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INTEGRATING DECISION SUPPORT SYSTEM (DSS) AND BUILDING INFORMATION MODELING (BIM) TO OPTIMIZE THE SELECTION OF SUSTAINABLE BUILDING COMPONENTS

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SUMMARY: *One of the challenges in sustainability analysis and its development is the optimum selection of sustainable materials to meet the project's requirements while doing sustainable design. This can only be achieved when project team adopt the use of a strategic approach while selecting the materials, although this could be a complex task for decision makers. Building Information Modeling (BIM) offers designers the ability to assess different design alternatives at the conceptual stage of a project. As a method of integration and through its modeling techniques, BIM can be used to assess the impacts of design alternatives on the energy saving of buildings all over their life. Furthermore, BIM has the potential to help designers select the right type of materials during the early design stage, and make vital decisions when selecting the materials that have sustainable impact on the building's life cycle.*

The main purpose of this study is to propose a methodology that integrates BIM with decision-making problem-solving approaches (i.e. Entropy-TOPSIS) in order to efficiently optimize the selection of sustainable building components at the conceptual design stage of building projects. Therefore, a Decision Support System (DSS) is developed by using Multiple Criteria Decision Making (MCDM) techniques to aid the design team decide on and select the optimum type of sustainable building components and design families while doing conceptual design of proposed projects, based on three main criteria (i.e. environmental factors, economic factors—"cost efficiency," and social well-being) in an attempt to identify the influence of design variations on the whole building's sustainable performance.

The multi-criteria procedure embedded in the DSS relies on numerical models to simulate alternative situations, as well as ranking the alternatives and select the best ones based on both the owners' strategic preferences and the availability of sustainable materials in the market. The set of models included in the DSS describes the relationship between sustainability criteria, manufacturers' sustainable materials and the interactions between project team that take place during the design of sustainable building projects. This paper aims at exposing the feasibility of using BIM for analysing the life cycle costs of sustainable buildings at the conceptual stage. The design alternatives suggested by the DSS are evaluated in an integrated environment that joins BIM concept and Life Cycle Cost (LCC) method to analyze the operational cost of the whole building. An actual building project is used to validate the workability and capability of the proposed methodology.

KEYWORDS: *BIM, Decision Support System (DSS), Life Cycle Cost (LCC), Sustainable Design, Green Building*

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1. INTRODUCTION

The variety of project boundaries, decision-maker preferences, and the availability of sustainable materials make the decision-making process more difficult in terms of sustainable development purposes when designing sustainable buildings. While, owners want to use sustainable products in their proposed building projects, a decision on the ideal ones can be questioned especially when suppliers offer diverse types of green materials.

A typical manufactured product, in the building industry, consists of various components where each of its elements may consist of several materials. In many cases, products' elements, which are furnished by a chain of suppliers, are processed, assembled and finally released to customers (Aumonier, 2013).

The Multiple Criteria Decision Making (MCDM) approach is a well-known branch of the decision-making process. It deals with decision problems under the presence of a number of decision criteria, where a decision-maker needs to choose from either the quantifiable or the non-quantifiable or the multiple criteria. Usually, sustainability objectives are conflicting due to their dependency on each other and therefore, the solution is highly dependent on the decision maker's preferences, which is mostly a compromise. Generally, two different methods are used to solve the MCDM problems, those are: the Multiple Objective Decision Making (MODM) method and the Multiple Attribute Decision Making (MADM) method. MODM deals with many objectives in order to come up with an optimal solution to achieve the set objectives, which sometimes conflict one with another and accordingly makes the goal to attain an ideal solution more challenging and problematic. Whereas in the MADM method the decision maker transacts with alternatives that have variety of performance attributes and factors, which can be either qualitative or quantitative (Shanian and Savadogo, 2006). The MADM method is generally a discrete method, with limited numbers of pre-determined alternatives. It specifies how to process the attribute's information in order to reach an ideal choice. Rao (2007) thinks that this method needs both inter-attributes and intra-attributes comparisons and should involve appropriate explicit trade-offs. To model these attributes, most of the MADM methods are presented through a decision matrix. This matrix consists of: 1) alternatives; 2) criteria; and 3) relative significance of criteria. In this matrix, all the components should be normalized to a comparable scale.

Generally, there are various MADM techniques (i.e., crisp; fuzzy approaches) to use during the decision making process, however in this proposed study, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is used for ranking the alternatives. TOPSIS is one of the objective weighting methods in MCDM; it is a method of compensatory aggregation that compares a set of alternatives by identifying weights and normalizing scores for each criterion and calculating the geometric distance between each alternative and the ideal one, which is considered as the best score for each criterion.

In recent years, with the advancement of technology, applying MCDM methods has become considerably simpler for decision makers and users who are involved in complicated mathematical problems and multiple alternatives. Thus, Decision Support Systems (DSS) are generated to assist in the problem-solving process by combining quantitative data and qualitative knowledge/perceptions; processing information in order to present, compare, and rank potential alternatives; and, ultimately, selecting the one that meets the established decision criteria (Lu et al., 2007). Besides considering the decision-maker (DM) priorities and preferences, the development of a Decision Support System (DSS) can also help DM in financial/non-financial constraints and objectives (Lu et al., 2007). DSS can improve decision makers' efficiency, productivity and effectiveness. It can also facilitate the communication between different parties in an organization and contribute to a quick problem solving.

Building Information Modeling (BIM) is a recent method of approaching the design and documentation of building projects by considering their entire life cycle, including all information related to designing, simulating and operating them through the use of different integrated tools.

Life Cycle Costing (LCC) method is used to estimate the overall costs of a project and to select the design that would provide the lowest overall cost of ownership without sacrificing its quality and function. The LCC evaluation and analysis should be performed early during the design process while there is still a chance to refine the design to ensure a reduction in the running costs later on during the operation stage of the project (WBDG, 2010).

The essential objective of life-cycle costing is to evaluate the possible economics of different alternatives. However, there are other important cost factors beside the initial capital cost that have a significant contribution to the overall cost throughout the life cycle of a project. Some of these factors are operating, maintenance, and repair costs beside the thermal insulation properties and methods that influence the running costs of the project.

While, maintenance and repair costs can be provided by the owners, obtained from a published database, or obtained from the manufacturers (Haviland, 1978), energy efficiency studies should be performed by designers to forecast the operating costs. It is commonly known that Life Cycle Cost is the sum costs of owning, running (maintaining and operating), and demolishing a facility over an assigned period of time, therefore, the LCC equation includes four variables: 1) The relevant costs of ownership: initial cost, running cost, and replacement cost; 2) The future income, such as annual income from renting/leasing the facility and/or its salvage value at the end of the study period; 3) The period of time over which these costs are incurred; and 4) The discount rate (inflation or deflation rate) that should be used to adjust the future costs in order to compare them with the current ones (Alshamrani, 2013).

Lowest life-cycle cost (Lowest LCC) method is the most easily-interpreted measure of economic evaluation in construction projects. Some other methods of economic measurements used are Net Savings (or Net Benefits), Savings-to-Investment Ratio (Benefit-to-Cost Ratio), Internal Rate of Return, and Payback Period. These are consistent with the Lowest LCC measure of evaluation method if they use the same parameters and length of the study period (WBDG, 2010).

Operational expenses for energy, water, and other utilities are based on consumption, current rates, and price projections. Since energy and water consumption, and building configuration and envelope are interdependent, operational costs are usually evaluated for the building as a whole rather than for any individual building components. Energy costs are often difficult to be accurately predicted during the conceptual stage of a project's life, therefore assumptions must be made about the historical energy usage, occupancy rates, and weather data that impact the energy consumption. At the conceptual stage, data related to the amount of energy consumed by a building can be retrieved from an engineering energy analysis or from some specific computer applications such as eQuest©, Green Building Studio© (GBS) while other applications like ENERGY PLUS (DOE), DOE-2.1E and BLAST cannot be used at that stage because they require more detailed information and data input that usually is not available until later stage in the design process (WBDG, 2010).

This study reviews the different decision-making methods and their applications in selecting sustainable materials. Furthermore, it describes the methodology used to integrate Building Information Modeling concept and Decision Making technique through the development of a model that incorporates a decision support system (DSS), which systematically incorporates the selection of sustainable components and material into a BIM environment. The DSS is based on Building Information Modeling (BIM) principles, and associated with environmental and socio-economic indicators for sustainable development. In particular, the DSS evaluates green building materials provided by different suppliers and suggests the best ones that fit the sustainable design requirements. Furthermore, the model is integrated with LCC method that would help in evaluating and validating the different design alternatives that are recommended by the DSS in order to identify the one that leads to the most effective operational cost (energy cost).

2. LITERATURE REVIEW

Standard approaches for decision-making problems are classified into different classes. Lu et al. (2007) list the most significant classes as follow:

- Structured, where the process for achieving the best solution is known as the standard method, which can be described by using statistics for comparing products in terms of cost or quality.
- Unstructured, where problems generally have fuzzy natures in which human intuitions are the basis of most the decision making.
- Semi-structured, where problems are a combination of both the structured and structured ones and the ideal solutions for these problems are based on mixing both the standard approaches and the human judgements.

According to Simon (1977), a decision-making process consists of three phases: "Intelligence", "Design", and "Choice". Several years later, he added, "Implementation" as the fourth phase. It is during the intelligence phase that the problem is defined while in the design phase a model will be presented to define the assumptions where inter-relationships among the variables are identified. The ideal solution will be selected for the defined model during the choice phase. It is also necessary to validate the model by viability tests. After confirming the model's workability, it will be the implementation phase, which is used to solve a real problem. In case of any failure during this last phase the whole process will be repeated starting from the intelligence stage.

Commonly, the decision-making modeling step is considered to be the most fault-finding step in the whole decision-making processes (Simon, 1977). Thus, it is essential to properly define the problem in order to formulate the model. Generally, there are different approaches used to solve the decision-making problems. For instance, Analytic Hierarchy Process (AHP) is a decision-making method that allows decision makers to consider both qualitative and quantitative aspects of the decision-making process (Lu et al., 2007). The Paired Comparison Analysis method is employed in cases where alternatives are related to each other. Yet, Lu et al. (2007) think that this method permits decision makers to consider priorities that are sometimes conflicting to the project demands. Grid Analysis, which is known as a matrix or multi-attribute theory, is an effective approach that a decision maker can cope with many alternatives and criteria. In this method, the criteria and alternatives are first defined, after that the importance of relative factors is identified, and finally decision makers would be able to assign weights to their priorities, which are combined with the importance of each criterion. Another approach is the Decision Tree model, which is a graphical presentation of the decisions and their potential results. This predictive model consists of data-sets of observations that are connected to each other by a tree structure in the form of nodes and leaves. A leaf demonstrates the expected value of a variable where each interior node stands for a variable (Simon, 1977). Computerized Decision Support Technology is a tool by which the decision maker will be able to employ large numbers of complex models in a short period of time. Furthermore, this technology would help decision makers to share, store, update, and transmit data faster and to reduce the risks of human errors (Lu et al., 2007).

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method that was originally developed by Hwang and Yoon in 1981. The principal objective of TOPSIS is to select the best alternative with the shortest distance from the ideal alternative (Yoon, 1981). They assumed that if each factor takes decreasing and increasing variations, it makes it possible to find the ideal solution.

In the TOPSIS method, vector normalization eliminates the units of criterion function where vast ranges of material features and their performances are involved. Furthermore, the results can be ranked according to their preferences and their numerical values. This ranking gives a clear comprehension of the similarities and differences between preferential alternatives while other MADM methods (i.e. ELECTRE) show only the ranking values of the alternatives regardless of their differences and similarities. The main pitfall of the pair-wise comparisons in AHP methods avoided. While working with vast numbers of alternatives and attributes, TOPSIS is easier to use and less time consuming.

Due to the variety in MADM approaches, there are different methods available to use for the material selection, these include: TOPSIS, ELECTRE, VIKOR, ANP, PROMETHE, etc. Each of these methods has advantages and disadvantages during the decision-making processes. Therefore, researchers have applied diverse approaches in order to recognise the proper technique. For example, as a practical application, Jahan and Edwards (2013) applied the VIKOR method to select the right type of materials. On the other hand, Peng and Xio (2013) used the ELECTRE decision-making technique for the purpose of selecting the required materials. Recently, Liu et al. (2014) employed the novel hybrid multiple criteria decision-making, which considers qualitative and quantitative factors simultaneously. This method is a combination of both the ANP and the VIKOR approaches.

Based on Mansour et al. (2013), one of the most common techniques is the analytical hierarchy process (AHP) method. This method has been used to select hybrid natural and glass fiber reinforced polymer composite materials for automotive brake lever design. Whilst, Shanian and Savadogo (2006) choose TOPSIS multiple-criteria decision support analysis for the materials selection of metallic bipolar plates for polymer electrolyte fuel cells. Yousefpour and Rahimi (2014) propose the combined AHP-TOPSIS method to select the best coating material for corrosion. Peng and Xio (2013) combine the PROMETHE method with the Analytic Network Process (ANP) under a hybrid environment to select materials. In green supply chain management, Hsu et al (2013) use the DEMETEL method to develop a Carbone management model of materials and supplier selections. Jahan and Edwards (2013) utilize a target based normalization technique for the materials' selection, while Kasaei et al. (2014) apply a quality function deployment method for choosing the aerospace engineering materials.

The impact of BIM on the design practice is significant because it raises new ways and processes of delivering design, construction, and facility management servicing them. Owners not only require buildings to be designed and delivered on time, within budget, and with high quality but they also want to know the cost of running them beyond the design and construction (Clayton et al, 1999). Based on Kubba (2012) and Becerik-Gerber and Rice (2010), the development of a schematic model prior to the generation of a detailed building model allows the designer to make a more accurate assessment of the proposed project and to evaluate whether it meets the functional and sustainable requirements set forth by the owner; this helps increase project performance and overall quality. The advent of BIM along with the emergence of global challenging issues like sustainability, and life cycle cost of buildings, requires designers to incorporate basic performance analyses starting at the early stage of design. Those performance analyses include special quality analysis, energy performance, social impact and environmental performance into a framework of BIM concept by further development of virtual buildings (Kam and Fischer, 2004). An integrated BIM system can facilitate the collaboration and communication processes between project participants during the early design phase to effectively provide a well-performing building later on during the operation phase (Hungu, 2013). BIM concept allows multidisciplinary information to be superimposed within one model by incorporating structural, mechanical, electrical, plumbing and lighting information into a single model (Tucker and Newton, 2009). It helps owners visualize the spatial organization of the building as well as understand the sequence of construction activities and the project duration (Eastman et al., 2008). Combining sustainable design strategies with BIM concept has the potential to change traditional design practices and to efficiently produce high-performance designs for proposed buildings. BIM technology can be used to support the design and analysis of a building system at the early design phase. This includes experimental structural analysis, environmental controls, construction methods, the selection of new materials and systems and detailed analysis of the design processes (Jalaei and Jrade, 2014).

Decision support systems (DSS) have been applied in a many contexts. One approach used a simple form to provide help in managing water uses, identifying water quality problems, evaluating the performance of pollution control programs, and presenting technical information to public, specialist, and non-specialist decision makers (El-Gafy, et al., 2005). The study conducted by Juan et al. (2009) focus on developing an integrated decision support system for office building renovation that not only assesses current conditions but also provides solutions on implementing sustainable renovation for decision makers. These solutions must optimize the trade-off between improved quality and investing cost for each suggested renovation action. As for the decision support system, solutions are determined by a novel hybrid approach that combines A* and genetic algorithms (GA). Another study described the implementation of a decision support system, for a large apartment building project, in which clients can make cost based decisions that meet their requirements, while designers can control the costs of both the resource planning and interior design (Lee et al., 2008).

Jadid and Badrah (2012) implemented a decision support system to select the materials for projects under design or construction by consultants and owners. The study focused on issues related to materials approval, selection criteria and materials information management. The described system included database and decision support components. The database can enhance the functionality of the selection process as it provides a source of information to feed into the decision support component. The decision support component relies on the quantitative methods of value engineering. Yang et al. (2013) introduced the development of a multi-criteria decision support system (DSS) to improve the understanding of the best practice's principles associated with the impacts of low-cost green building materials and components. The DSS presented in their study provide designers with useful and explicit information that will aid decision-makers in their choice of materials for low-cost green residential housing projects. The prototype DSS is developed by using macro-in-excel, which is a fairly recent database management technique used for integrating data from multiple, often very large databases and other information sources. Abdallah et al. (2013) presented the development of an automated DSS that is designed to optimize the selection of green building measures, which can be used to upgrade existing buildings. The developed DSS helps minimizing the total upgrade costs required to accomplish a specified LEED-EB certification level such as silver or gold; and maximizing the number of accredited LEED-EB points within a specified budget of upgrade costs. The DSS is designed to identify a set of optimal upgrade decisions that accomplishes these two optimization objectives.

Several studies were done in the past focusing on the application of LCC analysis to sustainable building projects. Alshamrani (2012) study focuses on evaluating school buildings using sustainability measures and life-cycle costing technique. In his paper, he explains the development of a framework that helps school boards to select cost-effective and sustainable structure and exterior envelope types for new school buildings. The selection procedure is represented based on the Leadership in Energy and Environmental Design (LEED) rating system and life-cycle cost analysis techniques for typical structure and envelope-type alternatives. Fourteen different structure and envelope types (e.g., steel, concrete, and wood) are evaluated in various combinations covering both conventional and sustainable alternatives.

Kats et al. (2003) study the "Costs and Financial Benefits of Green Buildings". Cost data was gathered from 33 individual LEED-registered projects (25 office buildings and 8 school buildings) with actual or projected dates of completion between 1995 and 2004. They demonstrate conclusively that sustainable buildings are a cost-effective investment, and accordingly their findings should encourage communities across the country to "build green." They assume a 20-year term for benefits in new buildings' inflation. The results of testing these buildings show an average of 30% reduction in energy use if compared with the consumption associated with the minimum energy code requirements. Where, their energy costs are \$1.47/ft²/yr, which led to cost savings of about \$0.44/ft²/yr and a 20-year present value (PV) of \$5.48/ft². The additional value of peak-demand reduction from green buildings is estimated at \$0.025/ft²/yr, with a 20-year PV of \$0.31/ft². That report assumes a value of \$5 per ton of carbon, indicating a 20-year PV of \$1.18/ft² for emissions reductions from green buildings. Moreover, the calculation of rough conservative values for Construction and Demolition in new construction is \$0.03/ft² or \$3,000 per 100,000 ft² for building construction only. To be conservative, the report considers that green buildings experiences on operation and maintenance cost decline on a trend of 5% per year. This equals a savings of \$0.68/ft² per year, for a 20-year PV savings of \$8.47/ft². Productivity and health values for LEED-certified and silver-rated buildings showed savings of \$36.89/ft², while for LEED-gold and platinum buildings show savings of \$55.33/ft². The data indicate that the average construction cost for green buildings is almost 2% more, or about \$4/ft2, whereas in California this value is substantially less than it is generally perceived. As a conclusion, the NPV for a 20-year time period shows a total estimated savings of \$48.87/ft² for LEED-certified and silver, and a total estimated saving of \$67.31/ft² for LEED-gold and platinum levels. A common way to determine the green cost is to compare the project's final budget with the initial budget. This tends to include all cost coverages, not only those associated with LEED points. Optimizing the design from an energy/cost perspective can be seen as a selection problem of the best types of buildings components. These components mainly include the roof, floor, doors, windows and walls where their selection is done from a pre-defined list of available alternatives for each of these components (Nour et al., 2012). Ihm and Krarti (2012) use a sequential search technique to optimize the design of residential buildings in Tunisia. They try to minimize the life cycle costs of energy, while increasing the building energy efficiency. Wang et al. (2005) performed a multi-objective optimization and improvement technique for buildings' design. The intend of their study is to assist designers in achieving cost-effective green building design based on the life cycle analysis methodology. Nielsen et al. (2002), Winkler et al. (2002), and Huberman and Pearlmutter (2007) also study in detail the importance of applying life cycle cost analysis and the need for its optimization and modeling challenges. Using Building Information Modeling (BIM) with LCC and energy consumption and analysis during the design stage would lead to an efficient automation in the data flow between different databases, analytical and mathematical applications. Easy access to comparable data gives designers the potential to focus on the operating stage of buildings, as well as improving the optimization of their energy consumptions and expenditures (Krigsvoll, 2007). This study aims on incorporating the total annual energy costs of building(s) through a LCC module that uses inputs from the BIM/gbXML module and then providing the results to the project team to make the right decision. Predicting the annual energy consumption however, is a challenging procedure that requires energy simulation by using weather data, thermal properties of used materials for different building components and information related to HVAC systems and other appliances. It is envisaged that the output of the BIM tool would be input to the energy analysis tool by using the gbXML file format (Bazjanac et al., 2011). The Green Building XML schema — known as "gbXML" — was developed to facilitate the transfer process of the information stored in building information models and to enable the integration and interoperability between different design models and other engineering analysis tools. Furthermore, gbXML facilitates the exchange of building information, which includes product characteristics and equipment performance data between the manufacturer database, the BIM models and the energy simulation engines. One of the benefits of gbXML is its ability to carry detailed descriptions of a single building or a set of buildings that can be imported and used by energy analysis and simulation tools (Kumar, 2008).

The major limitation in using energy simulation tools is the issue of their interoperability with BIM. Another limitation is the lack of information needed at the conceptual stage of the project. Since the lifecycle costs of building elements are provided in the form of annual cost per unit area (\$/ft2), it is essential to extract the quantities from the model to estimate the cost of every building component. Then, the overall life cycle cost of the building can be calculated. The literature review confirmed the effect of building performance on its Life Cycle Cost and the need of its optimization. This is achieved by using an integrated BIM platform that would be used to select suitable building components from different alternatives that leads to a minimum lifecycle cost and energy consumptions.

3. SCOPE AND SIGNIFICANCE OF THE STUDY

It is commonly known that designing a building that is energy efficient is more expensive to construct but its future costs are reduced over the entire life cycle. Even though the efficient co-ordination of people, tools and technology can lead to significant benefits in the quality and performance of buildings, there are many challenges to be faced. An integrated design process, interdisciplinary collaboration, complex design analysis, careful material and system optimization are required to solve this problem (Nofera et al., 2010). Although previous studies described several methods and techniques used by designers to select optimum combination of building components, authors could not find any research that has been implemented with the focus on integrating BIM concept with a decision Support System (DSS) to simulate alternative situations, as well as ranking the alternatives and select the best ones based on both the owners' strategic preferences and the availability of sustainable materials in the market.

Therefore, this research intends to introduce various analytical BIM-based integrations, which can be used during the conceptual design stage to select optimal design alternatives on the basis of multiple criteria. Life cycle cost technique is applied to evaluate the economic performance of various types of materials and building components. Sustainability concepts are applied to design and to provide healthy, comfortable and productive buildings. Sustainability criteria are evaluated by experts in the AEC industry in North America using relative weights comparison and applying decision making techniques. This can be used as a basis for assisting designers and engineers to obtain subtle knowledge about the application of information technology in sustainable design and to pave the way for further improvement. Creating and linking such a DSS to BIM tool has the potential to aid designers design sustainable buildings and animate them easily and efficiently at the conceptual stage. Part of this integrated methodology is to develop new plug-ins within BIM tool to run the DSS by designers when selecting appropriate building components and materials based on project's requirements and attributes in addition to analyse the LCC of different design alternatives.

Numerous types of software currently used in the construction industry, such as Autodesk Revit Architecture©, Autodesk Green Building Studio© (GBS), Statistical Package for the Social Sciences (SPSS©) and Microsoft Excel©, are used in the development of the integrated model. The successful implementation of such a model represents a significant advancement in the ability to do sustainable design of a building at the early stages of its life, to optimize the selection of sustainable building components and materials through a comprehensive DSS, and to evaluate and analyse the LCC of the different design options.

4. METHODOLOGY

One of the main expected contributions of this proposed study is the development of an integrated model that incorporates a Decision Support System (DSS) to help designers in selecting the best type of sustainable building components and materials and associated designs for proposed building projects based on owners' requirements. Traditionally, designers choose materials based on their known characteristics or by selecting the ones that has been used in previous projects. This practice usually creates multiple problems related to expectations, standards, and owners' budgets. The failure of this traditional method can be handled by using the MADM method, which is based on a complex comparison between available alternatives. The development of the proposed methodology that integrates different applications, as represented in Fig. 1, will be implemented through the following five sequential phases:

Phase 1 consists of designing the model's relational database, which is needed while doing the design of sustainable buildings. Loucopoulos (1992) states that a consistent information system depends on the integration between databases, programming languages, and software engineering and that its life cycle incorporates the interrelated technologies of conceptual modeling and database design. The design and development of this database is accomplished in two steps starting with the conceptual modeling and ending with the physical implementation. First, problem investigation and user needs are recognized based on a comprehensive literature review. Then the database requirements are identified and the conceptual design is carried out. Second, the implementation of the data model requires that the transformation process be made from the conceptual to the logical design (Jrade and Alkass, 2007). Only afterwards the physical implementation is made by creating a list of related tables used to store the collected data based on the selected Work Breakdown Structure (WBS). The information related to green materials is stored in an external database in the form of predefined design families that can be recognized by BIM tool. The reason for developing a separate database is to have it loaded every time the BIM tool (e.g., Autodesk Revit) opens, which is done by defining its path that is linked to the predefined library of the BIM tool. The data related to green materials is saved as family files with the format of either RFA or Revit project file with RVT format, which can be identified by the BIM tool. Thus, in the external sustainable database, up to 3,000 design families are collected from the Smart BIM library webpage, suppliers' web pages, the USGBC and CaGBC websites, as well as published data and are arranged based on the 16 divisions of the Masterformat WBS. Different types of information such as details about the materials used, suppliers' contact data, assigned keynotes, potential LEED points and assembly codes are stored in the external database.

Phase 2 focuses on customizing the BIM tool to fit the modularity requirements of the model. The first step is to design and implement a 3D module capable of storing newly created families, and their associated keynotes for components commonly used in buildings by using certified green materials. The module is linked to the database developed in Phase 1. Keynotes are textual annotations that relate text strings to specific elements in the model, which are in turn linked to an external text file. They are used as an external link to the element itself with specific style and specifications. Moreover, it is very important to select a unique code for each item that is stored in a separate line in the database to ease and simplify the query and selection process.

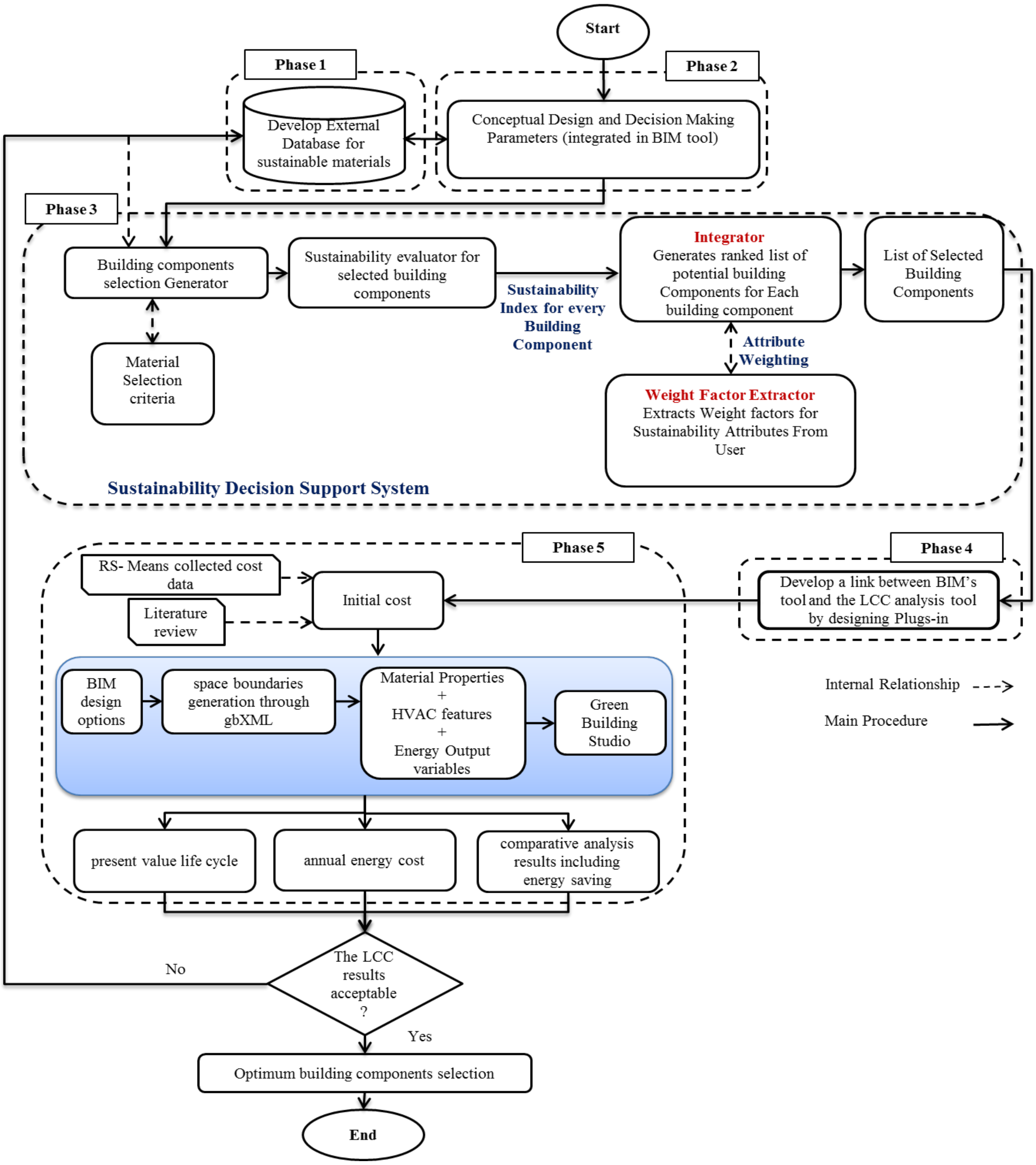


FIG. 1: Flowchart of the integration Process

Phase 3 consists of the developing of a DSS module, which assists in selecting sustainable building components. The DSS uses the conceptual design and decision-making parameters, along with material selection heuristics to generate a list of alternatives for each design component from the materials database. Once the set of alternatives has been generated, the weight factor extractor demands the user to enter weightings for the sustainability attributes. Alternatives in the MADM method are often defined by some attributes that are qualitative (Hwang and Yoon, 1981). For comparison purposes, qualitative attributes need to be converted into quantitative scales. This conversion usually takes place by utilizing five-point Likert-type scales (Lu et al., 2007). Although these scales convert the qualitative attributes to numbers, in many cases, these scales are not able to clearly distinguish the differences between close scores (e.g., high and very high). To solve this problem, Saaty (1980) comes up with a nine-point scale where more intervals have been employed. Values for the sustainability attributes (e.g., the importance factor of every attribute to each other) will be collected from experts in the AEC industry. Then, the user's weightings are integrated with the attribute values for each potential material and sorted to get a relative ranking of the feasible materials for each building component. The building components/products with the highest ranking are recommended by the system. The user reviews the DSS recommendation for each building component, and selects a component for each design element based on his/her professional judgment and/or the system's suggestion. While the building components are selected by the user, the DSS does an internal check using a built in knowledge-base to detect any potential conflict between the different components and materials. The list of recommended materials for each element is modified automatically as materials are selected for the design components.

Phase 4 focuses on creating a plug-in, which is a type of algorithm that adds functionality to the BIM tool by integrating it with the energy analysis and simulation tools. Plug-in or add-in are terms used in BIM tools to signify a module containing an algorithm that makes use of the BIM tool's Application Program Interface (API). The BIM tool used in this study has a .NET API, which means that any of the .NET compliant programming languages (C#, VB.NET, F#, etc.) can be used to develop a customized plug-in. While each language has its own relative benefits, C# has been used in this study due to its simplicity, usability and powerful ability to underlay the .NET framework.

Phase 5 concentrates on the development of life cycle cost analysis module that helps in exporting the 3D design created in BIM tool using the gbXML file format. The LCC procedure starts first by calculating the initial construction costs, which evaluate the capital costs for the existing LEED®-certified buildings. The cost data used in this module is collected from RS- Means publications. Since this study only focuses on the operational cost (energy cost), an evaluation of the total annual energy cost of the created design is computed. Among the available tools that have the capability of calculating the energy consumption, energy cost and implementing LCC analysis is Autodesk Green Building Studio© (GBS), which is going to be the most relevant software for this study. The direct link between GBS and Autodesk Revit through the gbXML format makes GBS as an ideal tool to import and export the 3D design information between the different tools including the geometric data, which is needed to do all the necessary analyses. Most building energy cost comparisons can be made using the annualized energy consumption method and its associated cost and information.

In this study, the outputs extracted from GBS will be used by designers to evaluate the present value and the annual costs as well as to make comparative analysis of the energy savings and emissions reductions. This will help designers evaluate different design alternatives from their initial and operating costs perspectives. The target is to compute and compare the operating cost of these alternatives and to determine the most economical one over the project's life cycle.

5. SELECTION AND CHARACTERIZATION OF THE TOPSIS METHOD

The unique characteristics of the TOPSIS method make it an ideal choice to solve the material selection problems. In TOPSIS, a vast range of materials' features and all their performance attributes are involved. To implement and use TOPSIS during the material selection process, the main impact of each potential factor that influence that process should be considered with respect to the other factors.

In TOPSIS, the results can be ranked according to their preferences and their numerical values. This ranking gives a clear comprehension of the differences in the preferential alternatives and their similarities, whereas other MADM methods (e.g., ELECTRE) show only the ranking values of the alternatives regardless of their differences and similarities. While working with vast numbers of alternatives and attributes, TOPSIS is more efficient and faster.

The principal objective in TOPSIS is to select the best alternative with the shortest distance from the ideal one (Yoon, 1981). To achieve this goal, we have to find the farthest distance from the negative ideal solution and the closest to the positive ideal solution. The unique features of TOPSIS explains its popularity and efficiency where the vector normalization eliminates the units of criterion function so any change in one attribute can be presented in a direct or opposite behavior by the other factors.

Shanian and Savadago (2006) think that in an MADM problem, it is important to know the relative significance of each criterion. As a common approach, the weights are presented in a normalized set in which their total sum equals to one. Meng (1989) consider that Entropy is a measurement of the disorder degree in a system that can also be an indicator that shows the effective information provided by the data. The entropy method can be used not only to quantitatively estimate the data, but also to objectively calculate the relative weight of information (Shannon, 1948). If entropy values are lower, the numerator degrees are more proportional, implying as close to perfect entropy as possible. Conversely, if entropy values are higher, the numerator degrees have a more irregular inflection. Entropy weight method is introduced to obtain the relative weight of each attribute (Qiu, 2002). Each attribute is assigned a measured value to calculate the entropy values. The entropy values for each criterion are then compared, and the relative significance levels of each other are calculated (i.e., the relative weight). Next, the entropy weight is obtained based on the appraisal matrix information.

Pratyush and Jian-Bo (1998) believe that Entropy method is a technique used to evaluate the amount of uncertainty that is represented by a precise probability distribution. Furthermore, Huang (2008) agrees that a broader distribution shows a highest level of uncertainty than does a sharply packed one. Applying the entropy method requires the following two steps:

(1) Step one, Normalization of values

The Entropy method applies a different procedure to normalize the values. Accordingly, it divides the value of each element (r_{ij}) of the weight matrix by the sum of the all elements' values ($\sum_{i=1}^{m} r_{ij}$) to calculate the normalized values of the weight matrix' elements, p_{ij} using Equation [1].

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \quad j = 1,2,\dots,m \qquad [1]$$

(2) Step two, Calculation of the entropy for the criterion

To calculate the entropy values (E_j), Equation [2] is employed where k=$\frac{1}{Ln\,(m)}$, (m) is the number of criteria, and (p_{ij}) is the normalized value of the weight matrix elements.

$$E_j = -k \sum_{i=1}^{m} [p_{ij} \ln(p_{ij})] \quad j = 1,2,\dots,J; \;\; i = 1,2,\dots,I \qquad [2]$$

One benefit of the entropy method is the possibility to mix the decision priorities with the sensitivity analysis. Thus, the final weight is the combination of both them. If the criterion's priorities are similar to the decision-maker's ones then the set of weights can be calculated by using Equation [3], where d_j equals$1 - E_j$. In this equation it is considered that all the criteria have the same priority.

$$w'_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \forall_j, \quad d_j = 1 - E_j, j = 1,2,\dots,J \qquad [3]$$

In the case of applying priority based on the project limitations, previous experience or any particular constraint of design, the weights are calculated by using a factor known as λ, which stands for the arranged order of increasing importance of the non-normalized subjective weights. After arranging the assigned weights, the sum of the normalized subjective weights (λ_j) should equal to hundred. The prioritized weights (w'_j) can then be calculated using Equation [4] in which w'_j is the Entropy weights without considering any priority.

$$w'_j = \frac{\lambda_j w'_j}{\sum_{j=1}^{n} \lambda_j w'_j} \quad , \quad \sum_{i=1}^{n} \lambda_j = 100 \qquad [4]$$

The database module includes assessment of suppliers' materials and their BIM information. The information stored in this database is organized based on the main suppliers of the different building components including doors, roofs, windows, ceilings, floors and walls. Next, the important sustainability factors are identified from the literature review. Afterwards, the DSS is designed based on the applied decision-making approaches that involve TOPSIS and Entropy, which are used to choose the optimal alternative. Then, by connecting the database with the DSS, an integration interface is developed into the BIM tool (i.e., Autodesk Revit).

Fig. 2 presents the model's architecture. The data preparation consists of generating alternatives by assessing and reviewing suppliers' materials and their BIM families that are collected and stored in the database, and organizing the sustainability criteria that have the highest influence on construction projects. In the development of the BIM-integrated DSS model, selected criteria will be converted to dimensionless weights by employing Entropy methods, where the criterion weights are organized in a matrix form. To create the decision-makers matrix object oriented programming language, in this case C#, is used to program the DSS, which is integrated with BIM tool (i.e., Revit). Both matrices are imported into the background of Revit in the form of plug-in to run TOPSIS procedures. Finally, the optimal sustainable alternative is presented by the integrated DSS in BIM tool. The developed DSS is based on the multi-criteria assessment weighting scale technique combined with Entropy, which enables comparison and ranking of different alternatives and scenarios. The other method employed in this DSS, is the TOPSIS Logic, which is mixed with a weighted criteria matrix to show the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution.

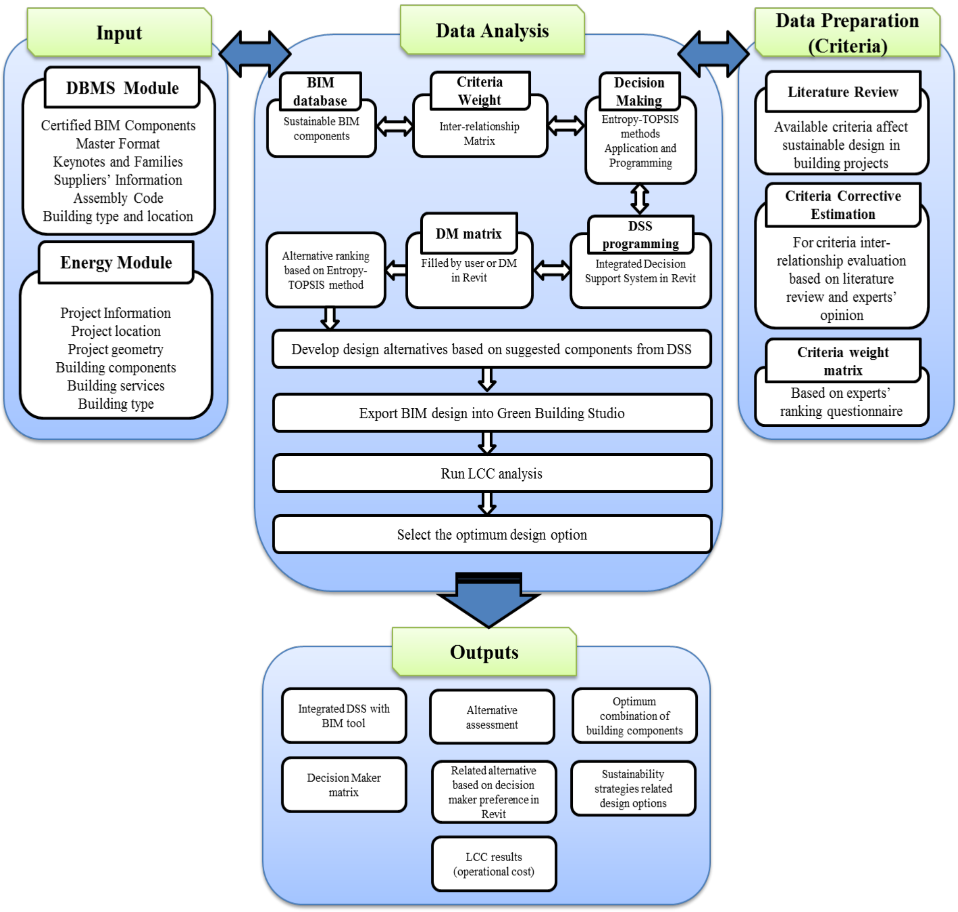


FIG. 2: Model's Architecture

Fig. 3 shows the main components of the proposed DSS. It contains: (1) Materials and building components available in the construction industry, (2) Project character (i.e. project orientation) as well as sustainability attributes selected by the experts, (3) Owners/decision-makers' fulfilment goals toward material selection based on their priorities such as time, energy consumption, total cost, life cycle cost, and positive social image of the building by meeting and supporting sustainability criteria.

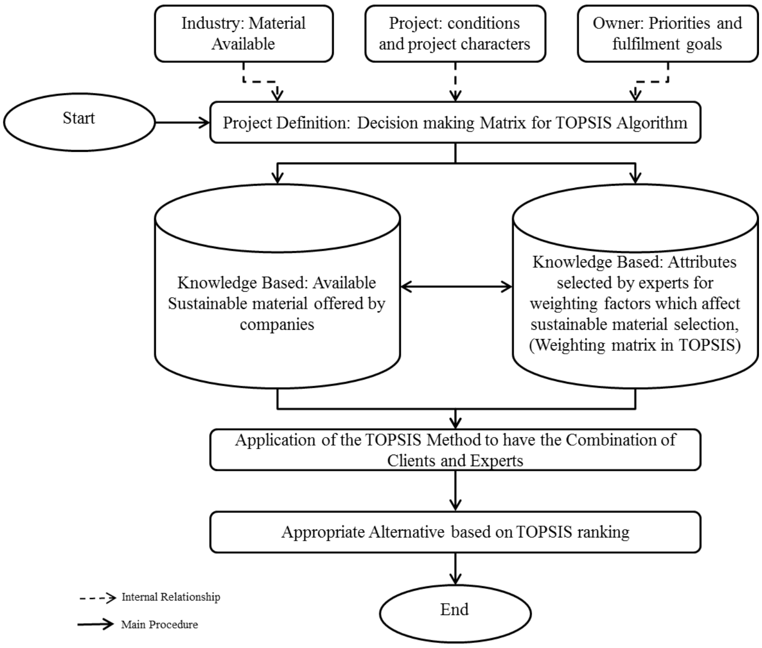


FIG. 3: Decision Support System Schema using TOPSIS algorithm

The most critical part in this study is the selection and arrangement of the criteria and attributes that affect the selection of sustainable materials for building projects. Basically, the assessment of the attributes is made based on the intense literature review, previous research work and survey completed by experts (information is collected from five sustainable construction material specialists and 25 sustainable design consultants). In this survey, the experts are asked to choose the criteria that have the highest significance on the sustainability of building projects. The criteria for sustainability are divided into three categories: 1) environmental, 2) economical, and 3) social criteria. Each of those categories includes sub-criteria that have been listed in the scoring system completed by experts. Table 1 shows the sustainability assessment criteria and sub-criteria.

TABLE. 1: Sustainability assessment criteria used for DSS

Main category	**Criteria**	**Sub Criteria**
Environmental criteria	Environmental Impacts (EI)	Global Warming Potential Ozone Depletion Potential Acidification Potential Eutrophication Potential Smog Potential HH Respiratory Effects Potential Weighted Resource
	Energy & Atmosphere	Operational energy as Lighting and power, cooling and heating, Minimum Energy Performance, Embodied energy as mining, manufacturing, on site process, transportation and final disposal, Onsite renewable Energy, Energy consumption during building life
	Material & Resources	The application of renewable material, Recycled content

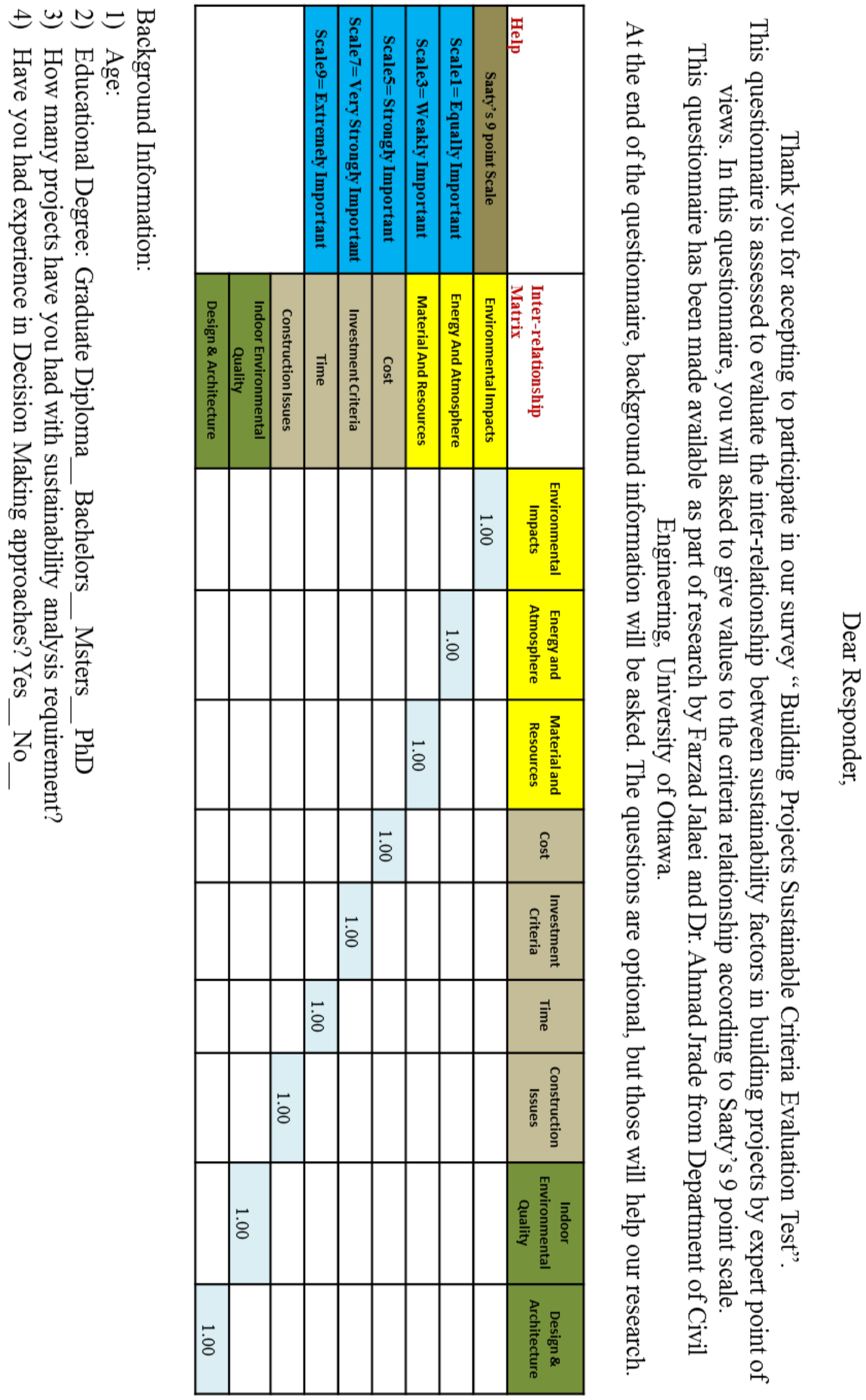
Main category	Criteria	Sub Criteria
Economical factor (cost efficiency)	Cost	Costs of resources and materials, Labor costs, Operation & Maintenance costs, Renovation and destruction costs
	Investment criteria	The speed of return on investment, Initial investment, Exchange amount
	Time	Approximated Construction time
	Construction issues	Constructability, Flexibility, Material and equipment availability
Social wellbeing	Indoor Environmental Quality (Health of occupants)	Indoor environment comfort, Low-Emitting Materials: Adhesives and Sealants, Low-Emitting Materials: Paints and Coatings, Low-Emitting Materials: Flooring Systems, Low-Emitting Materials: Composite Wood and Agrifiber products, Controllability of System: Lighting & Thermal Comfort
	Design and architecture issues	Daylight and Views, Productivity, Individualization and social identity, Physical space and performance, Aesthetics and architectural issues

6. MODEL IMPLEMENTATION & VALIDATION

Portion of the technical knowledge required in the development of the integrated model is obtained from an intense review of the literature and by consulting experts who have wide experience in sustainability and decision-making approaches. Next, is to identify the Criteria/attributes and accordingly calculating the Weight Matrix using the Entropy method to establish the Decision Maker's Matrix. The next phase is normalizing the decision-making Matrix (DMM) made by the Decision Maker and then multiplying the DMM by the Weight Matrices to get the weighted decision-making matrix in order to evaluate the Positive Ideal and Negative non-Ideal Solution and finally to calculate the shortest distance from the Positive Ideal Solution (PIS), farthest distance from the Negative non-Ideal Solution (NIS) and the relative closeness to the ideal solution for each alternative. After that, is ranking the alternatives based on their proportion of relative closeness. Weighting matrix applied in the TOPSIS method is validated by experts and is stored in the DSS, which will be integrated into BIM tool (Autodesk Revit) by developing a plug-in. By implementing the DSS plug-in, designer (Decision Maker) needs to fill the decision-making matrix, then the inputted data is processed in the background to run the next steps, which include TOPSIS logic. The final results will be presented as a descending-order ranking of the alternatives. Consequently, the highest rank belongs to the most appropriate alternative (the most proper material from the list of companies). The data set required for the development of the model is divided into two categories: (1) materials and components alternatives (data source is: vendors of basic assembly groups including doors, walls, windows, ceilings, roofs and floor that are made of sustainable materials) and their correspondent BIM families, (2) green building sustainability controlling criteria.

In order to define alternatives, information from the SmartBIM library website (http://library.smartbim.com) is collected and assessed. The SmartBIM Library is a web-based collection of predefined design families, which incorporate detailed information that can be integrated into the design workflow. Due to the big number of companies/factories that produce/supply building products, which are currently available in the market, only leading companies/factories with wider ranges of products have been selected. To ease the process of accessing the required data, the selected companies and their materials' BIM information are hyperlinked to the list of products in the developed plug-in. In order to obtain the weight criteria's matrix from the selected criteria as an output, experts' opinions have been utilized. In order to prepare it, a blank weight criteria matrix as shown in Fig.

4 has been handed to the experts for scoring purposes. The weight criteria matrix was sent to 28 selected experts and practitioners. Only 25 responses were received, 5 of them were from sustainable construction material specialists and the remaining 20 were from practitioners. Fig. 4 shows the matrix sent to participants and the relevant information generated by responses, which includes respondents' age distribution, education and sustainability knowledge.



Dear Responder,

Thank you for accepting to participate in our survey " Building Projects Sustainable Criteria Evaluation Test".

This questionnaire is assessed to evaluate the inter-relationship between sustainability factors in building projects by expert point of views. In this questionnaire, you will asked to give values to the criteria relationship according to Saaty's 9 point scale.

This questionnaire has been made available as part of research by Farzad Jalaei and Dr. Ahmad Jrade from Department of Civil Engineering, University of Ottawa.

At the end of the questionnaire, background information will be asked. The questions are optional, but those will help our research.

Help	Inter-relationship Matrix	Environmental Impacts	Energy and Atmosphere	Material and Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Saaty's 9 point Scale	Environmental Impacts	1.00								
Scale1=Equally Important	Energy And Atmosphere		1.00							
Scale3=Weakly Important	Material And Resources			1.00						
Scale5=Strongly Important	Cost				1.00					
Scale7=Very Strongly Important	Investment Criteria					1.00				
Scale9=Extremely Important	Time						1.00			
	Construction Issues							1.00		
	Indoor Environmental Quality								1.00	
	Design & Architecture									1.00

Background Information:

1) Age:
2) Educational Degree: Graduate Diploma__ Bachelors__ Msters__ PhD
3) How many projects have you had with sustainability analysis requirement?
4) Have you had experience in Decision Making approaches? Yes__ No__

FIG. 4: Study Criteria Weight Matrix Scheme

To merge all the collected responses into one matrix, a normality behavior test for the responses of each question has been run by using the Statistical Package for the Social Sciences (SPSS©) software's normality analyzing tools. The obtained results show that all the responses had normal distributions. Therefore, for each correlative score, the normal distribution's average is substituted. Table 2 shows the un-weighted criteria matrix organized based on experts' opinions.

TABLE. 2: Un-weighted Criteria matrix assembled by experts' opinions

	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	1.00	0.14	0.11	5.00	3.00	3.00	3.00	5.00	1.00
Energy And Atmosphere	7.00	1.00	0.17	6.00	5.00	1.00	1.00	7.00	1.00
Material And Resources	9.00	6.00	1.00	9.00	9.00	9.00	9.00	5.00	7.00
Cost	0.20	0.17	0.11	1.00	7.00	1.00	0.17	0.17	0.14
Investment Criteria	0.33	0.20	0.11	0.14	1.00	0.17	0.17	0.20	0.14
Time	0.33	1.00	0.11	1.00	6.00	1.00	7.00	1.00	1.00
Construction Issues	0.33	1.00	0.11	6.00	6.00	0.14	1.00	1.00	3.00
Indoor Environmental Quality	0.20	0.14	0.20	6.00	5.00	1.00	1.00	1.00	0.20
Design & Architecture	1.00	1.00	0.14	7.00	7.00	1.00	0.33	5.00	1.00

To convert the un-weighted matrix to a weighted one, the Entropy weighting approach has been employed. First, the matrix is normalized. Second, the entropy of the weights is calculated. Third, the (d_j) factor, which deducts Entropy values (E_j) from one, is estimated. Finally, the weighted criteria are determined by taking the ratio between each d_j and the sum of all the d_j(s) as represented in Table 3.

TABLE. 3: Weighted Entropy matrix

	Environmental Impacts	Energy And Atmosphere	Material And Resources	Cost	Investment Criteria	Time	Construction Issues	Indoor Environmental Quality	Design & Architecture
Environmental Impacts	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy And Atmosphere	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Material And Resources	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00
Cost	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00
Investment Criteria	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Time	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00
Construction Issues	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00
Indoor Environmental Quality	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00
Design & Architecture	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13

Part of designing and developing the DSS is to write an algorithm in the form of a plug-in in BIM tool, which is Autodesk Revit in this case. This plug-in enables users/decision-makers to evaluate the selected materials based on their sustainability features while doing the conceptual design of proposed buildings. The plug-in is programmed using C#, the object oriented programming language, and is imported into the toolbar of Autodesk Revit as a shortcut. Fig. 5 presents the developed plug-in after importing it into Revit's toolbar. TOPSIS, once run, begins its procedures by employing two matrices: the criteria weighted matrix and decision maker's matrix. The developed plug-in helps users import weights into the decision-makers matrix, which are recognized by the user's comparison results, based on the available products in the external database of BIM tool. The criteria matrix is coded and inserted in the background of the plug-in's program. As shown in Fig. 5, by using the plug-in, decision makers can compare and score the alternatives of different assembly groups.

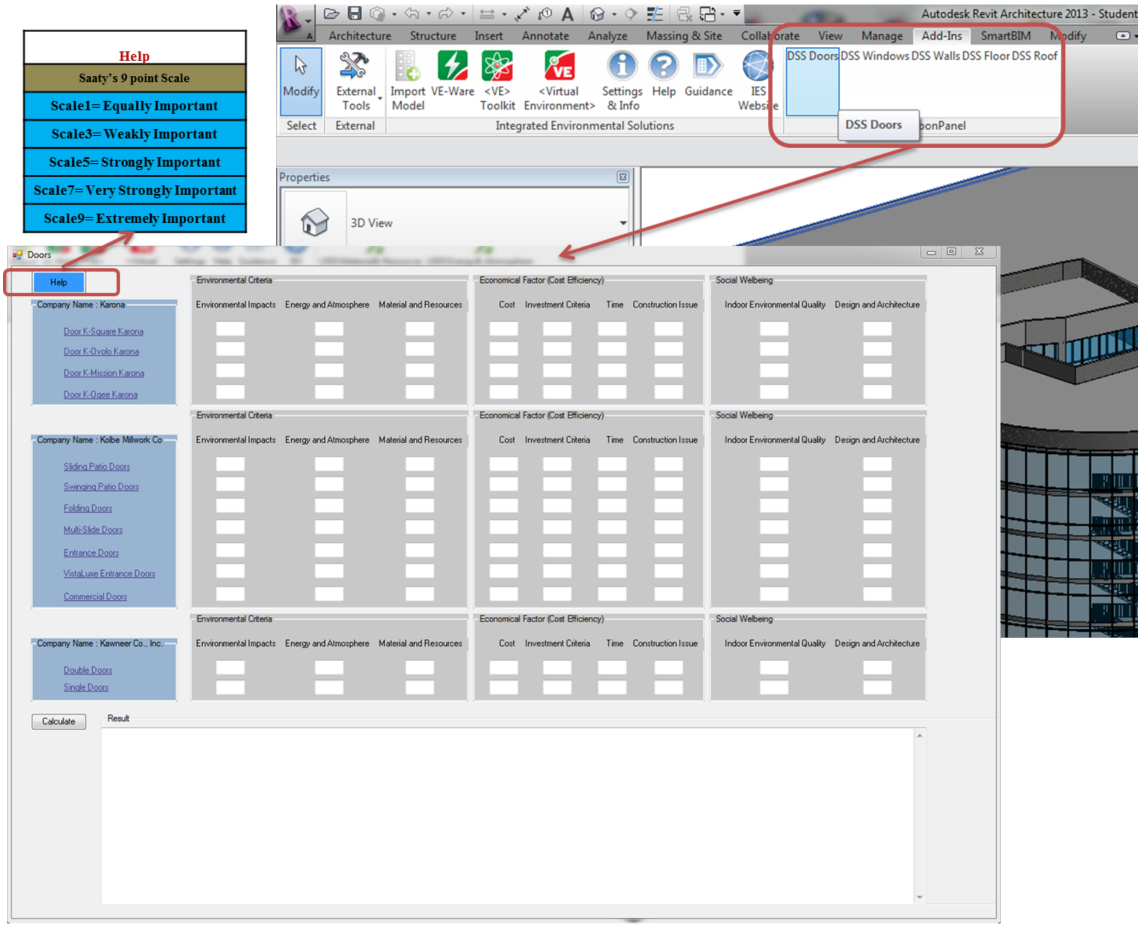


FIG. 5: Snapshot of DSS plug-in developed in Autodesk Revit

To validate the developed model, its performance is examined through the use of an actual five floor office building project that can house around 300 people (occupants), which is currently under design in the City of Ottawa. The proposed construction site has a total area of 46,980 ft^2 and the building's gross area is 88,587 ft^2. Building functions are distributed into three categories: public, semi-public and private. Public function is related to both ordinary people and employees such as conference and exhibition rooms. Semi-public spaces include secretary offices and managers' rooms, which are used by employees and visitors. Employees' offices and private gathering rooms are considered as private spaces used by employees and managers. In order to control the sunlight, louver systems are installed to improve indoor daylighting to limit glare and redirect diffuse light. The authors created a 3D conceptual design of the current project. The associated sustainable components and materials of the design are selected from the developed external database. The components used in the design of this case project have their specifications as it is recommended by the DSS plug-in. Every component, such as floor, wall, roof, and window has its associated sustainability information linked to the families inherited into BIM tool, which includes manufacturers' web pages and contact information. Fig. 6 shows a rendered snapshot of the sustainable office building, which is created by using the developed model.

The designer needs to select and decide on the sustainable materials and components provided by different suppliers' to create alternatives for the current building including doors, roofs, ceilings, walls, windows and floors. To use the developed DSS, the designer must use TOPSIS plug-in loaded in the toolbar of Autodesk Revit. After running the plug-in, the decision maker is asked to create the decision-maker matrix by scoring the alternatives based on the defined criteria. Every product is linked to its Producer website or SmartBIM library webpage that provides the user with all the required technical specifications of that product. The help button in the plug-in provides the user with information on how to fill the blank spaces in the form based on the nine-point ranking scale.

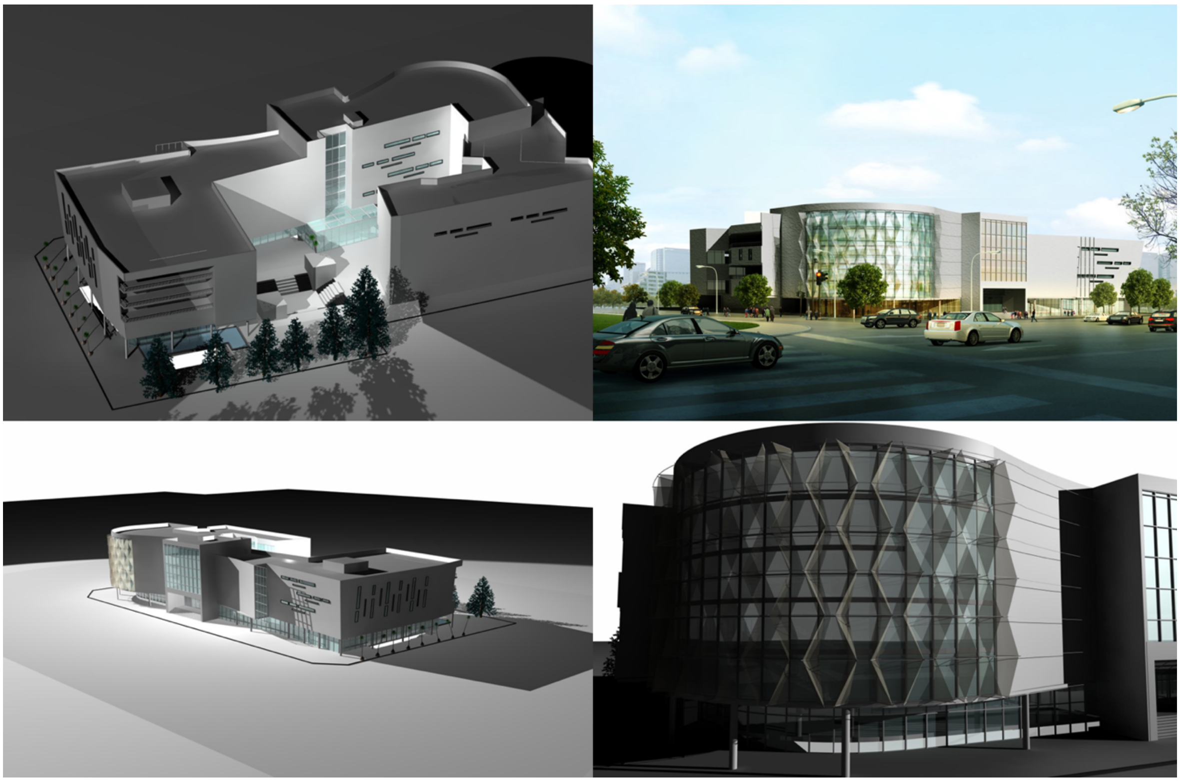


FIG. 6: Snapshot of the sustainable case building model (Office Building)

To get the results, the user is required to click on the calculate button included in the tool bar designed in the DSS. The final results will be presented as a ranked list of alternatives and their associated producer names, as well as the (EI_i) factor. For instance, the snapshot of the filled DM matrix and the final sorting of the alternatives for the door component is shown in Fig. 7.

To apply the LCC analysis method, the authors created two conceptual design options of the current project where its associated sustainable components and materials are selected based on the first two alternatives recommended by DSS (for instance, Kolbe Millwork Co Vista Luxe Entrance Doors and Kolbe Millwork CoCommercial Doors) for every building component. In order to have an accurate energy analysis of the building case project, the created 3D geometric model must be converted into an analytical model. First, all the spaces are converted into rooms. In BIM tool, rooms are considered to be equivalent to zones that need to be defined. A thermal zone is a completely enclosed space bounded by its floors, walls and roof and it is the basic unit for which the heat loads are calculated. The extent of a "room" is defined by its bounding elements such as walls, floors and roofs. Once a "room" is defined for the purpose of analyzing the building's energy, these bounding elements are converted into 2D surfaces representing their actual geometry. However, overhangs, which do not have a room, are considered to be shading surfaces. In order to determine whether a room is an interior or an exterior one it is important to define it's adjacent in the analytical model. By using the GBS plug-in in BIM tool, designers will directly transfer the created model of the building to GBS via the gbXML formats.

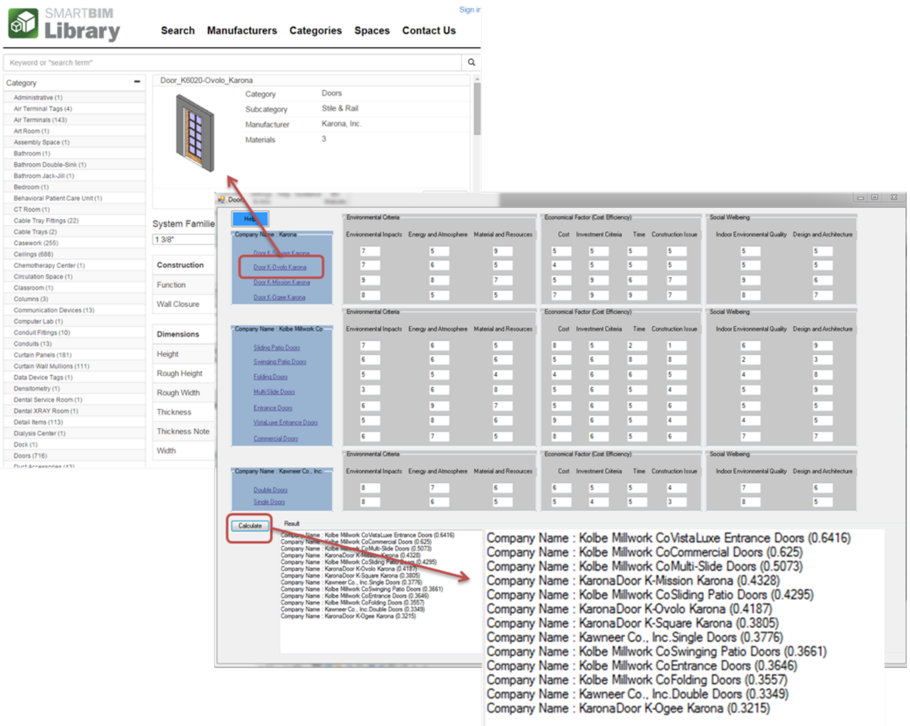


FIG. 7: The snapshot of filled form in the DSS and the results for door component

The results of the base run analysis are illustrated in Fig. 8, where the annual energy cost and life cycle cost for the 1st design option are $114,838 and $1,564,094 respectively, while those for the 2nd design option are $139,103 and $1,894,588 in the same order. Other information such as annual CO_2 emission, annual energy and life cycle energy are provided in the base run as well. Fig. 9 provides graphical representations of the information related to the monthly cost of the total energy, electricity and fuel (natural gas) for each of the two design options. A careful evaluation and comparison of the cost data presented in the graph show that the total energy cost of the 1st design option is on average around $2,000 less than the 2nd option for every month. The average electricity cost for the 1st option shows a drop of around $1,000/month if compared with the 2nd one, while option 2 has around $1,000/month more than option 1 in the cost of fuel (natural gas). Comparing the results shown in Fig. 8 and Fig. 9, the first design option recommended by the developed DSS can be considered as the optimized alternative.

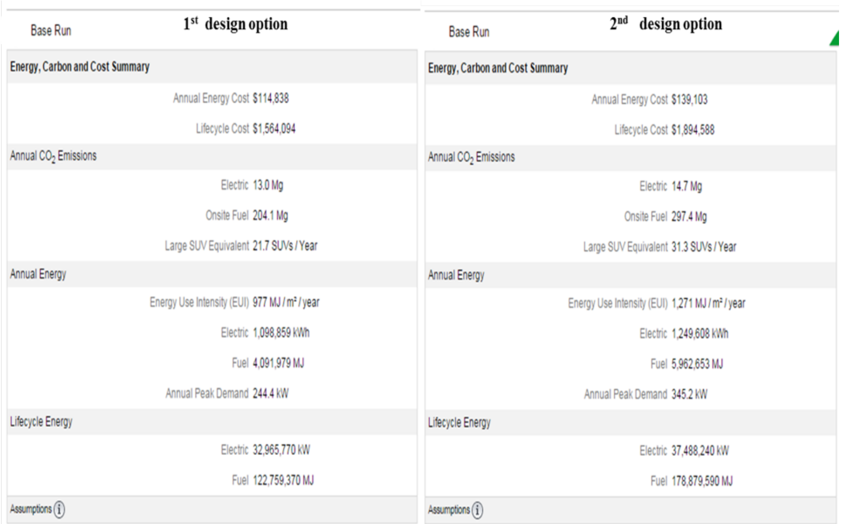


FIG. 8: The base run analysis results in GBS for two design alternatives

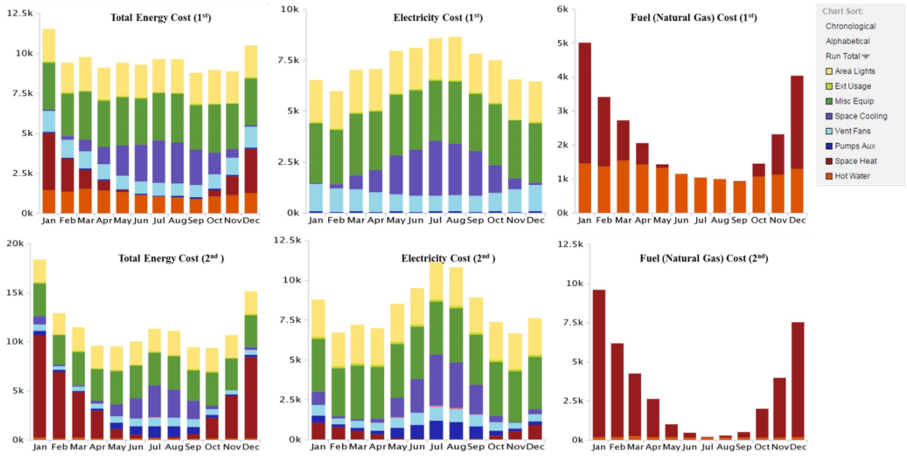


FIG. 9: Monthly cost analysis results for Total Energy, Electricity and Fuel (Natural Gas) for two design options

7. CONCLUSION

This study aimed to investigate the feasibility of integrating BIM, DSS and LCC. An efficient framework for this integration is created and developed that takes into consideration the sustainable design requirements and the functionality of the BIM tool. The intent of this study is to help decision makers take important decisions related to the continuation or dismissal of proposed buildings at the conceptual stage. The novelty highlighted in this paper describes the development of an integrated model that includes a Decision Support System (DSS) used by designers to decide on and select the optimum type of sustainable building components for proposed projects based on owners' priorities and sustainability criteria. The developed DSS is integrated into BIM tool through an automated process by creating new plug-ins so that users start doing design of a proposed sustainable building at the conceptual stage in a timely and efficient way. Using a BIM-LCC integrated platform moves the design decisions forward at the early stage especially when comparing different design alternatives, which is considered to be an attribute of this research.

The case project used in the validation section was in its very early design stage. Since its design was not completed yet, authors received brief information about the project from the owners and their consultants. Based on the provided information, the authors created a Revit model of that project and accordingly applied the developed method that its analysis results were discussed with the project team for feedback. During that discussion, the DSS generated in the BIM model were presented to the design team and suggested for consideration into the case project. It was proven that in case of using the recommended products for every building component, the developed design option has a 17% benefit on energy cost as well as on its life cycle cost, which can be considered as the optimal alternative and which validates the workability of the developed DSS. Applying a comparative LCC analysis between different design alternatives is considered as a benchmarking practice that is offered to the design team to give them a proper feedback on making decision related to the materials selection and in case of any changes to the design and/or materials selection, the LCC results will be changed.

It worth to mention that the focus of this manuscript is the conceptual design stage where the design is at its earliest stage and accordingly as it changes the costs will change, therefore an accurate estimate of the costs for proposed projects is not achieved at the conceptual stage where the margin of errors is high and the level of accuracy is low. Since every case project has its own sustainability specifications, a detailed comparison of the results between them is not helpful for validating the developed model. The main idea behind validating the developed model is to test its workability, dependency and accurate outcomes to help designers make constructive decisions during the conceptual design stage of project's life.

The integrated model is user-friendly, efficient and easy to use. As it is validated, the combination of building components proposed by the DSS, represent a minimum LCC values when compared with the other suggested combination. Although this is an ongoing research, its potential for more development is proven to be possible. The DSS database is on a small scale, but it can definitely be expanded to Online Analytical Processing (OLAP) design in order to enable relevant green material producers to update their information online periodically.

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