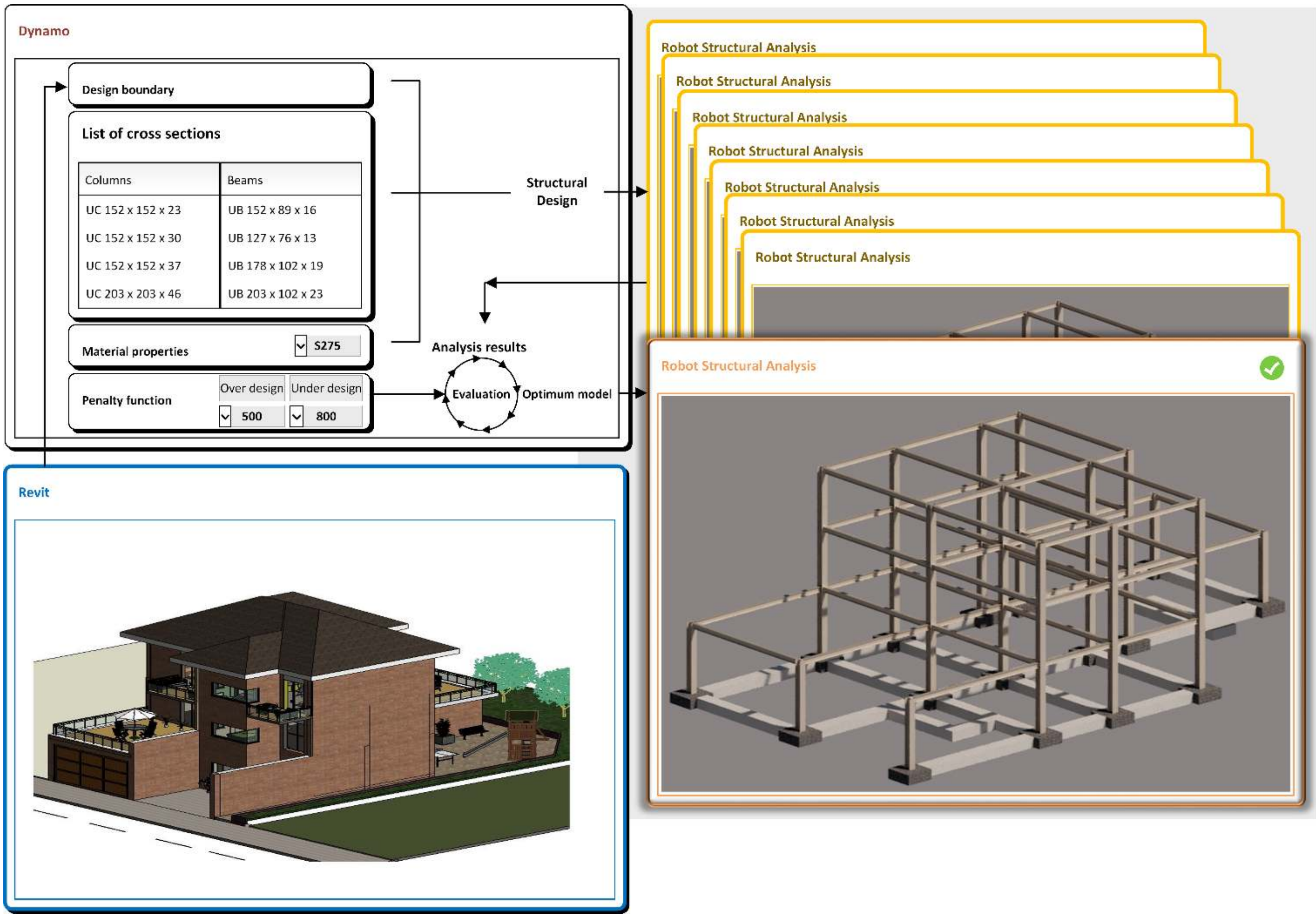

Figure 12: proof of concept prototype OSD framework

Weight score =weight of structure + penalty function (1)

7 Conclusions, discussion and future work

This paper presented the results of a state of the art PhD research on the optimisation of the structural design and analysis process at the early stage in BIM. This research started with a comprehensive literature review on the relevant projects and similar works to highlight the existing knowledge gap and challenges in the industry. A conceptual framework was developed to present new methods to solve the existing issues. This framework was justified and validated through data analysis of an online questionnaire distributed to professionally accredited structural engineers in IStructE, ICE and ASCE. Thereafter, a proof of concept prototype was developed to demonstrate the workability of the OSD framework. This paper presented the results of the questionnaire and explained how OSD framework solves the issues reported to the online questionnaire.

The OSD framework is developed as a potential solution to the existing lack of a BIM integrated framework adopting visual programming in a widely used BIM platform to facilitate structural design, analysis, and optimisation in an automatic process. One of the significant challenges that OSD solved is the integration between architects and structural engineers. In this scenario, OSD framework synchronises parametric data of the architectural model into the structural models to provide a dynamic workflow between architects and structural engineers. Therefore, any change in the architectural model will be automatically updated in the structural models. However, the main objective of this framework if to provide a wide variety of optimised structural designs based on the requirements. The main purpose of this framework is to facilitate the structural design optimisation process. Therefore, OSD is developed to be used by user with or without a great knowledge and background in programming.

The author is expanding the framework to be used in other areas such as multidisciplinary optimisation of suspension bridge (topology and size optimisation), architectural optimisation of façade panels based, etc.

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