A SUSTAINABILITY EXTENSION OF BUILDING INFORMATION MODELLING FOR CONCEPTUAL STEEL DESIGN

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ABSTRACT

Capturing the building product in a single information model with high interoperable capabilities has been the subject of much research efforts in at least the last three decades. Contemporary advancements in Information Technology and the efforts from various research initiatives in the AEC industry are beginning to show evidence of progress with the emergence of building information modelling (BIM). BIM presents the opportunity of electronically modelling and managing the vast amount of information imbedded in a building project, from its conception to end-of-life. Researchers have been looking at extensions to expand its scope. Sustainability is one such modelling extension that is in need of development. This is becoming pertinent for the structural engineer as recent design criteria have put great emphasis on the sustainability credentials in addition to the traditional criteria of structural integrity, constructability and cost. With the complexity of designs, there are now needs to provide decision support tools to aid in the assessment of the sustainability credentials of design solutions. Such tools would be most beneficial at the conceptual design stage so that sustainability is built into the design solution starting from its inception. The sustainability of buildings is related to life cycle and is measured using indicator-terms such as life cycle costing, ecological footprint and carbon footprint. This paper proposes a modelling framework combining these three indicators in providing sustainability assessments of alternative design solutions. It employs the principles of feature-based modelling to extract construction-specific information from product models for the purposes of sustainability analysis. A prototype system is implemented using .NET and linked to the BIM enabled software, Revit Structures™. The system appraises alternative design solutions using multi-criteria performance analysis.

Keywords: sustainability, BIM extension, conceptual design, feature-based modelling

1. INTRODUCTION

Among the lifecycle stages of the building product, the design stage presents the best opportunity to influence costs and impacts (Ding, 2008; Kohler and Moffatt, 2003). This makes targeting the design stage for incorporating building performance issues such as sustainability important. The situation therefore creates demand on the development of decisions support tools to guide designers early in the design stage when changes can easily be accommodated with very minimal consequences. The result is that such systems transmit as additional challenges to the already existing goal of capturing the building product in a single information model with high interoperable capabilities. These challenges still exist with the newly emerging BIM, although with improved opportunities for expansion and extension to capture vast amount of information related to various AEC domains. In the structural engineering domain, decision support tools for guiding engineers in their early design iterations based on sustainability measures have not been sufficiently explored. This paper presents a modeling framework aimed at incorporating sustainability to inform the conceptual design process of steel-framed buildings using principles of feature-based modeling. It proposes using the life cycle approach to explore cost, carbon and ecological footprint accounts in buildings. The paper highlights the need for domain-specific sustainability analysis in the discussion of BIM extensions in Section 2; examines the developments towards design specific sustainability modeling in Section 4. An overview of the selected sustainability indicators is given in Section 5 before presenting the framework used in the implementation of a prototype in Section 6; followed by the summary of the paper.

2. BIM EXTENSIONS

BIM is becoming a popular term in the AEC Industry because of the international campaign for its adoption in project execution. It is said to represent the next generation of IT which 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 the vast amount of information imbedded in typical building project. Thus, the possibility of expanding the BIM scope has already been demonstrated by researchers in various plausible extensions. An example is the multi-dimensional computer model (3D to nD modeling project) developed by researchers at Salford University, United Kingdom. The project aims to facilitate the integration of time, cost, accessibility, sustainability, maintainability, acoustics, crime and thermal requirement into the modeling of building information (Lee et al., 2006). Modeling 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 (Hu et al., 2010; Zhang and Hu, 2011). Disaster preparedness aspect in the building operation phase is geared towards improving training games by modeling hot dynamic conditions and the building behaviour over time in the event of fire (Ruppel et al., 2010; 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 well emphasized (Kohler and Moffatt, 2003). One area of challenge has been the development of sustainability appraisal 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 on conceptual design iterations via the emerging BIM process. The Building Research Establishment Environmental Assessment Method (BREEAM), used in the UK, is yet to be incorporated into BIM. It is currently being used to guide project development and to rank already completed buildings. 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 has 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 (Oti and Tizani, 2011).

3. TOWARDS THE MODELLING OF DESIGN-SPECIFIC SUSTAINABILITY INFORMATION

The fragmented nature of the AEC industry is linked to the complex and unique nature of the building product which requires the participation of individual/groups from distinct professional platforms. These professional platforms, however, are not independent as their specifications and designs must accommodate, interact and relate with one another throughout the building's lifecycle. The drive for effectiveness and efficiency in managing the inter-dependence among the platform has given rise to principles such as concurrent engineering, collaborative engineering, distributive collaboration etc in the AEC industry. In all these, IT plays the key role of being the kernel for modeling, storing, exchanging information/data within and across platforms. The role of international standards, open formats and product models such as IFC, gbXML, etc in enhancing the management of information in the industry cannot be over-emphasized. In overcoming the associated shortcomings with AEC information management, researchers, have had the vision of capturing all the information imbedded in the building product in a single information model. Even with the evolution of BIM, embodying parametric objects governed by rules of geometry, attributes and relations; this vision is yet to be fully realized. The inclusion and accessibility of other design information such as cost estimation, selection of construction methods, construction scheduling, productivity analysis and project management associated with various construction practitioners still need tackling (Zhang et al., 2011).

In the effort to improve the usability of BIM with respect to extracting and querying construction-specific information, Nepal (2011) employed the feature-based modeling (see Figure 1) approach to develop feature ontology to aid recognition of building features. A feature is an information unit or element representing a region of interest within a product (Brunetti and Golob, 2000). Feature-based modeling (FBM) has its root in mechanical engineering for integrating CAD and CAM systems (Shah and Rogers, 1988; Motavalli et al., 1997; van Leeuwen and de Vries, 2000). Two key requirements of FBM systems are extensibility and flexibility which typically characterize the dynamic nature of design (Van Leeuwen and Wagter, 1997). Previous works (van Leeuwen et al., 1996; Van Leeuwen and Wagter, 1997) on applying FBM in AEC has given an industry-adapted (architecture) definition of features as "*a collection of high-level information defining a set of characteristics or concepts with a semantic meaning to a particular view in the life-cycle of a building*". This provides a take-off point for modeling buildings structural-specific sustainability information that can inform the conceptual design process. Brunetti and Golob (2000) recognized the

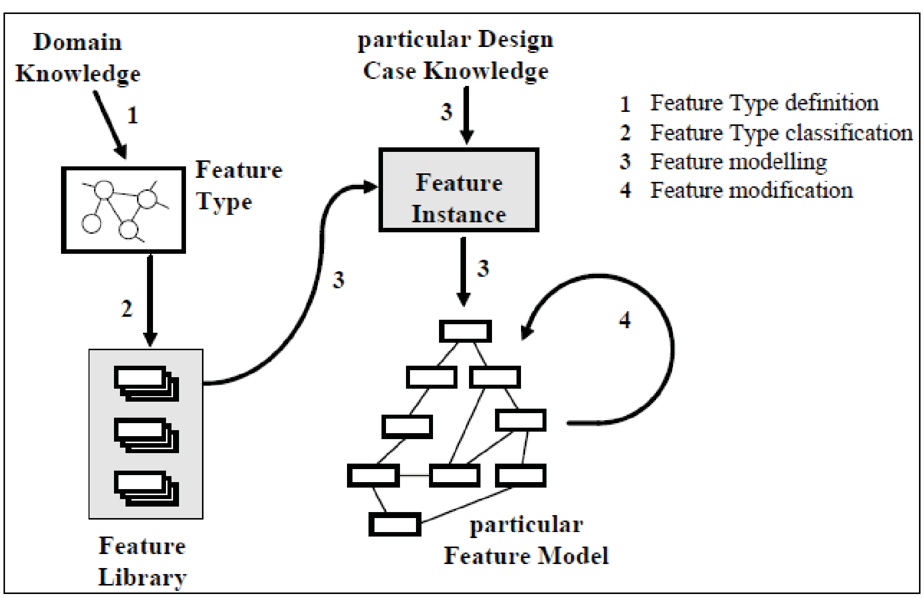

Figure 1: Activities in feature based modelling (van Leeuwen et al., 1996)

highly complex informal data characterising conceptual design and have proposed using FBM principle in incorporating the representation of conceptual design information into the development process of an integrated product model. However, it is yet to be applied to sustainability information modeling to the benefit of the structural engineer's conceptual design iteration.

4. FBM FOR SUSTAINABILITY MODELLING IN CONCEPTUAL STRUCTURAL DESIGN

Three approaches have been identified in FBM; design-by-features, feature recognition and a hybrid of both (van Leeuwen et al., 1996). Design-by-feature develops designs from high level features generated from primitives and/or user-define features embodying design intents largely based on geometry. In the feature recognition approach, as the name implies, features are extracted from already designed artefacts based on recognition (data interpretation and analysis by computer algorithms or user) to build up a feature model. Feature recognition is proposed in this research to extract relevant structural domain information from a product model (BIM) for the purpose of performing sustainability analysis. The representations of the four key activities (Figure 1) applied in this research are presented in the subsections.

4.1 Feature Type definition

Feature type may be generic or specific. It is generic when it forms the building's core model and is among the formalized common concepts in the AEC industry; and on the other hand specific, if it is not part of the AEC common domain (Van Leeuwen and Wagter, 1997). Since a prototype implementation is intended in the research, the features selected are largely of the generic type. They include column, beam, floor, roof and cladding systems. These features could also be termed as "component features" (Staub-French et al., 2003; Staub-French and Nepal, 2007).

4.2 Feature Libraries

Feature types are classified into sections contained in the Feature Library which is a function of a particular domain area in the AEC industry. The Feature library in this research is implemented through MS SQL DBMS within the .NET Frameworks and contains various instances of the feature type mentioned in the previous section. Figure 2 shows the UML schema diagram of the Feature Library with respect to column Feature Type. Column is a feature type that belongs to a section within the AllSectionData, UC254x254x73 is a type of column representing one of the examples of a feature instance and has material properties, cost, boundary conditions (end connection) etc.

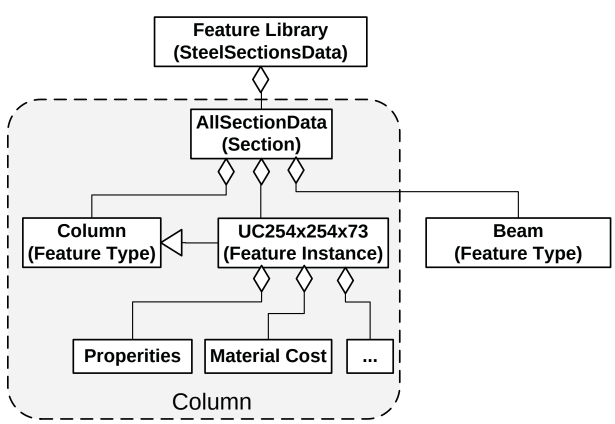

Figure 2: Column mappings in the Feature database

4.3 Feature modelling

This refers to the instantiation of a selected feature type that suits the type of information to be modelled (van Leeuwen et al., 1996; Van Leeuwen and Wagter, 1997). This aspect is executed in the C# object oriented environment through interfacing with BIM enabled tool such as Revit Structure™. It entails recognizing and extracting the considered feature types from a particular design model (drawing) compare and abstract relevant information from the feature library for appropriate collation and onward sustainability analysis. This aspect is further discussed in Section 6.

4.4 Feature modification

The modification of features that could take place during the operation of the prototype is largely related to the issues concerning the chosen sustainability indicators (discussed in Section 5). However, the intention for feature modification include the possibility of altering the values of various attributes of features, deleting or introducing new relationships between features which trigger features to respond in some particular manner (Van Leeuwen and Wagter, 1997). Some of the modifications associated with feature modeling process used in the structural sustainability modeling include: altering of cladding area; specification of discount rates and estimated maintenance costs; indication of associated lifecycle boundaries for the sustainability analysis etc

5. SELECTION OF INDICATORS FOR SUSTAINABILITY

Researchers have pointed out the need to develop sustainability indicators that could be applied worldwide (Ortiz et al., 2009). It is essential for such indicators to mimic the essence of the sustainable development concept of economic, environmental and the social pillars (Singh et al., 2007). However, the methodologies to accounting for the social aspect of sustainability are not fully developed (Kloepffer 2008) and does not significantly influence the structural conceptual design process of steel-framed buildings. Thus, the overall social benefits of projects would have been clearly defined from the onset and have minimal effect on structural design decisions. The proposed modelling extension framework therefore reflects the economic and environmental aspects of sustainability of steel framed buildings. LCC technique is used to account for the economic sustainability and a combination of carbon footprint and ecological footprint indicators to account for environmental sustainability. The theories and background surrounding these indicators have been discussed in Oti and Tizani (2011); as such a brief account is given here.

The life cycle cost of a structure is the sum of all the cost incurred in its life time. This includes initial costs (design and construction); operation (utilities) cost; periodic maintenance (including repair); and eventual dismantling or demolition. Sarma and Adeli (2002) summed it up in Equation 1 where the life cycle cost ($C_{Lifecycle}$) is given as Single Present Worth. It discounts future costs and inflation based on the discounting factor ($\frac{1}{(1+i)^{y_n}}$). Where, i is the discount rate and y_n stands for the time in period of years associated with the different cost components 1 (Maintenance) to 6 (Dismantling).

$$C_{Lifecycle} = C_{Initial} + \sum \frac{1}{(1+i)^{y_{n1}}} C_{Maintenance} + \sum \frac{1}{(1+i)^{y_{n2}}} C_{Inspection} + \sum \frac{1}{(1+i)^{y_{n3}}} C_{Repair} + \sum \frac{1}{(1+i)^{y_{n4}}} C_{Operating} + \sum \frac{1}{(1+i)^{y_{n5}}} C_{Failure} + \sum \frac{1}{(1+i)^{y_{n6}}} C_{Dismantling} \quad (1)$$

On the aspect of the environment, no single indicator is sufficient to comprehensively monitor and account for the totality of associated human impact (Best et al., 2008). Indicators need to be combined to capture different aspects and interpreted jointly depending on defined goals. As such carbon footprint and ecological footprint, which are complementary, provide information on the impact placed on the atmosphere and on the biosphere respectively (Alessandro et al., 2010). Carbon footprint can be defined as a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann and Minx, 2007). This implies a lifecycle methodology which exclusively discourages events of under-counting or double-counting emissions. On the other hand, Wackernagel et al, (Wackernagel et al., 2004) expressed that ecological footprint measures how much life-supporting natural capital, expressed in biologically productive area, is necessary to meet the resource demand and waste absorption requirements of a given population with links to demographic trends, economic expansions, changes in resource efficiency and economic prosperity. Based on human settlements and infrastructure, ecological footprint (EF) assumes that artefacts occupy agriculturally fertile lands hence the productivity of cropland is used as the basis for expressing the ecological footprint in global hectares (gha) of built-up area (A) as given in Equation 2. The equivalence factor (EqF) and yield factor (YF) are, respectively, the crop yield attainable in an area with an assumed level of input (water or fertilizer) and the relative productivity of a given country with the global average of the same bioproductive area.

$$EF_{buit-up}\ (gha) = A_{built-up}(ha)\ \times\ EqF_{built-up}\ (gha/ha)\ \times YF \qquad (2)$$

6. IMPLEMENTATION OF THE SUSTAINABILITY MODELLING PROTOYPE

This section presents the sustainability modelling framework and its implementation. It briefly discusses the components of the framework and how the various constituent objects relate in the operation of the model. An insight into the proposed implementation modalities for selecting the best design solution is also given.

6.1 Modeling framework

From FBM perspective, the framework (Figure 3) consists of the conceptual model, the feature extraction activity and the feature modeling aspect. The conceptual model is essentially a building product model (drawing) in a BIM enable tool which is capable of allowing the extraction of feature components for sustainability analysis built into the feature modeling process. 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. The framework is being implemented in a prototype system which is dependent on significant amount of data and knowledge base. This encompasses methods for construction and fabrication of steel materials, associated costs, life cycle information; combined with the application methodologies of the selected sustainability indicators. The research uses the object oriented programming (OOP) in C# application within the .NET Framework environment to develop a sustainability computer-integrated model. The outputs of the prototype will be fine-tuned by sensitivity analysis to increase the reliability of the probabilities in the estimations of sustainability indicators.

6.2 Framework implementation

The prototype implementation which is currently targeted at steel structures is in two parts and employs the feature modeling approach. The first aspect involves investigating how contemporary process modeling techniques could be used to implement a sustainability model in the .NET environment using C#. The second entails integrating the sustainability model to conceptual building design iterations in the building information modeling process. This second aspect is developed based on the processes associated with feature extraction activity.

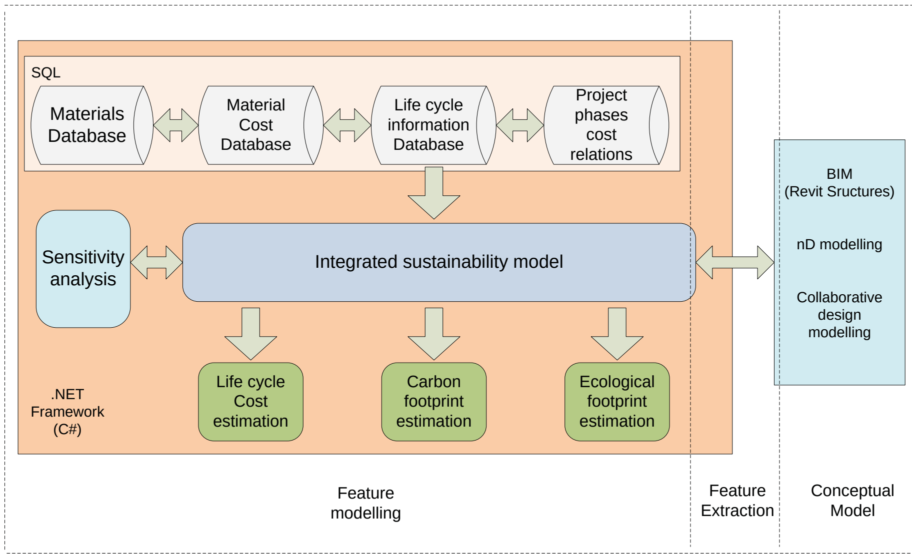

Figure 3: Proposed sustainability modelling framework

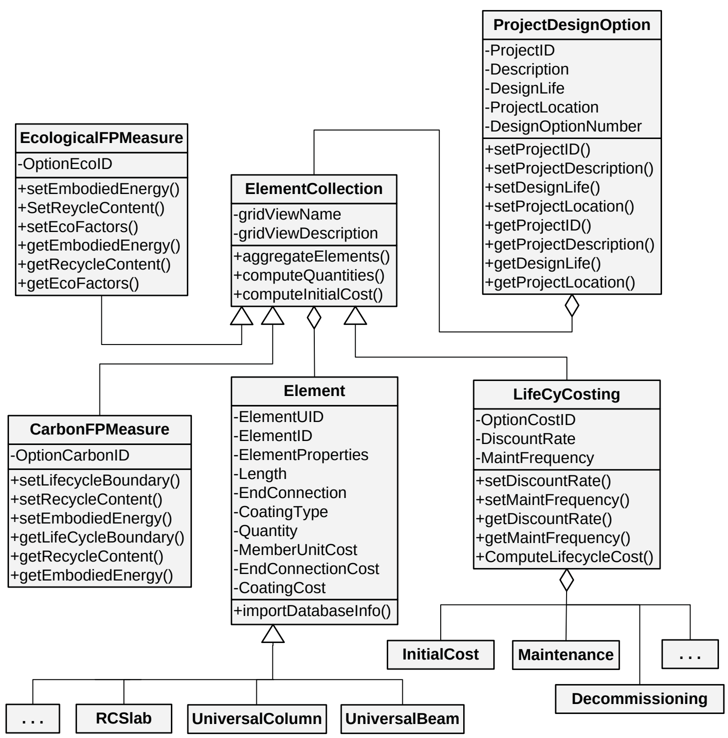

Figure 4: Implementation class diagram for the structural sustainability framework

The elicitation of a use-case has been used to guide the programming direction. It entails the structural engineer registering his project information and design details, and feeds 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. At this stage, the onus rests on the engineer on how to combine the indicators to make a judgement vis-à-vis other factors such as prestige, future potential changes and project longevity (Bull 1993). The class diagram that ensued from the process is depicted in Figure 4. It currently consists of ProjectDesignOption, ElementCollection, Element classes; and the sustainability indicator classes: LifeCycleCosting, EcologicalFPMeasure and CarbonFPMeasure. The Element Class obtains its members when the user triggers feature extraction activity. Thus, structural feature types are recognized from the product model and interaction with the feature library (database) is instantiated to get appropriate data needed for estimating associated sustainability measures. The ElementCollection gathers this information for the sustainability indicator classes to synthesize and obtain the appropriate measures.

In implementing the aspect relating to the selection of the best option among design alternatives, Multiple Attribute Decision Making (MADM) is employed in developing the sustainability score of the various design solutions. This is a more suitable option of multi-criteria decision analysis since the number of conceptual design options to be compared will be finite (Yeo et al., 2004) with their respective attributes obtained from running the prototype. The method also allows for the comparison of attributes with different units of measurement by the use of weighting factors. Thus the desirability score for each option is given by Equation 3 (Norris and Marshall, 1995). It gives the summation of the contribution of each attribute with respect to the cardinal numerical score for each alternative conceptual design solution.

$$D_j = \sum_{i=1}^{n} w_i \; x_{ij} \qquad (3)$$

Where, D_j = Desirability score for a particular alternative
n = Number of attributes associated with the options
w_i = Weight (normalised) of attribute or criteria
x_{ij} = Score of the alternative on the particular criteria

Figure 5 shows a snapshot of a typical output case from a routine testing of the prototype. The user is required to load alternative design solutions into the prototype and specify the relative weights for the sustainability indicators before generating the performance scores of the solutions. The most favourable option will be the solution with the highest desirability score.

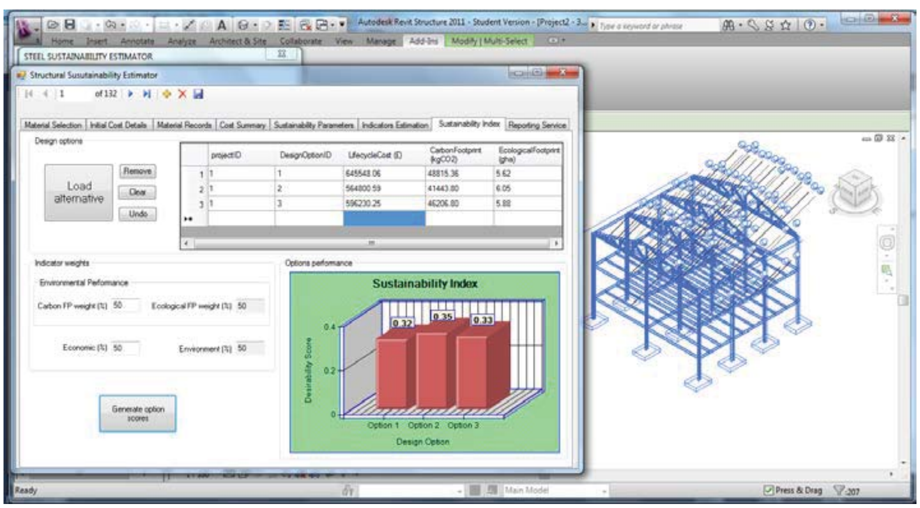

Figure 5: Snapshot of prototype output showing design option scores

7. SUMMARY

This paper discussed an integrated framework, based on feature modeling technique to depict the sustainability of the structural engineer's conceptual design of steel-framed building. The framework combines three key sustainability indicators, life cycle costing, carbon footprint and ecological footprint measures, for the assessment of sustainability. LCC accounts for economic sustainability while carbon footprint and ecological footprint give a measure of the impact on the atmosphere and biosphere, respectively, of the environment. The basic programming representations of the implementation of the computer-integrated sustainability framework in the form of a prototype system have also been presented. The goal of this investigation is to establish an information model that captures data and process needs of the designer in considering sustainability issues at the early design stage. The implementation of the prototype tool is in progress and it is based on significant amount of data collected from existing life cycle process inventories and cost databases associated with construction methods and materials. The management of these data has been implemented in Microsoft SQL within the integrated C# object-oriented environment of Visual Studio .NET Framework. Currently, the core aspect of the prototype which targets structural steel framing system is near completion. Further work is directed at optimizing the MADM of choosing desired project design option and applying it on a case study. This will help to assess the prototype implementation on the performance of the framework in informing designers on sustainability and if associated decision making process in the conceptual design of steel-framed buildings have been improved.

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