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Optimisation of Structural Design by Integrating Genetic Algorithms in the Building Information Modelling Environment

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***Abstract*—**Structural design and analysis is an important and time-consuming process, particularly at the conceptual design stage. Decisions made at this stage can have an enormous effect on the entire project, as it becomes ever costlier and more difficult to alter the choices made early on in the construction process. Hence, optimisation of the early stages of structural design can provide important efficiencies in terms of cost and time. This paper suggests a structural design optimisation (SDO) framework in which Genetic Algorithms (GAs) may be used to semi-automate the production and optimisation of early structural design alternatives. This framework has the potential to leverage conceptual structural design innovation in Architecture, Engineering and Construction (AEC) projects. Moreover, this framework improves the collaboration between the architectural stage and the structural stage. It will be shown that this SDO framework can make this achievable by generating the structural model based on the extracted data from the architectural model. At the moment, the proposed SDO framework is in the process of validation, involving the distribution of an online questionnaire among structural engineers in the UK.

***Keywords*—**Building Information Modelling, BIM, Genetic Algorithm, GA, architecture-engineering-construction, AEC, Optimisation, structure, design, population, generation, selection, mutation, crossover, offspring.

I. Introduction

BUILDING Information Modelling (BIM) is one of the promising recent developments in the AEC industry [1]. BIM represents a new paradigm within AEC, one that encourages collaboration of the different AEC roles on the same model, or Common Data Environment (CDE) [1]. The model can be constantly updated to reflect any decision changes which are then instantly available to other CDE users. The model can be interrogated in many different ways depending on the requirements/interests of a particular user group e.g. construction processes (clash detection), construction planning/programming, whole building life cycle [2]. BIM can be thought of as a system for the processing and managing of (often) very large amounts of data for the use by disparate groups of individuals/organisations all with the ultimate aim of the production of a final project outcome [3].

Extant literature demonstrates some of the efficiencies possible with appropriate use of BIM procedures and technologies rather than conventional process, for instance: more than 82 percent improvement in company's productivity, noticeable economic advantages in term of return on investment (ROI) [1], more efficient communication [4]. Results from a study by McGraw-Hill Construction, which surveyed about 300 BIM practitioners in 2008, reported that BIM adoption had improved aspects of their project's success in areas such as; quantity take off (57%), scheduling (45%), estimating (44%), energy analysis (38%), project management (35%), structural analysis (32%), LEED/green analysis (32%), storm water analysis (19%), facility management (18%) [5].

As the uptake of BIM has increased by the larger AEC organisation, so the adoption of BIM has been increasingly demanded as a requirement for project contracts by clients, consultants, and contractors. This has been particularly required since the UK government's mandate for full BIM level 2 collaboration on all public funded projects by 2016 [6]. Despite this, the comprehensive uptake and adoption of BIM has yet to be fully adopted [7]. As users continue to gain expertise with BIM, it is expected that there will be further capitalisation of the technology's potential and push for new ways to improve in areas such as sustainability and building operations [5].

As a point of reference to evaluate the importance of BIM in civil and structural engineering, consider singular events during the industrial revolution that greatly changed the industry/profession. The first commercial electric welding machines, pre-stressed concrete and the development of the Bessemer process for the mass production of affordable steel are a few examples of these events. BIM has the potential to become one of these very important new developments which could provide great efficiencies and advances in the civil and structural engineering industry/profession [8]. On the other hand, by increasing demand for BIM technology, BIM-enabled structural design has increased. Hence, it is important to consider new ways to further improve and develop techniques within and utilising BIM processes/technologies to deliver better results [3].

According to AECOM, the following technologies are the future of the BIM [9]:

- 3D workflow development.

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- Automatic checking and evaluation the design model based on predefined constraints.
- Continues approach for the automation and parametric design.
- Adapting Artificial Intelligence (AI) and machine learning methods to facilitate decision making processes.

This research is a part of an extended project, which started with the work of Goulding et al., with the aim of developing a conceptual framework for a Generative BIM workflow (G-BIM) [10]. This framework enables designers to automatically generate alternative conceptual architectural designs at an early stage by integrating both design method and computational architecture. This research continues the G-BIM workflow in the architectural area and suggests a SDO framework.

II. Structural Design

Conceptual structural design development has great effects on the whole constructability, cost, and general performance of a building [11]. In these early stages, vital decisions are made including type of the structure, feature, layout and different dimensions. Mistakes/miscalculations or misunderstandings made in the early stages of a project become increasingly more difficult and costlier to correct as the project progresses [12]. According to Larsen and Tyas, getting the initial concept right can result in a reasonable design which meets architect's requirements as well [13]. On the other hand, getting the concept wrong can result in technical, financial, and architectural disasters [11].

Fig. 1 compares the traditional approach of building process (black line) with the BIM approach (blue line). In this figure, effort/effect is a function of time and shows how shifting the effort in building process to the left side (early stage) can affect the process in terms of cost efficiency and fundamental capability in changing the design. This would suggest that engineers were able to analyse, compare, and evaluate the behaviour of several possible preliminary structural designs quickly and efficiently during the early stages of the conceptual design, the potential for greater overall project success would be increased.

Although, there have been limited attempts to use technology to generate optimised conceptual structural design alternatives [15], [16]. In general, engineers are forced to rely on their own knowledge and experience to produce conceptual designs and to attempt to optimise them manually, through iterative and time-consuming processes, thus reducing the time available to consider other possible alternatives. However, the current technology has provided efficient potential to improve the structural design process by using the advantage of automatic optimisation methods.

As asserted by Mora et al., the conceptual design must meet several parameters including: involve multiple views from all the project team, support design refinement, enable exploration of alternative design solution (thereby enabling possible adjustments in the design) [17], [11].

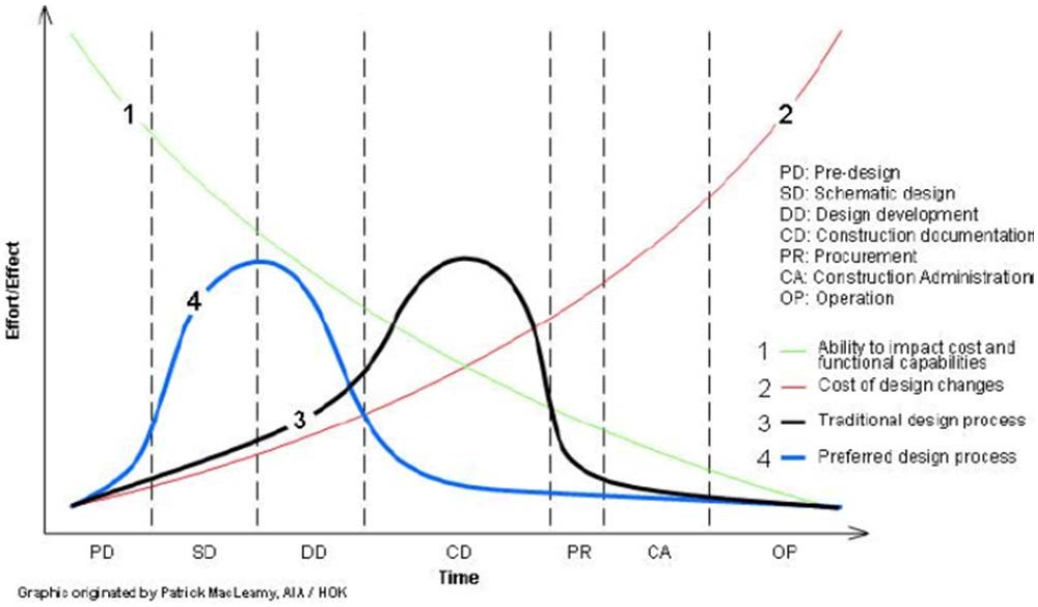


Fig. 1 Transferring the main efforts in design process to the early stage [14]

Structural design can be optimised through generation of design alternatives to evaluate materials, layout and elements behaviour against different factors including: live, dead and seismic load, type and height of the building, maximum deflection and so on [18]. In this scenario, a practical structural system, presents a structurally stable and harmonised layout that provides continues load paths to the ground [19], with a reasonable investment.

Therefore, this research is aimed at enabling conceptual structural design exploration and optimisation through an automated process.

The SDO framework is based on BIM environment, and

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represents a unique approach to automatically produce and analyse conceptual structural design alternatives and optimise them until they meet the requirements (project defined criteria and constraints). Thereafter, the most optimal structural design will be modified in a BIM environment. This process would have the advantages of an organised modelling approach, the use of the efficient features of BIM structural design processes including; collaboration, a visualisation platform, and it would contain its own structural design elements at global dominant and standardised data exchange interfaces that improved its performance and reduce the entire construction cost [20].

III. Optimisation

In the structural optimisation process, the main concern of an engineer is to recognise the behaviour of the structure in different situations. These behaviours include the stresses, deformations, stability, eigenfrequencies and so on. Hence, this time-consuming process requires a reliable optimisation method to find the optimum among alternatives [21].

According to British Standards Institution, structural optimisation contains four dominant considerations [22]:

1) Design constraints; dealing with stress, deformation, damping, stability and eigenfrequency. These constraints are formulated according to related Eurocodes.
2) Fabrication constraints; related to residual welding distortions, welding methods, structural dimensions, plate thicknesses and description of available profiles series.
3) Cost function; includes the cost of the material, assembly, welding, cutting and painting based on fabrication sequences.
4) Mathematical methods; the solution of the constrained function minimisation problem requires practical mathematical method.

Literature demonstrates that several researchers have suggested methods, which tend to replace the designer in favour of automation in the conceptual design stage [23]. To name a few; the International Code Council's (ICC) tried to develop and initiate SMART codes into BIM to provide automatic code checking [8], Software Environment to support the Early phase in building Design (SEED) [24], Building Entity and Technology model (BENT) [11], PointSketch [25], Multi-Reasoning Model (M-RAM) [26], CADRE [27], TEAM [28], A-TEAM [29], GAs [30] and the research has been done by Ponterosso and Fox [16] are examples of methods aimed at supporting early design exploration.

The aim of this paper is to outline the development of a multi-stage framework including four stages; Data Collection/ Organisation Scheme, SDO, Evaluation, Modifications in BIM environment. This paper explains the general process of the conceptual framework and the optimisation process. Thereafter, the conceptual framework will be analysed, amended, and developed through semi-structured and unstructured questionnaires and interviews from experts in structural design and analysis and BIM. The modified framework will be used to build up the conceptual prototype by using Machine Learning theory and AI such as GAs.

This prototype will be used to design, analyse, and optimise conceptual structural design alternatives automatically.

IV. Methodologies

This research will use Creswell's guidelines [31] to choose the most suitable methods and design the approach to develop the research. In this scenario, a mixed-method approach has been used to develop the theoretical foundation of this research. Hence, this study starts with a qualitative approach to provide a broad-based knowledge about the current methods and software support adopted for conceptual structural design. Thereafter, the research will narrow down in more focused detail by using a quantitative approach to investigate design protocols in terms of design stability, cost efficiency, design diversity and time productivity of the process.

V. Framework

This framework presents an automatic process of SDO at the conceptual stage in a BIM environment. This framework has the potential to efficiently assist the engineers by reducing the time and effort during the iterative process of structural design during the early stages. The SDO framework involves four steps of Data Collection/ Organisation Scheme, SDO, Evaluation and Modifications in BIM environment.

A. Data Collection/ Organisation Scheme

During the development of the coding stage, the essential information, data and concepts including limits, constraints and codes in structural design and analysis will be gained and classified to run the SDO process. According to the framework, this stage contains five main parts:

1) Regular coding: This coding will be used regularly before design process starts to identify which type of material or element would be preferred to be used. In this scenario, the engineer can benefit from his experience to reduce the time of the modelling process by limiting the available elements [15], [32]. Further coding would be generated, which will request the engineer to identify the required analysis type (displacement, stresses, strain, and ext.)
2) Extracting data: In the SDO conceptual framework, the architectural model will be used to extract the structural design data and requirements. Thereafter, based on these data, structural design, analysis and optimisation processes will be started through an automatic process.
3) Design: preliminary coding will be generated once and embedded in the software. This method will be used to design the structure based on specific structural constraints and codes.
4) Analysis: preliminary coding will be generated once and embedded in the software. This method will be used to analyse the design. In this scenario, specific codes and constraints will be used to ensure that the structure will be statically stable and economic.
5) Optimisation: A practical SDO method will be used to automatically design, analyse and optimise the structural design.

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B. SDO

According to Farkas and Jármai [33], structural optimisation is defined as a design approach searching for better results, which better meet engineering requirements. The most important requirements and concerns for a modern load carrying structure are the safety and fitness for production and economy. Design and fabrication constraints can guarantee the safety, and minimisation of cost function can secure the economy factor.

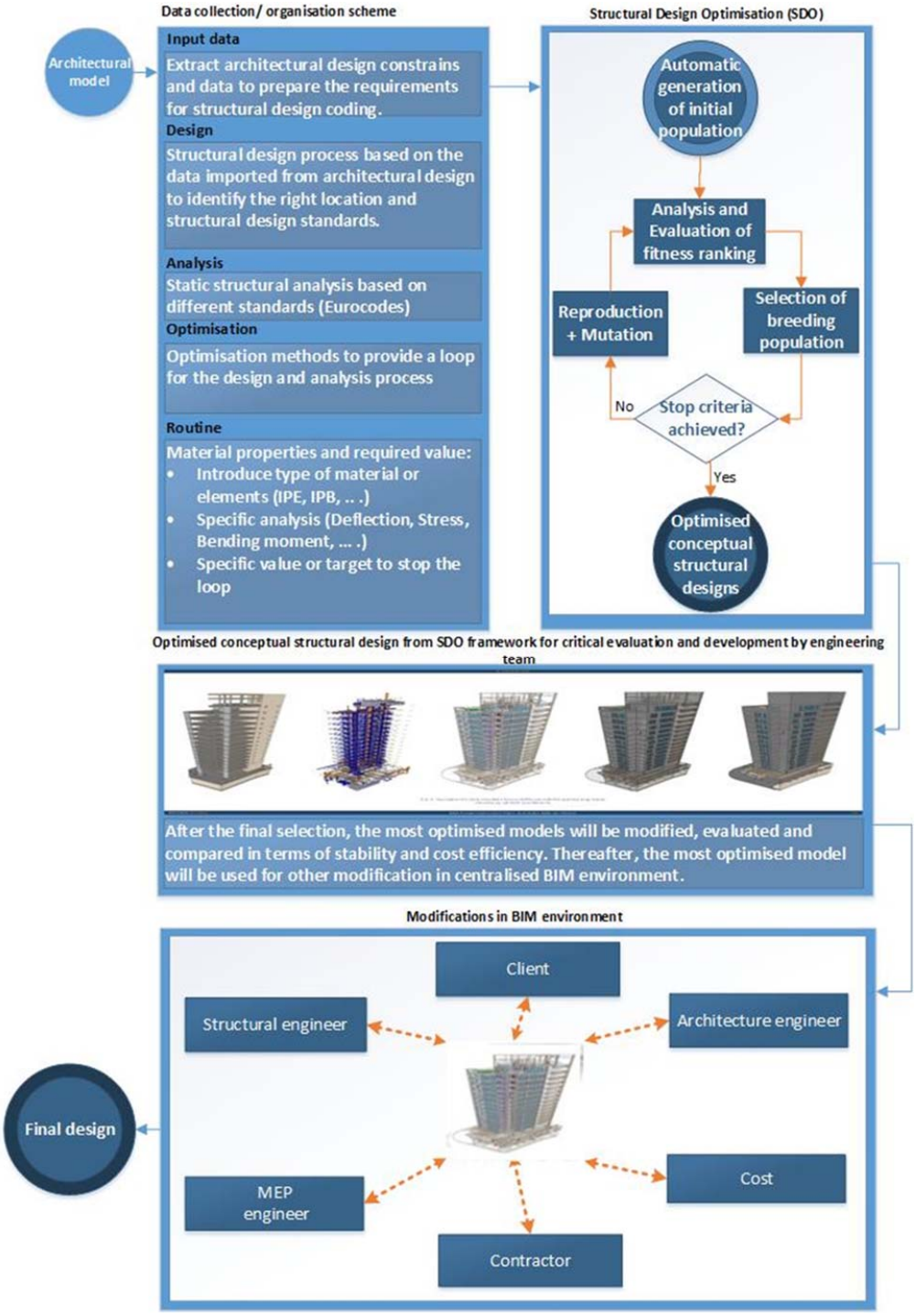


Fig. 2 Conceptual SDO framework

This provides an automatic loop for structural design, analysis and optimisation. The optimisation process starts generating initial populations of structural designs with design alternative based on the data extracted from the architectural model. The initial population will be evaluated against structural stability constraints (such as: displacement, stress,

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buckling and ext.). After the evaluation process, the most stable and economic models will be selected. Extant literature demonstrated that selection of variables has a vital importance during the optimisation process [33]. Hence, understanding the main characteristics related to the structure is very important in order to have an effective selection. In order to name a few of these characteristics: material, loads, geometry, topology, profiles, fabrication procedure, joints, cost. By adjusting these characteristics, better solutions will be achieved. After evaluation and selection, the surviving individual models will be evaluated against the required stop criteria (e.g. the difference between two generated optimal models is within a certain low percentage, or whether a certain specified number of generations has been analysed). If the stop criteria have not been achieved the process will repeat until the stop criteria are achieved. Once the optimal initial conceptual design(s) have been produced by the system, the resultant models will be modified in the central BIM software using the advanced BIM modelling features.

Recently, several new optimisation approaches developed such as; evolutionary methods, like GA [34], the Differential of Evolution (DE) technique [35], the Ant Colony method [36], [37], the Particle Swarm Optimisation (PSO) [38], the Artificial Immune System (AIS) [39] and the Harmony Search (HS) [40].

C. Optimised Conceptual Structural Design from SDO Framework for Critical Evaluation and Development by Engineering Team

When SDO is used, the most optimised structural designs will be sent to evaluation stage for final and manual structural evaluation and modification in terms of stability and economy. In this way, the engineers will save time and effort in the initial iterative process of conceptual design, analysis and optimisation. Additionally, they will receive alternative optimised models, which may require evaluation and amendment.

D. Modification in BIM Environment

After final structural evaluation, the most optimised model will be send for further modification in BIM. All the modifications will take place in central BIM software using the advanced BIM modelling feature.

VI. Future Work

As shown in Figs. 3 and 4, bridges and formworks are very rarely modelled in BIM by structural engineers [5]. This represents an opportunity for future research and further development in BIM.

VII. Conclusion

This paper presents suggestions for an efficient conceptual framework for SDO for use in the conceptual design stage. This research continues the work of Abrishami, Goulding, Pour Rahimian and Ganah that resulted in developing (G-BIM) prototype [10]. G-BIM has the potential to enable automation at the conceptual design stage, by analysing a large number of design possibilities.

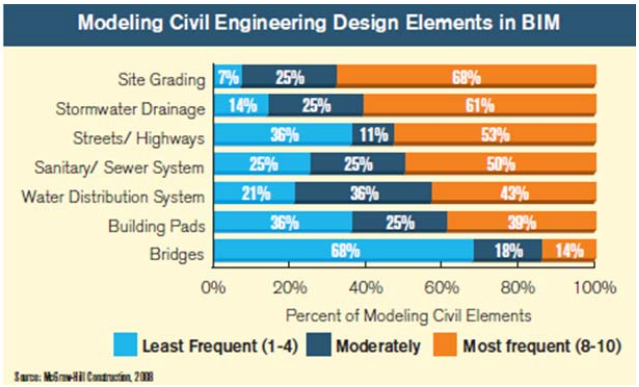


Fig. 3 Modelling civil engineering design elements in BIM [5]

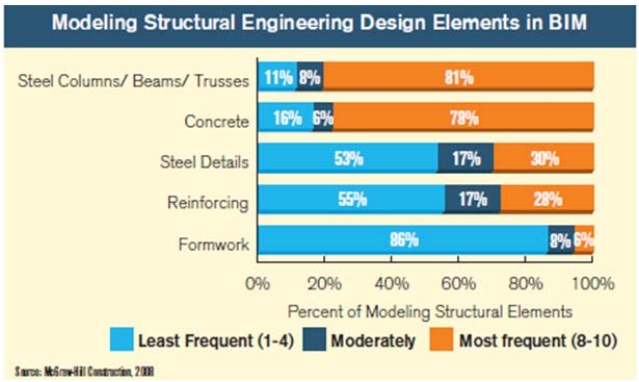


Fig. 4 Modelling structural engineering design elements in BIM [5]

In the SDO conceptual framework, the architectural model will be used to extract the structural design data and requirement. Thereafter, based on the extracted data from the architectural model, structural design, analysis and optimisation processes will be started through an automated procedure. Afterward, the most optimised conceptual structural design will be evaluated in terms of stability and economy and will then be passed on to the next stage for further modification in the BIM environment.

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