A BIM Extension For Sustainability Appraisal Of Conceptual Structural Design Of Steel-Framed Buildings

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ABSTRACT

With the contemporary improvements in construction IT, the use of building information modelling (BIM) has become a considered approach in construction transactions. This places demand on BIM to become fully matured and all-encompassing with respect to operations of various professional platforms and the performance measure of artefacts. Sustainability is one such measure associated with buildings. For the structural engineer, recent design criteria have put great emphasis on the sustainability credentials as part of the traditional criteria of structural integrity, constructability and cost. As such a means for assessing the sustainability credentials of design solutions to guide early design decisions has become a necessity. There exists decision-support tools to aid sustainability assessment of buildings; however, these tools will be more beneficial when built into the design solution from its inception. This paper highlights existing deficiencies and examines how contemporary modelling techniques can be employed to tackle identified gaps. The work proposes a prototype system for appraising the sustainability of design options at the conceptual design stage. The system is based on a framework which uses life cycle costing as a measure of accounting for economic sustainability and a combination of carbon and ecological footprint for the environment. It is implemented in C#, using .NET Frameworks and Revit API. This paper demonstrates that the utilized information modeling representations – in the form of a process model, implementation algorithms and object-based instantiations – can capture sustainability related information to inform decisions at the early stages of the structural design process.

INTRODUCTION

To achieve the maximum influence on building cost and impacts in the building life cycle, it is widely acknowledged that the design stage presents the best opportunity to incorporate sustainability measures into the project development process (Ding 2008; Kohler and Moffatt 2003). However, tools to inform the structural designer on sustainability at the early phases of design have not been sufficiently explored. With the recent emergence of BIM, the construction industry is presented with the opportunity of expanding the BIM scope to account for n-dimensional building performance elements such as sustainability.

This paper discusses an application of BIM in the sustainability appraisal of steel-framed structural system during the early stages of modelling design concepts. The sections in this paper include an overview of BIM and plug-in application, discussions on the need for sustainability applications, presentation of the framework for sustainability appraisal. The implementation of the framework in the form of a prototype known as Structural Sustainability Estimator (SSE) and illustrations of its use make-up the concluding part of this paper.

BIM AND PLUG-IN APPLICATIONS

The AEC industry is now conversant with BIM due to the wide campaign for international acceptance as a medium for construction related transactions. It is forecast that drawing production-focused computer aided drafting (CAD) and the next generation of IT will involve processes of generating, storing, managing, exchanging and sharing of building information in an interoperable and reusable way (Cruz 2008). Though the scope is yet to be fully defined (NIBS 2007), its benefits in project implementation and information management are envisaged to be enormous. BIM has the tendencies for continuous expansion to closely mimic, as much as possible, the vast amount of information embedded in typical building project.

Thus, the possibility of expanding the BIM scope has already been demonstrated by researchers in various plausible plug-ins and extensions. An example is the multi-dimensional computer model, 3D to nD modelling project (Lee et al. 2006). The project aims to facilitate the integration of time, cost, accessibility, sustainability, maintainability, acoustics, crime and thermal requirement into the modelling of building information. Modelling nD aspects is demanding and involves extending the building information model to incorporate the various building life cycle design information which are vast and cut across the different building professional platforms. This warrants issue-specific approach; hence researchers have begun tackling specific aspects or components. In the construction stage of the building lifecycle, efforts to fuse 4D technology (construction scheduling) with BIM for better construction performance are also underway (Zhang and Hu 2011). Disaster preparedness aspect in the building operation phase is geared towards improving training games by modelling hot dynamic conditions and the building behaviour over time in the event of fire (Ruppel and Schatz 2011; Tizani and Mawdesley 2011).

In the planning and design stage, the benefits of the early incorporation of sustainability principle in guiding project decisions and design iterations have been emphasized (Kohler and Moffatt 2003). One area of challenge has been the development of standard sustainability tools to guide professionals in making conceptual design decisions among alternative solutions. Although a number of sustainability assessment tools exist, it has been difficult for engineers to apply them to conceptual design iterations via the emerging BIM approach. The Building Research Establishment Environmental Assessment Method (BREEAM), used in the UK, is yet to be incorporated into BIM. In the US, research efforts to incorporate Leadership in Energy and Environmental Design (LEED) criteria into BIM tools have been on-going. Nguyen et al (2010) has attempted using BIM to evaluate sustainability of architectural design by storing the LEED criteria indicators as project parameters in Revit Architecture software. These parameters are extracted when applied to a project to compute the maximum possible LEED ratings. While this work targets architectural designs, it is limited to the LEED sustainability parameters and will not be of direct benefit to the structural engineer's conceptual design iterations. The tendencies of subjectivity associated with different professional assessing sustainability indicators have been noted by Haapio and Viitaniemi (2008). This calls for building professionals to start thinking towards the direction of being responsible for the information on sustainability of their design specifications and materials as they do for the integrity of their designs.

THE NEED FOR APPLICATIONS ON SUSTAINABILITY

The awareness of the need for sustainability in construction is on the increase. Construction has a high economic significance with strong environmental and social impacts. The industry is a great consumer of both renewable and non-renewable natural resources and at the same time an active generator of pollutants and waste (Ding 2008). Hence, the industry is inevitably concerned about devising means to mitigate these impacts through the ideals of sustainable construction.

In one of the Institution of Civil Engineers (ICE) priority actions towards green economy, engineers have been called to engage in projects at the inception stage and contribute to the task of balancing Capital and Operational Carbon to minimise whole life emissions (ICE 2011). It is envisaged that as buildings become more energy efficient, in-use impacts reduce and embodied impacts become significant part of the total (Kaethner and Burridge 2012). Thus, greenhouse gas (GHG) emission reduction strategies and other building performance optimization techniques such as life cycle costing, energy profiling and lean construction all constitute efforts towards sustainability. These efforts are increasingly becoming IT-based. Also, contemporary IT systems present more effective and efficient performance tendencies as they constitute products of cumulative improvements in research. Selecting best strategic option before detailed design and construction begins can lead to greatest resources savings in infrastructure project. As laid out in ICE Priority 4, it is therefore crucial to develop a high level evaluation methodology for use at appraisal stage of projects to aid investment decisions (ICE 2011). These premises constitute key motivations for this research work.

A FRAMEWORK FOR SUSTAINABILITY APPRAISAL

The sustainability appraisal framework for this research is presented in Figure 1. It illustrates the relationship between the components of the framework based on Integration DEFinition Language 0 (IDEF0) notations. Starting from the top of the figure is the demarcation for the three major modelling components in the conceptual framework. First, there needs to be a building information model (conceptual model) in a design/modelling environment, secondly information or features need to be extracted (feature extraction) from the building model, and thirdly extracted information has to be synthesized (feature modelling) to obtain desired results. Next from the top is the control. The sustainability indicators constitute the control of the system which uses features extracted from the conceptual model as input into the system. The modelling database contains information that works as Mechanism based on the functional instantiations. The output of the system gives scores of design options obtained from multi-criteria decision analysis. The proposed sustainability modeling framework reflects the economic and environmental aspects of the sustainability of steel-framed buildings. It uses LCC techniques to account for the economic sustainability and a combination of carbon footprint and ecological footprint measures to account for environmental sustainability.

Two groups of requirement, sustainability modelling and software implementation, were used to guide the framework implementation in is research. The sustainability modelling requirements based on life cycle criteria include definition of the system boundaries, accounting for the energy and mass flows in the system, establishing the building functional unit and making consideration for the time various components remain useful in the building before the need for replacement. The implementation requirement are generality, formality, flexibility and ease-of-use. These high level requirements have been discussed in Oti and Tizani (2012).

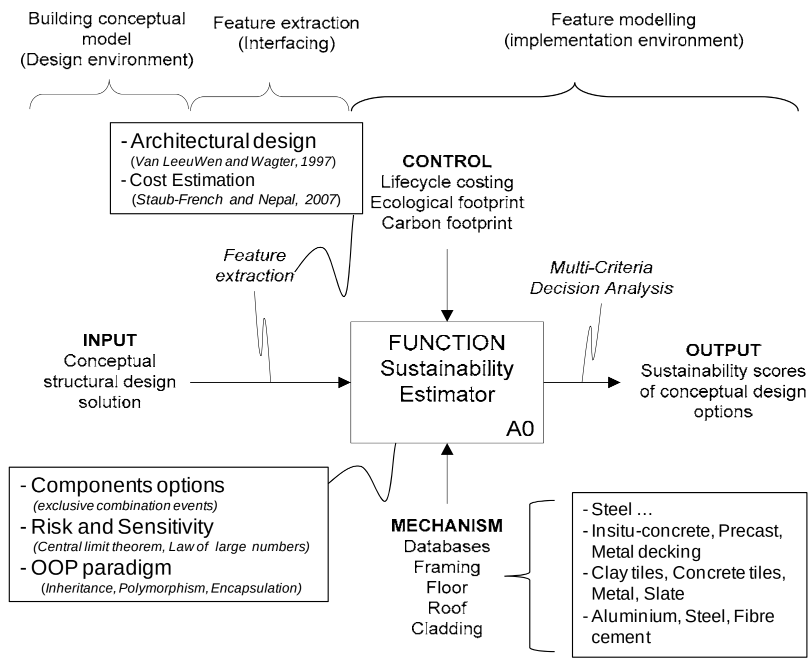

Figure 1. Structure of sustainability appraisal framework.

Figure 2 gives the top level sustainability estimation algorithm employed in this research. The algorithm commences with a call to the structural sustainability estimation (SSE) programme. This can be done in a building information modeling environment such as the user interface of Revit Structures while carrying out conceptual design and modelling of a building. The next requirement in the sequence of events is to provide requisite identification for the project by registering project information and assigning design option IDs. The sequence of events then flows through a decision making process on three alternatives (Manual entry of building elements, Assess building from Industry Foundation Classes (IFC) model or Assess building from native BIM format) to extract building features for onward sustainability assessment. Once this decision is made and the relevant features are extracted, the sequence of assessment steps through the estimation of Initial Cost, Life Cycle Cost, Carbon Footprint, and Ecological Footprint. The designer could also explore performance combinations of materials in what-if scenario situations. After saving the estimated measures of the indicators, the process can be repeated for more design options and eventually compared on multi-criteria basis of the three sustainability indicators. The comparison identifies the most favourable design based on the relative performance of the design options. The last event in the sequence is to produce necessary reports from the assessment.

IMPLEMENTATION OF THE STRUCTURAL SUSTAINABILITY PROTOTYPE

This work targets the structural engineer as the designer. The system functionality is directed at the structural engineer becoming informed on the appraisal of the sustainability of alternative design solutions. The elicitation of a use-case guided the implementation of programming work in this research as discussed in Oti and Tizani (2012) . It entails the structural engineer registering his project information and design details, and feeding in required information related to cost components, impact of elements and time. The economic and environmental appraisal could then be carried through appropriate indexing and weighting strategy from generated results on the corresponding indicators.

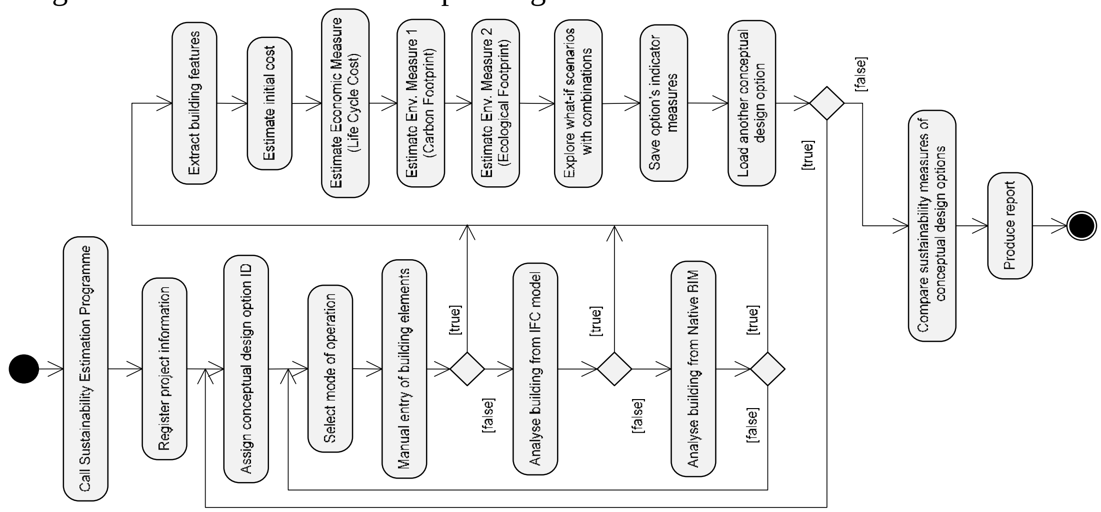

Figure 2. Sustainability appraisal implementation algorithm.

The goal of this work is to establish information modeling representations that capture data and process needs of the designer in considering sustainability issues at the early design stage. The implementation is based on significant amount of data that was collected from existing life cycle process inventories and cost databases associated with construction methods and materials. The management of this data was implemented in Microsoft SQL within the integrated C# object-oriented environment of Visual Studio .NET Framework. Figure 3 shows the class diagram of the main components of the implementation carried out in the programming environment. It constitutes the feature extraction part and the modelling aspects. The Command Class, assisted by the GeomHelper and GeomUtil, combines with the OperationMode Class to extract information from building models. Extracted information are passed unto the sustainabilityEstimator Class to perform the sustainability estimation of solutions. The sustainabilityEstimator communicates with the modelling database to draw up corresponding information on cost and lifecycle information to carry out typical sustainability analysis. The prototype has been interfaced with Revit Structures 2011 to run as an add-in tool. This has been achieved through requisite instantiations using Autodesk Revit API software development kit. The programme can be called by the designer during a building's structural modelling activity through the external link embedded in the Revit Structures.

ILLUSTRATIONS USING THE PROTOTYPE

The prototype is called from Revit Structures modelling environment through the link for external tools housed in the Add-Ins Tab. The prototype can be operated in three modes, Manual, Automatic or IFC options. In the Manual Mode which is rather cumbersome, the designer manually supplies information about each member of a structure one after the other. For the automatic and IFC modes, information about relevant structural elements (columns, beams, floor and roof) are automatically extracted from digital building model or file for onward sustainability analysis. The current capabilities of the prototype include identification of optimal design solution using multi-criteria decision analysis, performance of risk analysis and the sensitivity of structural elements. The prototype can handle rectangular-shaped buildings of varying sizes and number of floors. It can also be used to compare the sustainability of varying number of design solutions of steel framed buildings.

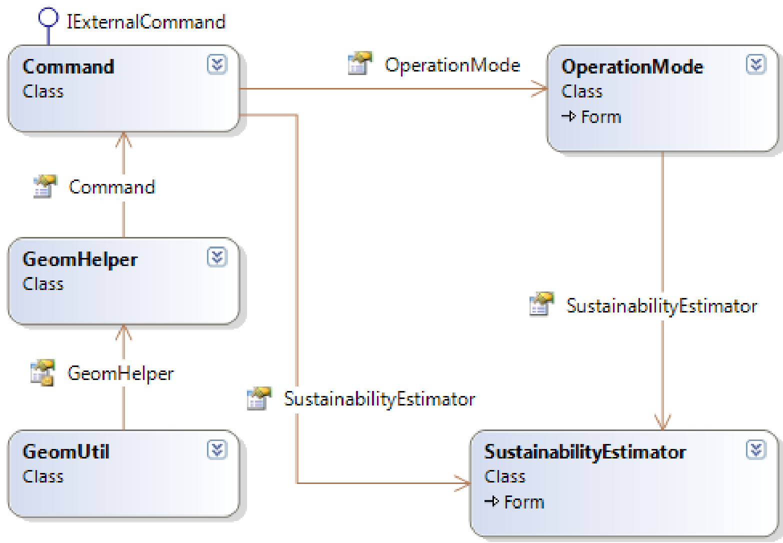

Figure 3. Static structure of prototype main implementation components.

The presentation interface of the prototype takes the familiar Windows environment characteristics as shown in Figure 4. In this illustration, (a) shows the three conceptual design structural framing options of an office buildings. For operation in the Automatic Mode, the SSE programme can be called when one of these models are selected. The Operation Mode Form (b) shows up to receive the project information which in-turn calls-up and configure the second part (SustainabilityEstimation Form) of the SSE for further operation. The designer then progresses through eight tab pages to finalizes the estimation process. He/she is required to provide information related to maintenance, life cycle boundary, discount rate and decommissioning option. In the Indicator Estimation page, the designer is able to explore what-if scenarios for different combinations of building components and also perform risk and sensitivity analysis of these components as shown in (c). The multi-criteria analysis result of the comparison of the sustainability measures of the various design option is presented pictorially in a column chart (d), depicting the relative desirability scores of the options. Results from the analysis can be saved up, exported to Word, PDF or Excel file (d).

CONCLUSION

Sustainability requirements in construction have warranted the need for structural engineers to become better informed on the relative sustainability of alternatives design solutions. BIM presents opportunities for integrating the modelling of sustainability performance into the early stages of building design. This paper presented a system to depict the sustainability of the structural engineer’s conceptual design of steel-framed building. The work established processes for extracting relevant structural information from buildings in BIM formats. It employed modelling representations that captured data and process needs of the designer in considering sustainability issues at the early design stage.

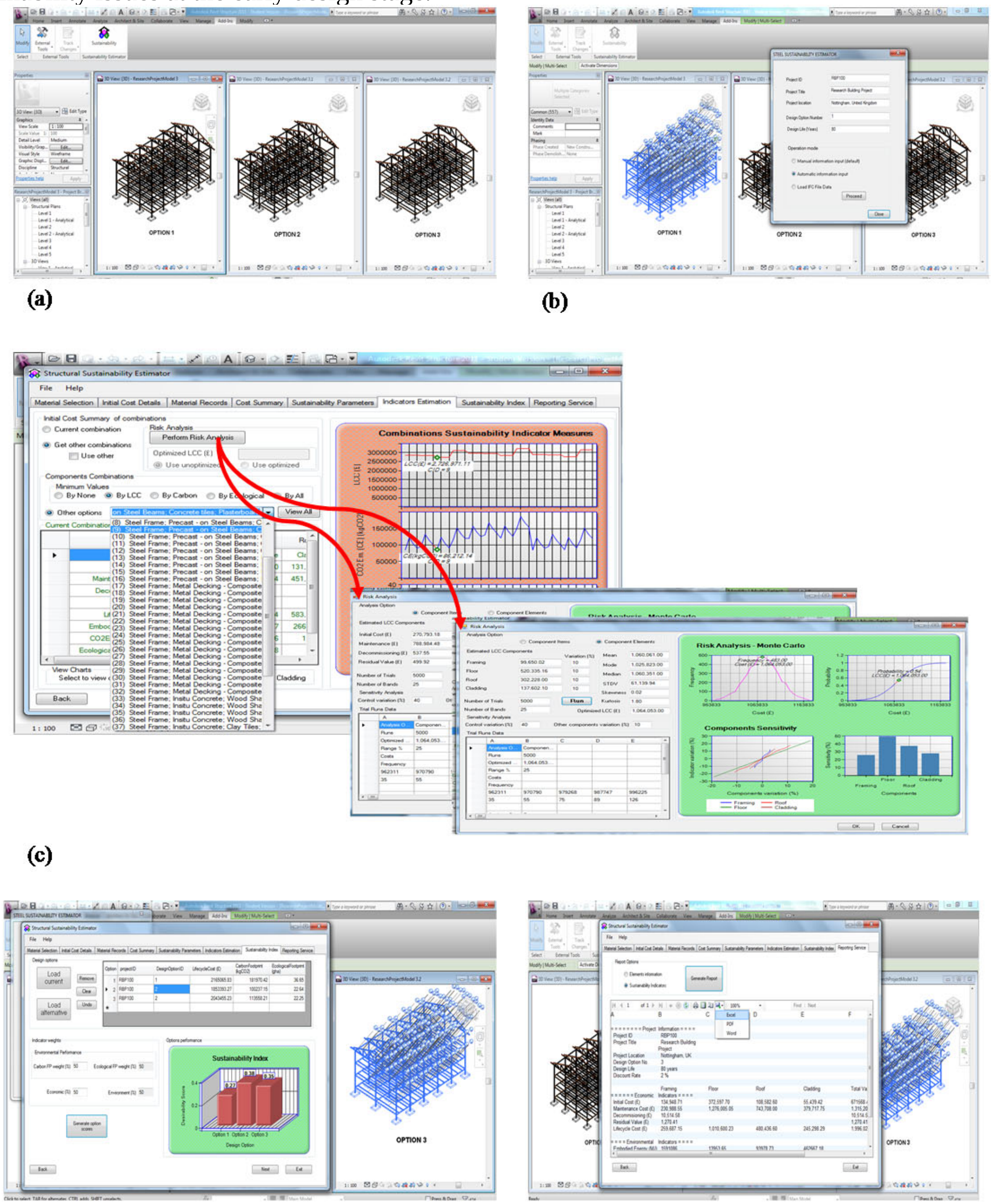

Figure 4. Outputs of the prototype ((a) Options of structural solutions, (b) Operation Mode, (c) Risk analysis and Component's Sensitivity, (d) Options performance scores (e) System reporting).

This paper concludes that the utilized information modelling representations can be used to capture n-dimensional performance requirements related information such as sustainability to inform decisions at the early stages of the design process. Thus, with adequate maturity of this demonstrated concept, structural engineers will become better informed on the sustainability of their alternative design solutions. This will not only promote sustainability awareness among structural engineers but will also be able to contribute to the larger efforts of managing resources efficiently for the present and future generations.

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