Minimising Material Waste by Utilising BIM and Set-based Design in the Structural Design of Reinforced Concrete Slabs

Abstract

Considering the significant amount of material wasted in the construction industry it should be a business case for companies to pay more attention to reducing waste, which would have also a major impact in the environmental issues of the projects. Although structural engineers and architectures have different roles in the design process in selecting construction systems and materials, they provide building information together. Building Information Modelling (BIM) could provide an opportunity for all relevant stakeholders to share their knowledge and experiences in the early stages of design and a platform for structural engineers to utilise Set-based Design to considering different alternatives for optimal design of systems. This research suggests enhancing an intelligent decision support model in parallel with stakeholder's participation to achieve the optimal final solution in terms of material waste by narrowing down the structural alternatives. The example used in the paper is reinforced concrete slab, but the same principles are applicable to all structures.

This research will focus on describing the BIM features, which could help the structural engineers to rank their criteria and select optimised design solutions. In addition, this paper will be a part of the first author's PhD dissertation and analysis the pertinent literature.

Keywords; BIM, Set-based Design, structural engineering, waste reduction, concrete slab

Introduction

The construction industry is an activity producing significant part of material waste; building industry consumes approximately 40% of world's raw material (Koskela, 1992) and in the UK from the 420 million tonnes of materials used annually 120 million tonnes, 28%, becomes waste (Network Waste UK, 2012) already in construction phase the waste of material can constitute 2...3 % of the total construction costs, which is about the same as typical profit margin in the industry (Network Waste UK, 2012). Previous research has indicated that the main reasons for physical waste in the construction industry are inappropriate preparation, inaccurate processing of materials and incorrect decisions in the design stage (Ballard, 2000).

The main reason for errors and delays in most processes is inconsistent and ambiguous information. Therefore construction industry requires explicit storage to share and exchange the project information between all participants (van Nederveen et al, 2010). It is commonly known that design and construction projects are too often running over budget and schedule because of errors and changes during the construction. BIM is expected to address some of the fundamental reasons for these problems by ensuring "getting the right information in the right format at the right time in the right place" (Tolman, 1999). "BIM is a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä, 2006). The timely and correct information would help project shareholders to make more rational decisions and reduce mistakes and rework (Autodesk, 2011).

Eastman et al, (2008) examined three main impacts of BIM in design phase: 1) Conceptual design, 2) Integration of engineering services, and 3) Construction-level modelling. Conceptual design determines the basic framework of the construction design in terms of general spatial layout, massing and structure taking the site and other local conditions into consideration. The integration of engineering services can cover many factors of a building's performance, e.g. analysis of structural engineering, ventilation, temperature control, energy distribution, water consumption, waste disposal, lighting, acoustics and air flows. Construction-level modelling covers detailing, specifications, cost estimation, including composition and placement rules to expedite the generation of construction standards and construction documentations.

Danatzko (2010) highlighted some sustainable structural design methodologies including diminishing material use, material production energy and embodied energy creating lifecycle analysis/inventory and ensuring reuse. This research will examine the linking between Set-based Design and BIM in selecting most efficient system for pre-casted concrete slabs in structural design. At this point the research is in its early stages so the paper presents the initial framework for the future work.

1. Set-based Design and Point-based Design

In the philosophy of design, the term of DTM (Design Theory Methodology) has been described as a study of determining the method and thinking of designers to develop the efficient structures for the design procedures (Wynn & Clarkson, 2005). The design in structural engineering means the entire planning procedure for a new building or infrastructure including mathematical calculations, and the requirements usually come from the client's functional requirements and building codes defined by Government bodies. The structural design can be categorised in two stages: 1) feasibility study involving a comparison of the alternative solutions for structures and selection of the most suitable types, and 2) detailed design of the chosen structure (Arya, 2009). The main criterion in structural engineering is ensuring that the strength of materials and components at any critical point is sufficient for all stresses and loads affecting that part. The design principles would support Point-based or Set-based system. Commonly engineers use Point-based Design, where a single option of feasible design will be selected based on designer's experience and subsequently the design will be modified by more information (Lee et al, 2012).

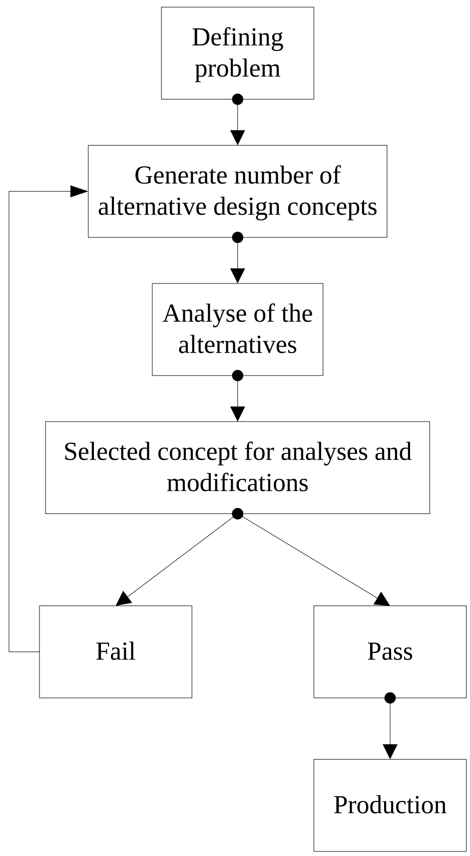

Figure 1: Point-based process

In the Set-based Design, various design alternatives are considered by specific stakeholders at the same time and the information necessary for evaluating different options from multiple perspectives is transferred between these stakeholders. The main difference between Set-based Design and Point-based Design is that in the Set-based Design the engineer maintains several alternatives while in Point-based Design the selection is made in earlier phase and the possible alternatives are not examined from several viewpoints in detail. "In particular, in the structural engineering phase, the design includes all permissible design options ranging from schematic design to construction detailing, and these could be modified and postponed until the decisive stage rather than materializing them before all of the requirements have been suggested" (Lee et al., 2012).

By using BIM the process does not only address the clashes between construction components but designers can produce and analyse alternative solutions faster than if they provide them separately (Parrish, 2009). This makes using Set-based Design more efficient in the BIM environment than when using traditional methods.

BIM provides tools for structural engineers to obtain models from architects and therefore easier access to correct information to define, for example, details of rebar conjunctions in concrete slab. According to Arya (2009) "Most failures are as a result of poor detailing rather than incorrect analysis".

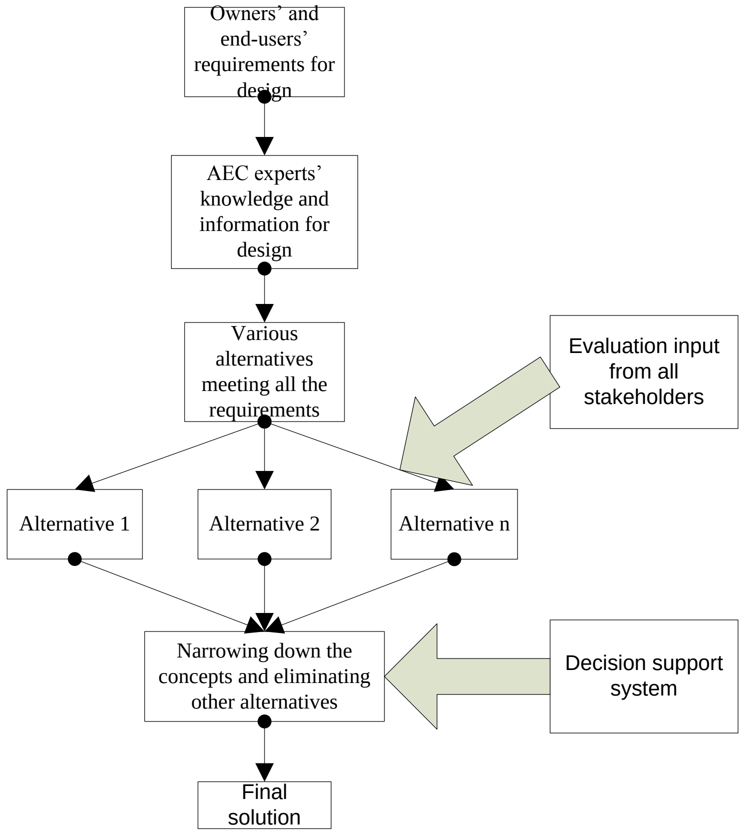

Figure 2: Set-based Design procedure

3. Designing Reinforced Concrete Slab using Set-based Decision-making

Concrete slabs can be divided into solid, precast or in situ structures. However, these are not all the alternatives, which must be considered. As the main criterion is safety, punching failure in high stress at the supports is a key aspect in designing structure of slabs (Arya, 2009). To avoid this failure engineers must take into consideration deep slabs and large diameter columns, and therefore the designer must consider several integrated design alternatives, including Shear Hoops, ACI Shear Stirrups, Shear Ladders and Stud Rail. All key stakeholders should rank these alternatives considering their different aspects. A new possibility in the BIM environment could be to use some advanced decision-making method - AHP, Choosing by Advantage, Multi-attribute Utility Theory or Robust Decision Making - to choose the optimal solution considering safety, economical and waste aspects.

During designing of concrete slab, structural engineers can select the applicable building code through a variety of software. In designing concrete slab deflection is a critical factor in addition to ultimate limit state of bending and shear. The choices of slabs would begin by solid, precast, and afterwards for each main choice there are large numbers of alternatives. By considering on Set-based Design based on BIM, the type of final slab would not be selected until last phase of design.

Procedure of Set-based Design is categorised in Mapping Design Spaces, Finding Compatible Combinations of Design, and Making Commitment (Parrish et al, 2007). In the Mapping Design Spaces phase there are three main factors; the first is the minimum depth of slab (d_{min}), second is the minimum area of bars (A_{Smin}) and the third is the minimum and maximum clear distance between bars (S_{bmin} & S_{bmax}) (Arya, 2009). All these factors impact on material usage in reinforcement concrete slab. The factors, which can change the outputs, can be categorised in two groups. In the first category are factors, which are related to resistance or quality of materials, such as yield tension of steel (f_y) and maximum size of aggregate in concrete (h_{agg}). Increasing the values of these factors the minimum total area of bars in slab section (A_{Smin}) will decrease and the minimum cleared distance of the bars (S_{bmin}) will increase, which means that the total amount of steel in slab will be reduced according to following equations (Arya, 2009).

$A_s \geq 24$ % A_c When f_y = 250 N/ mm^2

$A_s \geq 0.13$ % A_c When f_y = 460 N/ mm^2

h_{agg} + Bar Diameter ≤ S_b ≤ 3d or 750 mm

The second category is related to factors, which designers can control, and they have key role in minimising waste of material and in finding compatible combinations of design. In the designing of reinforced concrete one of the significant parameters is the amount of steel in section area of concrete (ρ), and there are large number of potential combinations using bars with different diameters which can fulfil the requirements. Hence in the last phase of Set-based Design all these alternatives will be narrowed down to the final optimal concrete slab which is determined by the optimal depth of concrete, the optimal amount of bars, the optimal clear distance between bars and finally the optimal span (one way slab or two way slab).

According to Howard (1988) “Decision analysis stands on a foundation of hundreds of years of philosophical thought about uncertainty and decision-making”. The decision analysis is a process of understanding the problem, evaluating and solving. In the decision making to find an optimal solution for a structural component, an intelligent, BIM-based system could improve the process by narrowing down the alternatives and supporting stakeholders’ negotiation.

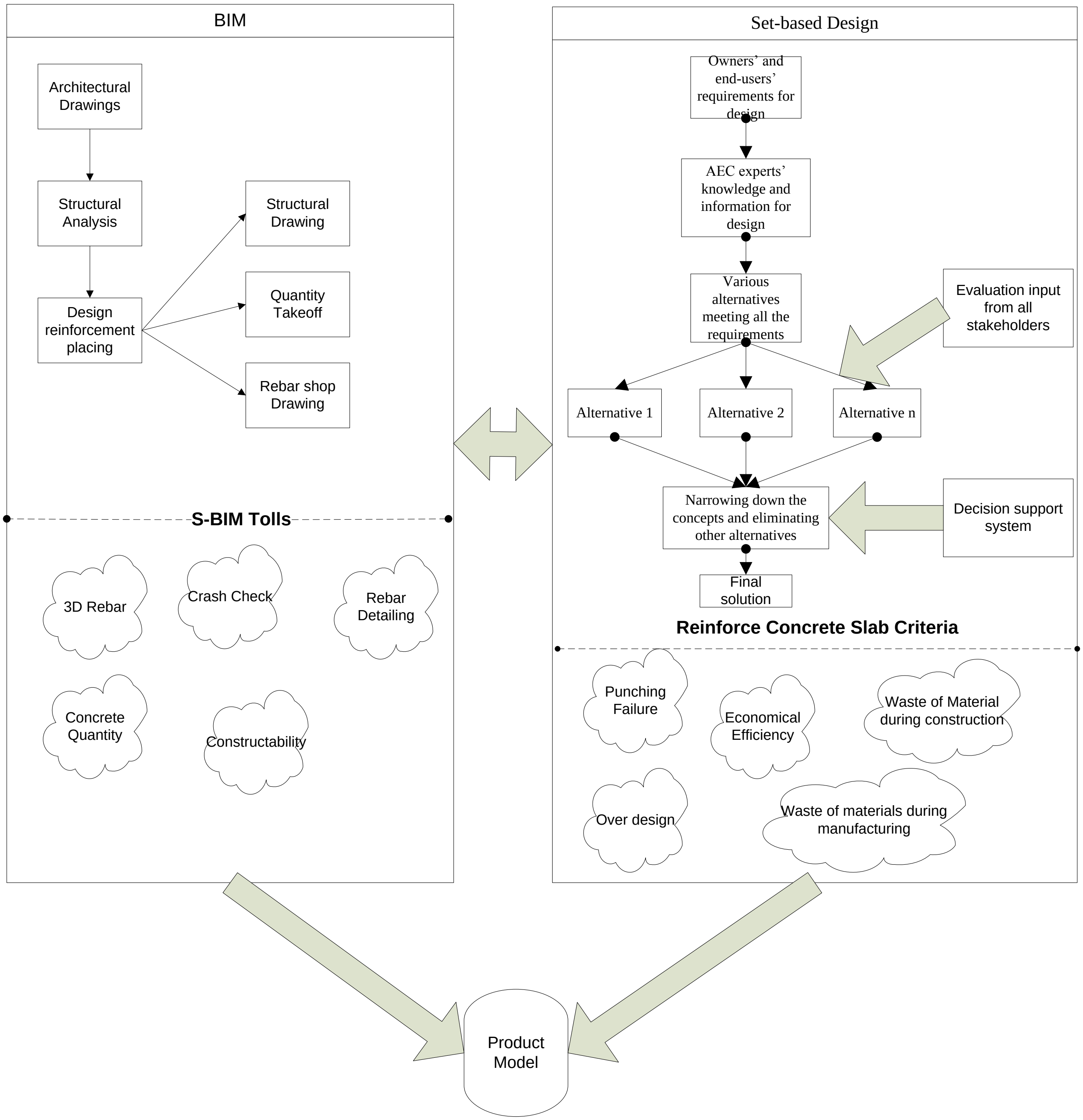

Figure 3: S-BIM in contingence with Set-based Design to selecting optimum alternatives

Key stakeholders can input their weighing on different factors by considering the current customer requirements and potential future requirements (resource and material) to such a system, and the system could first narrow down the alternatives and at the final stage "*find the total value for each alternative*" (Cariaga et al, 2007) by formulating the ranking based on various intelligent decision-making methods, such as Analytic Hierarchy Process, Choosing by Advantages, Multi-attribute Utility Theory or Robust Decision Making.

4. Conclusions

In addition to safety and durability of concrete slabs, minimising material usage will be critical factor for sustainable building design. To achieve this goal, Set-based Design has been suggested as an opportunity for all key stakeholders in the design phase to collaborate and utilise their knowledge and experiences in the decision-making. The combined use of BIM and Set-based Design will enable development and evaluation of a large number of alternative structural models. For reinforced concrete slabs those alternatives could be a combination of various materials with different resistances and various space designs. In parallel with determining various structural concrete slabs by key stakeholders, an intelligent decision-making system would support the evaluation of material optimisation thus making the process of narrowing down alternatives in a more intelligent and efficient way.

The next step of this PhD research will be to examine appropriate intelligent decision-making processes in the integrated BIM environment for optimised structural design.

5- References

Arya, C. (2009). *Design of structural elements: Concrete, steelwork, masonry and timber designs to British standards and Eurocodes* (Third Edition ed.). New York: Taylor & Francis

Autodesk. (2011). Autodesk BIM 360: Collaboration & Data management for AEC Retrieved 29/03/2012, from http://images.autodesk.com/adsk/files/autodesk__bim_360_overview_whitepaper_april_2011.pdf

Ballard, G. (2000). Positive vs negative iteration in design. *International Group for Lean Construction IGLC, 8*, 17-19.

Cariaga, I., El-Diraby, T., & Osman, H. (2007). Integrating value analysis and quality function deployment for evaluating design alternatives. *Journal of Construction Engineering and Management, 133*, 761.

Danatzko, J. M. (2010). *Sustainable Structural Design.* The Ohio State University.

Eastman, C. M., Teicholz, P., Sacks, R., & Liston, K. (2008). *BIM handbook*: Wiley Online Library.

Howard, R. A. (1988). Decision analysis: practice and promise. *Management science*, 679-695.

Koskela, L. (1992). *Application of the new production philosophy to construction* PhD Thesis, Stanford University

Lee, S.-I., Bae, J.-S., & Cho, Y. S. (2012). Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures. *Automation in Construction, 23*(0), 20-32. doi: 10.1016/j.autcon.2011.12.008

Network Waste UK. (2012) Retrieved 20/05/2012, from http://www.networkwaste.co.uk/network-news/construction-waste-statistics

Parrish, K., Wong, J. M., Tommelein, I. D., & Stojadinovic, B. (2007). *Exploration of set-based design for reinforced concrete structures*.

Parrish, K. D. (2009). *Applying a set-based design approach to reinforcing steel design* PhD dissertation University of California Berkeley

Penttilä, H. (2006). Describing the changes in architectural information technology to understand design complexity and free-form architectural expression: ITcon Vol. 11, Special Issue The Effects of CAD on Building Form and Design Quality , pg. 395-408, http://www.itcon.org/2006/29.

Tolman, F. P. (1999). Product modeling standards for the building and construction industry: past, present and future. *Automation in Construction, 8*(3), 227-235.

van Nederveen, S., Beheshti, R., & Gielingh, W. (2010). Modelling concepts for BIM. *Handbook of Research on Building Information Modelling and Construction Informatics: Concepts and Technologies, Hershey, PA, IGI Global Publishing*, 1-18.

Wynn, D., & Clarkson, J. (2005). Models of designing. *Design process improvement*, 34-59.