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BIM-based approach for optimizing life cycle costs of sustainable buildings

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ABSTRACT

This paper proposes a framework that integrates Building Information Modeling (BIM) with Genetic Algorithm Optimization and Monte-Carlo Simulation. The developed framework helps in implementing a stochastic Life-Cycle Cost (LCC) model for building to select the optimum building materials alternatives and discover the most influential building system in each cost element starting from initial cost to end on life cost. Genetic Algorithms Optimization technique is utilized to select the optimum alternatives of building systems taking in consideration sustainability aspects. The Monte-Carlo Simulation model is used as a fitness function for the optimization model. The environmental aspect of building is achieved by considering the maximum number of points that can be awarded under the Leadership in Energy and Environmental Design (LEED) rating system. Sensitivity analysis is performed on the optimum solutions that are chosen by optimization a model to examine the effect of different building systems on LCC and its components through computing the rank order of building systems and the target output. A case study is presented to demonstrate the practical features of the proposed framework.

1. Introduction

The United Nations has proposed 17 sustainable development goals, which present a great challenge to not only governments but also a wide category of stakeholders. The significance of sustainable building towards realization of the United Nations Sustainable Development Goals is considered through Goal 11, Sustainable Cities and Communities. where, one of main targets of this goal focuses on the importance of providing building sustainable and resilient buildings utilizing local materials for least developed countries (UNDP, 2016). Selections of construction materials by designers and construction managers are often constrained by strict budget requirements. As a result, the materials' selection for new construction building is usually based on personal experience and manufacturer's information, or solely driven by the product's initial cost. However, having a building with low initial cost resulted from selection of construction materials without considering their sustainable properties would probably lead to a great rise in the total Life Cycle Cost (LCC) of the building. The LCC of building should be estimated first to evaluate the economic efficiency of building considering all cost elements. Also, for the buildings prone to seismic risk, LCC analysis is a critical issue in structural engineering. The expected loss including damage and repair costs is an important parameter for structural design. The integration between economic and computer technology allows for a more developed approach to design and implement the buildings than ever before (Vitiello et al., 2017).

Having a building with High LCC is expected due to the expenses that are paid throughout the lifecycle of building. However, the sustainable building is considered a long term strategy for decreasing the LCC during its lifecycle (Mansour et al., 2007). In fact, the initial cost of building represents only half of its total costs during its whole lifecycle or slightly higher than the total cost of cleaning and care taking, maintenance and replacement, and routine servicing (Wang et al., 2012). Therefore, the principles of sustainability and building materials with sustainable properties should be considered in the earlier stages of building. Selection of green-building materials has been considered as the easiest method for designers to incorporate the principles of the sustainability in building projects (John et al., 2005). Where, the lifecycle of

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green building includes different phases such as initial phase, design phase, construction phase, operation phase, and end of life phase. As well as, the information about each phase often includes different formats and types (Xu et al., 2014).

A number of research efforts have been made to evaluate the sustainability of building through predicting the LCC in different applications using either deterministic approaches or probability theory with the support of many mathematical approaches. Egan and Iacovelli (1996) used a LCC method to evaluate the total installation and operating costs of exterior wall assemblies that incorporate Exterior Insulation and Finish Systems (EIFS). Moussatche and Languell (2001) used a net present worth (NPW) analysis to evaluate the interior floor materials of the educational facilities in the state of Florida based on the 50-year service life. Aktacir et al. (2006) applied the Present-Worth Cost method to estimate a LCC using detailed load profiles and initial and operating costs to assess the economic viability of variable-air-volume (VAV) and constant-air-volume (CAV) air-conditioning systems. Shahata and Zayed (2008) developed a stochastic LCC for comparing various alternative strategies among water main rehabilitation techniques. Castro-Lacouture et al. (2009) introduced a mixed integer linear program (MILP) to improve green construction decision making through the selection of materials. The proposed model developed by both design and budget constraints to address realistic scenarios experienced by the decision maker. Also, the proposed model considered the constraints that describe the LEED requirements for the selection of material.

Wang et al. (2012) applied Monte-Carlo Simulation approach to the LCC management of public private partnership (PPP) and private financial initiative (PFI) projects to control the cost of building projects items. Alshamrani (2012) developed a Framework to select the suitable envelope and structure type for school buildings according to the LCC and sustainability points throughout their lifecycle. The LCC Forecasting Models were developed using Monte-Carlo Simulation to compare the performance of conventional and sustainable school buildings.

Kim et al. (2013) used Monte Carlo simulation to predict maintenance and repair costs of a hospital facility. The authors used a long normal distribution with most likely defined minimum and maximum values. Florez and Castro-Lacouture (2013) presented a mixed integer optimization model to help in the selection of suitable materials and design parameters for buildings using the LEED-rating system as a tool to evaluate the environmental requirements. The author considered the design considerations and the cost constraints as objective factors and the perceptions of user as subjective factor. Marzouk and Omar (2013) introduced a planning model of life cycle maintenance as a multi-objective optimization problem that was used to treat the sewer network condition and service lives as well as the LCC of the maintenance as a separate objective function using Monte-Carlo Simulation approach. Yang and Wang (2013) presented a framework integrate BIM with LCA by using BIM outputs to calculate the LCC. Their study automated the process of project evaluation and optimization. Also, Ding et al. (2014) presented a framework to manage the life cycle information only through BIM model. The framework doesn't consider risk analysis and choosing the most appropriate alternatives, considering the interaction between all variables. Jafari et al. (2014) estimated the LCC of the sustainable and ordinary housing retrofitting alternatives using Monte-Carlo Simulation by highlighting the significance of retrofit activities on the LCC of the house. Khalis et al. (2015) conducted a study for the extraction process of rapid and accurate parameters of a non-ideal p-n diodes such as the ideality factor, saturation current and series resistance using two technical methods. The first one, is used for solving the system of nonlinear equations using experiment results parameters. The second method is based on the least squares algorithm. Also, Masrour and Jabar (2016) conducted a study to discover the magnetic properties of Cayley trees of large molecules with dendrimer structure using Monte Carlo simulations. Cheng et al., 2016; Khalis et al. (2016) proposed a study to extract all solar cell parameters from a single I–V curve under one constant illumination level. Also, the study clarified the effect of light intensity and temperature on performance parameters of mc-si and pc-si solar cells. (2016) proposed an optimal design based on minimized LCC to optimize the design of chilled water pump systems of buildings taking into consideration the uncertainties of design inputs and models as well as the component reliability in operation using Monte-Carlo Simulation and Markov method. The study concluded that a high efficiency with a minimum total LCC could be achieved for the systems. Abanda and Byers (2016) developed a study to assess the impact of orientation on energy consumption in green buildings using BIM. Based on the results of the energy consumption to the different orientations, it concluded that a well-orientated building can save an acceptable amount of energy throughout its lifecycle. Lu et al. (2017) presented a review of published articles from 1999 to 2016 and 12 widely used types of BIM software, providing a holistic understanding and critical reflection on the nexus between BIM and green buildings. Saieg et al. (2017) conducted a systematic literature review to illustrate the synergies between Building Information Modeling, Lean construction and Sustainability fields in Architecture, Engineering and Construction industry. Masrour et al. (2017) used Monte Carlo simulations to investigate the magnetic properties of Ni2MnGa such as the Curie temperature TC(K) and to calculate the magnetic parameters. Masrour and Jabar (2018a, b) applied Monte Carlo simulations to investigate the ground state and magnetic properties of the spin Lieb nanolattice with three lattice sites with spins. Paiho et al. (2017) conducted a study to choose the most economic alternatives of heat pumps for Finnish new nearly zero energy residential buildings using LCC analysis. The study emphasized the effectiveness of the LCC analysis in determining economic efficiency of heat pumps and the study concluded that the economic order of the solutions did not change when the results were sensitized but the Ground Source Heat Pumps (GSHPs) were proven to be the most economic alternatives.

Tse et al. (2016) developed a study to analyze and evaluate the economic performance of a full scale water-based photovoltaic/thermal (PV/T) system in an office building considering the time value of money using net present value method The results showed that within the analysis time period of the model, a positive net present value is dominant in most cases. Cecconi et al. (2017) conducted a study aimed at supporting performance monitoring and energy management across the building lifecycle. The proposed study was automated and tested for robustness using Monte-Carlo Simulation. The paper showed that using a technique such as Monte-Caro during the design could be able to generate realistic scenarios for the spectrum of performance variability.

Valipour (2016) used the Optimization with neural networks to aid in the precipitation analysis in a humid region to detect drought and wet year alarms. Using the Optimization helped in the determination of the best role among the different phases, this led to improvement of network accuracy. Valipour (2015) used linear regression to evaluate the radiation-based models versus the FAO Penman–Monteith model to detect the optimum model under different weather conditions. Valipour (2015) used process flow diagram (PFD) and energy reference system (RES) to configure an Environmental flow diagram (EFD) to determine the pollution sources in the industrial companies. This approach has helped decision-makers to reach for the energy optimization and reduce environmental pollutants. Valipour (2012) conducted a study t to forecast the accurate estimation for the rainfall according to the climate conditions using time series models. The study concluded that time series models are better appropriate to rainfall forecasting in semi-arid climate.

Previous research efforts didn't take into account the effect of the uncertainty costs associated with building's systems on the economic and environmental performances of building. Further, they didn't consider both LCC and environmental performance as objective functions that can be optimized simultaneously. This paper addresses these gabs by proposing a framework that integrates Building Information Modeling (BIM), Optimization Modeling, and Monte-Carlo Simulation. The framework is considered a robust decision-making tool that selects the optimum building materials alternatives for each building system that achieve a minimum LCC and a maximum environmental performance of building and discover the most influential building system in each cost element starting from initial cost to end of life. It is worth noting that all previous research efforts dealt with the optimization model, adopting deterministic approaches. However, the Monte-Carlo Simulation model is used in this paper as a fitness function for the optimization model in order to take into account the stochastic nature of LCC. Also, the LEED-rating system is used to measure the environmental performance of the building. As the use of sustainable-building materials instead of traditional ones will help to gain points in LEED, which indicates the enhanced building environmental performance. The proposed stochastic LCC modelhelps in capturing any variation in cost data through considering all the cost elements throughout the lifecycle of sustainable building. Finally, sensitivity analysis is performed on the optimum solutions that are chosen by optimization model to examine the effect of different building systems on LCC and its components.

This paper focuses on evaluating the economic impact of sustainability through all phases of green building and measuring the degree of the environmental sustainability of building systems by using the Leadership in Energy and Environmental Design (LEED) rating system. Building Information Modeling (BIM) is considered an ideal digital tool for digitally representing the data repository of all information relating to the building lifecycle. In this paper, building information are stored and monitored in order to calculate the LCC and the degree of the environmental sustainability of building throughout its life phases.

2. Life cycle costs

Life cycle cost (LCC) analysis is considered an economic appraisal for existing asset or a potential investment, which takes into consideration the immediate and the longer term costs. LCC is the “cost of an asset or its parts throughout its lifecycle, while fulfills the performance requirements” (BS ISO 15686-5, 3.1.1.7). The purpose from LCC calculation is to enhance the decision-making process to form reasonable judgments on the economic performance of building through its useful lifecycle. Although the LCC progressed in long history of conventional LCCs since the 1930s, it is a relatively new tool within sustainability assessment. Currently, there are no standards available for the LCC of services and products in a sustainability context. However, in the building and construction sector, the ISO 15686-5 has been developed for Buildings and construction assets, 2018, makes a distinction between whole-life costs and life-cycle cost, where the latter is a part of the former (Schau et al., 2011). A LCC is dividing into four typically components to cover the overall projected costs of building throughout its lifecycle, which are initial cost (construction cost), operation and maintenance costs, replacement cost, and end-of-life costs including residual value. While, whole life costs are the sum of LCC, externalities, non-construction costs and income (Schau et al., 2011). The LCC is considered one of the three life cycle assessment (LCA) techniques that it can contribute in measuring the level of sustainable development. Globally, a green economy in the context of sustainable development is used as a main strategy to improve compatibility with the increasing resource needs of the growing population and the earth's diminishing natural resources. It is one of the reasons for the achievement of human well-being and social equity, while significantly reducing environmental risks scarcity of natural environmental resources. Therefore, there is a need for considering the three dimensions of sustainability using Life-Cycle Thinking tools in the decision-making process with an emphasis on the socioeconomic impact. A LCT allows incorporating sustainable development in decision-making processes by going beyond the more narrow traditional focus, which takes into consideration environmental, social and economic effects of a building over its entire lifecycle. The LCT is a holistic approach that considers sustainability factors over the entire life of a building, which works on reducing a building's used resources and negative environmental impacts as well as enhancing its socio-economic performance. Therefore, a LCT is used to assess the improvement degree of building sustainability throughout the building life (McConville and Mihelcic, 2007).

Owing to the significantly importance of the sustainability on the global level, the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) launched in 2002 an International Life Cycle Partnership, known as the Life Cycle Initiative (LCI). UNEP/SETAC Life Cycle Initiative aimed at enhancing the global consensus and relevance of existing and emerging life cycle methodologies and data management. The Initiative allowed users in anywhere around the world to put life cycle thinking into effective practice (Jolliet et al., 2004; Valdivia et al., 2013). Therefore, the research and development stage in any project that precedes the design stage is considered the foundation to manufacture cost-efficient products with minimal environmental impact, resource consumption and emissions. Therefore, economic and environmental considerations should be integrated as early as possible in the product development process like optimization parameters (Simões et al., 2013). Therefore, the integration of economic and environmental criteria is implemented in this paper using Building Information Modeling (BIM), Optimization Modeling, and Monte Carlo Simulation, which integrate LCC and LEED criteria with the basic sustainable requirements for building materials to achieve acceptable rank for the sustainability of building by considering a minimum LCC and maximum number of LEED-Credits points.

3. Proposed framework

The developed framework integrates Building Information Modeling (BIM) with two different models; Monte-Carlo simulation and optimization model as depicted in Fig. 1. BIM Model is used to represent the building geometrical information as a source of materials data such as quantities, lifecycle data and sustainability data. It is developed using Autodesk Revit (Building information modeling software). The main function of BIM in this study is to export different material data such as concrete, painting, plastering, flooring materials and bricks to simulation model. These data are used in calculating LCC and LEED credits. This is done by considering some steps. First, building materials library is developed in Autodesk Revit. This library contains the sustainable properties for each material (LEED data). Second, BIM model is developed and the materials are assigned to elements of the developed model. Finally, the building materials and its data are extracted from the model to be used in simulation and optimization models.

Monte-Carlo Simulation model is used to evaluate the LCC for building alternativematerials taking into consideration uncertainty

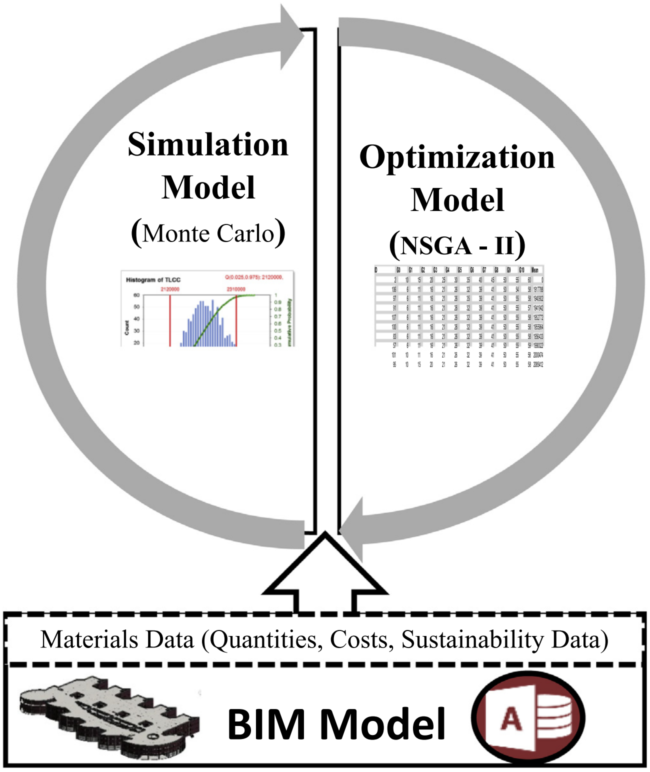


Fig. 1. Proposed life cycle cost framework for green building materials.

in costs through the analysis. Triangle distribution with defined minimum, most likely, and maximum values for each cost is used to calculate costs in the developed model based on the market prices for each building material. It is used as a fitness function for the optimization model. For each optimization trial, the optimization model retrieves the fitness function from the simulation model. The optimization model utilizes Genetic Algorithms (GA) optimization to select the optimum building materials scenarios that minimizes the LCC of building materials and grants the highest points in LEED rating system for the building.

In this paper, the construction systems in building are decomposed into substructure and superstructure works. These works are composed into eleven activities using Work Breakdown Structure (WBS).

4. Monte-Carlo simulation model

Monte Carlo method is a common name for a wide variety of probability techniques. Monte Carlo simulation is a powerful statistical analysis tool. It based on the use of random numbers (sampling) and probability statistics to investigate problems in fields as diverse as material science, economics, chemical and bio physics, statistical physics, nuclear physics, flow of traffic and many others. It is used to solve complex engineering problems because it can deal with a large number of random variables, various distribution types, and highly nonlinear engineering models (Gass and Assad, 2005). In this paper, the LCC projections of construction projects incorporate inherent and/or uncertain risks. Therefore, LCC forecasting models are developed using Monte-Carlo Simulation to determine the LCC of optimum building material scenario. The simulation model considers the eleven building systems for the evaluation. Each system has number of possible material alternatives. Each alternative is associated with a minimum and maximum LCC estimates. The four components of the LCC of building that were previously mentioned are considered to cover the overall projected costs of building. During the cost estimation process, each of these costs starting from initial costs to end of life costs is individually calculated for each competing alternative in each construction system of building. The total LCC of a building is sum of the LCC for all building systems. Due to the fact that the life span of most buildings ranges from 50 to 100 years, some cost elements are incurred at the outset and others may be incurred at different times throughout its lifecycle. Therefore, these costs could not be compared directly for getting a LCC of the building. In order to have an accurate total LCC, the time value of money is incorporated into the simulation models by converting each of the current year costs to present value. This process is conducted through employing a discount rate, which refers to the opportunity cost of money over the time period. In the simulation models, the discounted rate is used in discounted the future costs of building that are incurred through its lifecycle to determine the present value of these future costs, which include initial costs, operation and maintenance costs, replacement cost, and end-of-life cost including residual value.

In this paper, the real discount rate and constant dollar method were chosen to use in calculating the life cycle cost of building with discount interest rate equals 10%. Where, the cash flows can be included in LCC analysis either in constant dollar or in current dollar. The constant dollar method does not provide expectation of future rates of inflation and adjusted it into future costs. While, the current dollar method is used when there is a need for adjusting future costs to general inflation. To obtain the same present value from the two methods, different discount rates are used with constant-dollar amounts and current-dollar amounts. Real discount rate (exclusive of inflation) is used with the constant dollar method to reduce the future costs. While, nominal discount rate (inclusive of general inflation) is used with current dollar to reduce the future costs. While, nominal discount rate (inclusive of general inflation) is used with current dollar to reduce the future costs (Fuller and Petersen, 1996; Cheremisinoff, 2003).

In order to utilize the proposed framework in the future, Net Present Value (NPV) method is used as an economic evaluation method for the LCC. It is based on the time value of money concept. The LCC analysis of a building is performed through considering Beatty (2002) procedure. Detailed description of the followed procedure can be found elsewhere (Marzouk and Azab (2017). The sum of the present values of the individual discounted cash flows is calculated using Equation (1), taking into consideration the four components of the LCC of each building system.

$$\mathrm{NPV} = \sum_{0}^{n}\left(\frac{\mathrm{C_n}}{(1+\mathrm{i})^{\mathrm{n}}}\right) \tag{1}$$

where; NPV is net present value; C_n is the cash flow at year n; n is the year of cash flow; and i is the discount rate.

Table 1 lists the equations that are used for determining the present value of the LCC elements along with the description of application for each equation. It is worth noting that the analysis period must be the same for all alternatives while performing NPV analysis in order to obtain accurate results. For this reason, the length of study period is considered as the normal lifespan of the office building, which is assumed to be 80 years in this paper as per (Koroneos et al., 2007).

5. Optimization model

Optimization model uses the BIM data of green-building materials to calculate the LEED-credits points that would be achieved

Table 1
Life cycle cost elements.

No	LCC Elements	Description	Equation
1	PV of construction cost	It consists of the cash flows at time zero (C_0) such as material cost, labor cost and equipment cost.	$PV= C_0$
2	PV of operation and maintenance costs	Operation cost is related to the use of building system including energy costs. While, maintenance costs are the expenses of amendment, refinishing, or replacing sub components such as gaskets. “A” is the annual operation and maintenance cost	$PV = A\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]$
3	PV of replacement cost	It depends on the system service life. It occurs at the beginning of the system service life. If the system has a service life less than the life span of building, it will be replaced more than one time. “F” is the replacement cost that occurs after n periods in the future	$PV = F\,(1+i)^{-n}$
4	PV of residual value	It is the remaining value of system at the end of its life or at the time that it is replaced during study period. Where, it reflects the projected market value at the end of the study period “F” is the residual value that occurs after n periods in the future	$PV = F\,(1+i)^{-n}$

for the building and its related LCC that is retrieved from simulation model. This Model considers materials selection category in LEED, 2009 (V_3) for new construction and major renovations. Five credits from seven credits are selected to track the effect of their characteristics on the evaluation; materials reuse, recycled content, regional materials, rapidly renewable materials and certified wood. The other two credits, building reuse and construction waste management credits, are not considered in this paper; where the credit of building reuse is concerned with conserving the components of the existing building on the project land to incorporate them in constructing the new building. While, this study assumes that the project will be developed on a bare land. Also, the credit of construction waste management is concerned with developing and implementing a construction waste management plan to convert the waste from disposal into useful materials. For these reasons, building reuse and construction waste management credits are beyond the scope of this paper.

For each chosen credit, points can be awarded by selecting materials that achieve the requirements of sustainability based on their own sustainable data and then assembled to obtain the LEED points that could be awarded for the building. The number of LEED points awarded for the targeted five credits are eight points. Additional points are provided for achieving exemplary performance that exceeds the level of requirements for each credit. One point is awarded for each exemplary performance achieved by passing double the credit requirements and/or passing the next incremental percentage threshold of each credit. A maximum of three innovation points in design can be awarded for the exemplary performance (USGBC, 2009).

The LCC is determined using the material data that is extracted from BIM model and the predefined alternatives. The optimization model for the building is implemented by considering all systems of building, which account eleven building systems. Each system has a number of possible alternatives. Each alternative is associated with a certain sustainable material data and a LCC (Marzouk and Metawie, 2014). The optimization model is developed using genetic algorithm to select the optimum building alternatives that have a minimum LCC and maximum LEED-credit points. It uses NSGA-II genetic algorithm to solve multiple-objective problem in six steps (Deb et al., 2002):

1) Retrieve optimization model parameters; including number of generations, population size, mutation rate, and crossover rate. Then, generate the first population that contains the number of solutions.
2) Calculate the value of the objective functions for each solution
3) Find all solutions that are not dominated by other solutions (first front of non-dominated solutions)
4) Exclude the solutions of the first front and repeat the process to obtain the second non-dominated solutions which are dominated by the individuals in the first front only.
5) Repeat the process of non-dominating sorting and give a fitness value for each front. E.g., First front has a fitness value of 1 and second front has a fitness value of 2.
6) Create new child population using Genetic Algorithm operators of selection, crossover and mutation.

The decision variables (genes) for this algorithm are the eleven building systems. For each scenario with specific chosen alternatives, the optimization model is run to calculate the total LCC, total reused materials percentage, total recycled content value and percentage, total regional materials percentage, total rapidly renewable percentage, and total certified wood percentage of each building system. Then, it calculates the total LEED-credits point that would be achieved. The optimization algorithm tries to find the optimum scenario that achieves the objective functions.

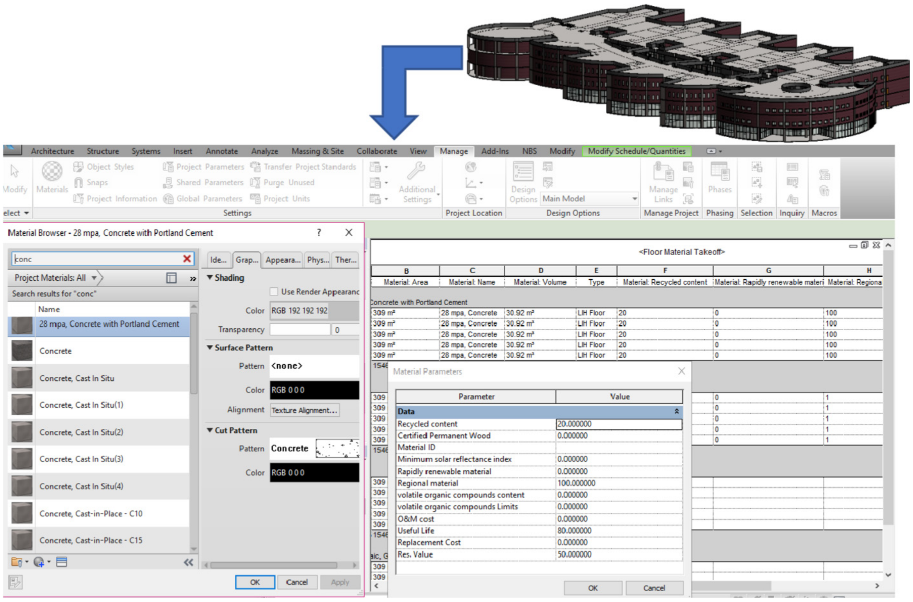
6. Case study

This section describes the implementation of the proposed framework on a university in Saudi Arabia. The university has three floors with a total area of 9000 m^2 per floor. Based on 2D CAD drawings, BIM model is developed using Autodesk Revit software. The different material data such as quantities and LEED data are extracted from the model (see Fig. 2). Based on the market prices for each building material is used in the model, a minimum and a maximum LCC estimates are determined for each system alternative taking into consideration the construction cost, the operation and maintenance cost, replacement cost and end-of-life costs including residual value related to each system alternative using the GA optimization model. Monte-Carlo Simulation models use these estimates to determine the LCC by using uniform distribution. The optimal solutions are obtained by integrating the genetic algorithms add-in with the Monte-Carlo simulation model. For Genetic algorithm operators in the optimization model, population size, number of generations, crossover rate, and mutation rates are set to 100, 1000, 0.7, and 0.2 respectively.

Based on the optimization model, the optimum solution has been obtained. The optimum scenario has a total cost of LE. 2,349,054 and 9 credit points out of 11 points available in LEED. The selected alternatives are marked with ‘*’ in Table 2. Fig. 3 shows the best results of the optimization model's scenarios in last generation. It shows different optimum scenarios with different LCC and LEED scores. The Figure shows that the relation between LEED credits and LCC are directly proportional; however, this relation isnot increasing with constant rate. Last scenario (11 LEED credit) has very high LCC with respect to the scored LEED credits.

7. Sensitivity analysis

Sensitivity analysis is conducted to discover the key building elements that affect the LCC and its components by computing the



Material Browser - 28 mpa, Concrete with Portland Cement

conc

Project Materials: All

Search results for "conc"

Name
28 mpa, Concrete with Portland Cement
Concrete
Concrete, Cast In Situ
Concrete, Cast In Situ(1)
Concrete, Cast In Situ(2)
Concrete, Cast In Situ(3)
Concrete, Cast In Situ(4)
Concrete, Cast-in-Place - C10
Concrete, Cast-in-Place - C15

Shading
☐ Use Render Appearanc
Color: RGB 192 192 192
Transparency: 0

Surface Pattern
Pattern: <none>
Color: RGB 0 0 0
Alignment: Texture Alignment...

Cut Pattern
Pattern: Concrete
Color: RGB 0 0 0

<Floor Material Takeoff>

B	C	D	E	F	G	H
Material: Area	Material: Name	Material: Volume	Type	Material: Recycled content	Material: Rapidly renewable materi	Material: Regiona
Concrete with Portland Cement						
309 m²	28 mpa, Concrete	30.92 m³	LIH Floor	20	0	100
309 m²	28 mpa, Concrete	30.92 m³	LIH Floor	20	0	100
309 m²	28 mpa, Concrete	30.92 m³	LIH Floor	20	0	100
309 m²	28 mpa, Concrete	30.92 m³	LIH Floor	20	0	100
309 m²	28 mpa, Concrete	30.92 m³	LIH Floor	20	0	100

Material Parameters

Parameter	Value
Data	
Recycled content	20.000000
Certified Permanent Wood	0.000000
Material ID	
Minimum solar reflectance index	0.000000
Rapidly renewable material	0.000000
Regional material	100.000000
volatile organic compounds content	0.000000
volatile organic compounds Limits	0.000000
O&M cost	0.000000
Useful Life	80.000000
Replacement Cost	0.000000
Res. Value	50.000000

Fig. 2. Materials data and quantities extracted from BIM.

spearman's rank order correlations coefficient between the costs of building systems and the target output. This is done using Crystal Ball program, which helps in analyzing risks and uncertainties associated with the Microsoft Excel spreadsheet models. Therefore, correlation coefficients are used to denote the sensitivity of the building systems according to the types of building. Monte-Carlo Simulation model is simulated five times to determine the effect of the LCC and each of its components on the building systems separately, considering the optimum scenario that has been chosen from the optimization model. Where, in each time of simulation a certain type of cost is chosen as a target output for the simulation as example: for the first time of simulation, the total initial cost of building will be chosen as the required output for the sensitivity analysis to examine the effect of the initial costs of building materials. while, the inputs of simulation model will be the other types of costs. In this case the values of these costs will remain the same without any change. In addition to, the initial costs for all types of building systems are inserted as an input model with its minimum and maximum values. For each simulation time, the distributions for costs of building systems are defined. After that, the Crystal Ball command icon is selected to run a simulation. For each simulation trial, Crystal Ball enters a random value into the cost cell based on the values that are used to define the distribution. Finally, the simulation model is run for 5000 trials to create a realistic possible outcome. The results are shown as a sensitivity graph between building systems against rank order correlation coefficient.

According to the previous steps, the model is simulated. The graphs of initial cost, operation and maintenance costs, replacement cost, end-of-life costs and LCC of a building are summarized in one graph as shown in Fig. 4. In which Fig. 4 represents a relationship between the eleven building systems and the correlation coefficient of the different costs for each system.

Values of the rank order correlation coefficient for the systems are between (+1) and (−1). Where, (+1) refers to a complete positive correlation between the inputs and outputs of the simulation model, which means that when the input is large; the output is also large. While, (−1) refers to a complete inverse correlation between the inputs and outputs of simulation model, which means that when the input is large, the output is small, and this leads to a complete inverse correlation between them. Finally, a sensitivity coefficient value of (0) refers to the absence of any correlation between the model variables.

8. Results and discussion

As the proposed framework is considered as a decision support tool, it aids decision makers to choose the appropriate materials based on based the correlation degree between the building materials and the costs components including the LCC of building. Fig. 4 depicts the correlation degree, rank order correlation coefficient, of each building system on the forecast cells of the LCC of and its four components.

According to the optimum scenario identified by optimization model, as shown in Fig. 4, the correlation coefficients for all building systems are positive, which means that there is a proportional correlation between the inputs and outputs of the model. This is due to that the inputs and outputs of the simulation model have the same units (i.e. the inputs and outputs represent costs).

8.1. Building systems and cost components correlation

For the sensitivity of initial cost, slabs and beam casting is the most influential system on this cost with a positive sensitivity coefficient equals to 0.65. It is followed by plastering, painting, column casting, doors and windows, block works, flooring, reinforced concrete foundation casting, plain concrete foundation casting, earth works, thermal insulation, and water insulation systems by a positive sensitivity coefficient ranges between 0.59 and 0.0 respectively. This means that there is a partial correlation between these systems and the total initial cost. While, possible inverse correlations don't exist for this scenario (see Fig. 4).

For sensitivity of operation and maintenance costs, it can be indicated that painting system has the highest influence on the operation and maintenance costs with a positive sensitivity coefficient equals to 0.83. It is followed by flooring system with rank coefficient equals to 0.49 and doors & windows system with rank coefficient equals to 0.19, plastering with rank coefficient equals to 0.12. While, block-works had a little effect on cost with a positive coefficient equals to 0.08. For other systems of buildings, they do not have any effect on this cost, which has a rank correlation equal

Table 2
Construction alternative data.

System Name	Material Alternatives	Description	LE/Unit		USD/Unit	
	ID	Name	Min	Max	Min	Max
PC Foundation Casting (PCF)	PcFn1*	21 mpa Concrete with Portland Cement	425.01	550.01	3323.578	4301.078
	PcFn2	15% Fly Ash Cement	467.51	605.01	3655.928	4731.178
	PcFn3	30% Fly ash cement	484.51	627.01	3788.868	4903.218
	PcFc4	Concrete Products with slag	552.51	715.01	4320.628	5591.378
	PcFc5	Precast Conc. 21mpa	765.01	990.01	5982.378	7741.878
RC Foundation Casting	RcFn1*	28 mpa Concrete with Portland Cement	935.00	1209.99	7311.7	9462.122
	RcFn2	15% Fly Ash Cement 28mpa	952.00	1231.99	7444.64	9634.162
	RcFn3	30% Fly Ash Cement 28mpa	969.00	1253.99	7577.58	9806.202
	RcFn4	Concrete with fly Ash 28mpa	986.00	1275.99	7710.52	9978.242
	RcFn5	Precast Conc 28 mpa	1275.00	1649.99	9970.5	12902.92
Water Insulation	WrIn1*	Cold Applied Bitumen	15.31	19.82	119.7242	154.9924
	WrIn2	High-density Polyethylene (HDPE) (5% reuse)	46.76	60.52	365.6632	473.2664
	WrIn3	Ansomat (5% reuse)	42.51	55.02	332.4282	430.2564
	WI4	Water Proofing Liquid	34.01	44.02	265.9582	344.2364
RC Columns Casting	CoCs1*	28 mpa Concrete with Portland Cement	1275.00	1649.99	9970.5	12902.92
	CoCs 2	15% Fly Ash Cement 28mpa	1317.50	1704.99	10302.85	13333.02
	CoCs 3	30% Fly Ash Cement 28mpa	1402.50	1814.99	10967.55	14193.22
	CoCs 4	Concrete with fly Ash 28mpa	1445.00	1869.99	11299.9	14623.32
	CoCs 5	Precast Conc 28 mpa	1657.50	2144.99	12961.65	16773.82
RC Slab Casting	SlCs1*	21 mpa Concrete with Portland Cement	1275.00	1649.99	9970.5	12902.92
	SlCs 2	15% Fly Ash Cement	1317.50	1704.99	10302.85	13333.02
	SlCs 3	30% Fly ash cement	1402.50	1814.99	10967.55	14193.22
	SlCs 4	Concrete Products with slag	1445.00	1869.99	11299.9	14623.32
	SlCs 5	21 mpa Concrete with Portland Cement	1657.50	2144.99	12961.65	16773.82
Block Works	Bk1*	Generic Brick (Clay Bricks)	357.28	462.36	2793.93	3615.655
	Bk2	Concrete Masonry Units (CMU)	397.27	514.12	3106.651	4020.418
	Bk3	Lightweight Aerated Concrete Block	1024.89	1326.32	8014.64	10371.82
	Bk4	Lightweight Precast Aerated Concrete Wall Panel System	1192.67	1543.46	9326.679	12069.86
Plastering	Ps1*	Cement Mortar	46.79	60.55	365.8978	473.501
	Ps2	American Clay Earth Plaster	90.99	117.75	711.5418	920.805
Flooring	Fl1	Ceramic Tile With Recycled Glass	45.95	59.47	359.329	465.0554
	Fl2*	Linoleum Flooring	169.11	218.84	1322.44	1711.329
	Fl3	Terrazzo	71.27	92.24	557.3314	721.3168
	Fl4	Wood Flooring	729.79	944.44	5706.958	7385.521
	Fl5	Natural Cork Flooring	652.22	844.06	5100.36	6600.549
Painting	Pn1	Jotun Paints	81.21	105.09	635.0622	821.8038
	Pn2	Hashmi Stone	154.35	199.75	1207.017	1562.045
	Pn3	Waterborne (or latex) Paints	93.05	120.42	727.651	941.6844
	Pn4	Stucco	160.90	208.22	1258.238	1628.28
	Pn5*	Terraco paints	74.61	96.56	583.4502	755.0992
Roof Insulation	In1	Solid foam (5 cm)	55.26	71.52	432.1332	559.2864
	In2	Rockwool	127.51	165.02	997.1282	1290.456
	In3	Blown Cellulose	110.51	143.02	864.1882	1118.416
	In4*	Rice Hulls	25.51	33.02	199.4882	258.2164
Doors & Windows Installation	D&W1	Wood Doors and windows 1	1562.46	2022.01	12218.44	15812.12
	D&W2*	Wood Doors and windows 2	693.23	897.12	5421.059	7015.478
	D&W3	Wood Doors and windows 3	739.81	957.40	5785.314	7486.868
	D&W4	Aluminum Doors and windows p.s Type	855.93	1107.67	6693.373	8661.979
	D&W5	Aluminum Doors and windows Tango Type	1089.65	1410.14	8521.063	11027.29

to 0.0 (see Fig. 4).

For the effect of the chosen building materials on the total replacement cost, Fig. 4 shows that painting system is the most system fungible, which has a high replacement cost during the operation lifecycle of building. It has the highest positive sensitivity coefficient equals to 0.99. It is followed by doors & windows system with a sensitivity coefficient equals to 0.1 and flooring system with sensitivity coefficient equals to 0.02. However, the other systems do not have any effect on this cost because their lifecycle exceed the lifecycle of the building.

For the sensitivity of end life costs including residual value, sensitivity graph (Fig. 4) shows that plastering system has the highest effect on the cost with a positive sensitivity coefficient equals to 0.82. It is followed by painting system with rank coefficient equals to 0.33, doors and windows system with rank coefficient equals to 0.30, block works system with rank coefficient equals to 0.27, and flooring system with rank coefficient equals to 0.27 respectively. While, water insulation, and thermal insulation systems have a little effect on this cost with a positive sensitivity coefficient with rank coefficient ranges from 0.01 to 0.02. Also, there islittle effect from concrete materials on the end life costs of building.

8.2. Building systems and the life-cycle cost correlation

For sensitivity of the chosen sustainable materials on the total LCC of building, the result shows that painting system has the highest effect on the LCC with a positive sensitivity coefficient equals to 0.62. It is followed by plastering, slabs and beam casting, flooring, doors and windows, block works, and column casting systems by a positive sensitivity coefficient ranges from 0.45 to 0.11 respectively, which refer to a partial correlation between these systems and the total initial cost. While, reinforced concrete foundation casting, plain concrete foundation casting, earth works,

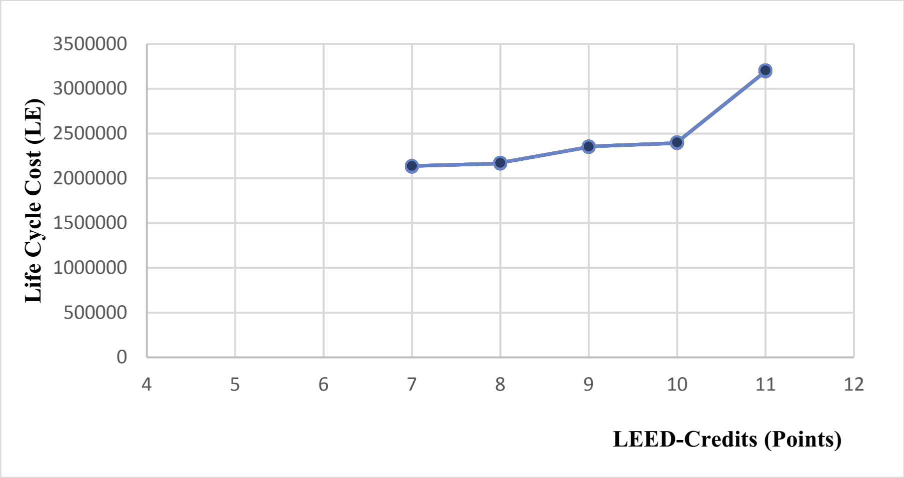


Fig. 3. The LEED-Credits points corresponding to each life-cycle cost.

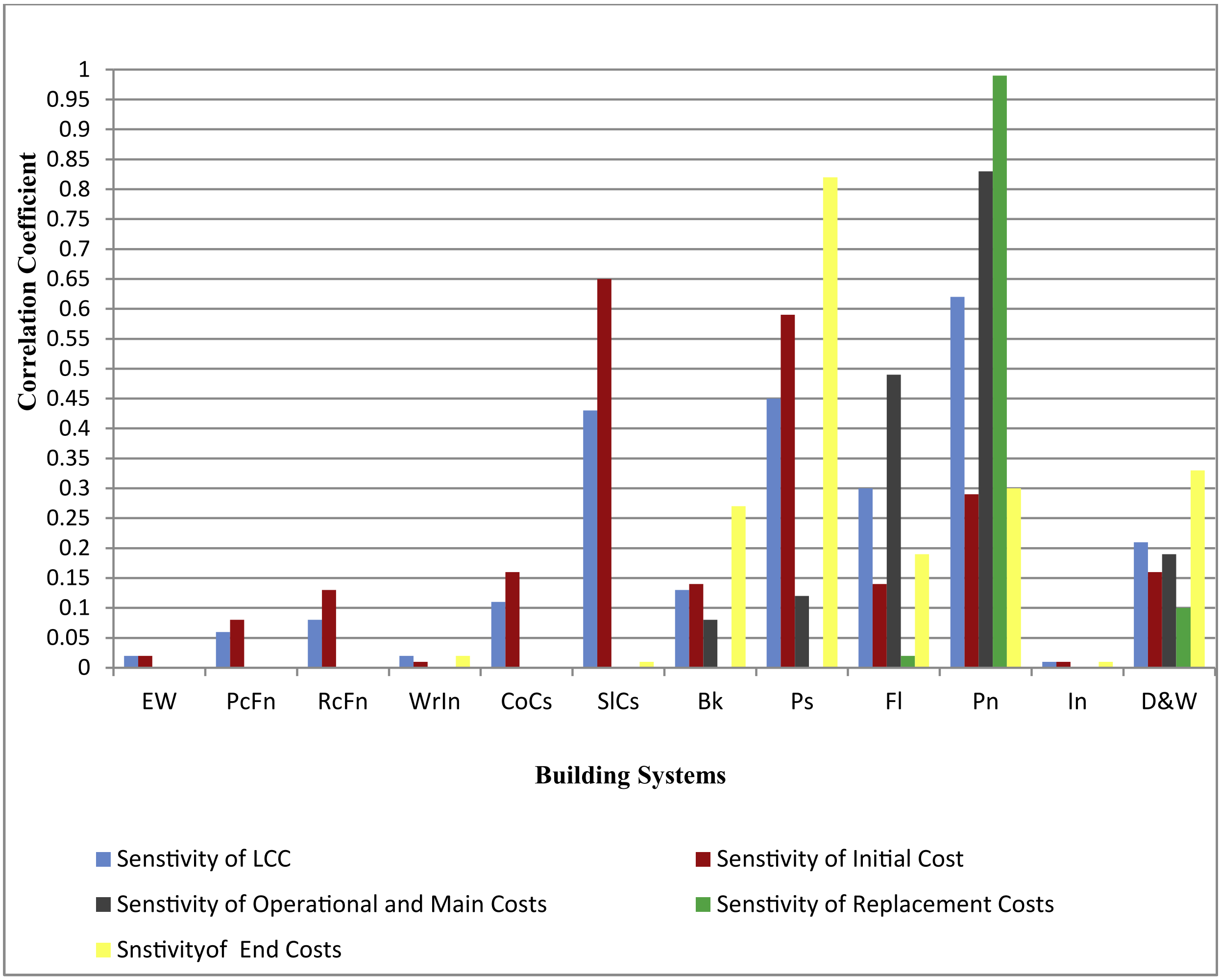


Fig. 4. Sensitivity Analysis of Building Systems against Rank Order Correlation Coefficient for All types of Costs.

water insulation, and thermal insulation systems have a little effect on LCC with a positive sensitivity coefficient ranges from 0.08 to 0.01 respectively. While, there is not any inverse correlation for this scenario (see Fig. 4).

9. Summary

Creation a sustainable building requires selecting building materials consume few costs through their lifecycle. Since the LCC estimation of construction projects contain inherent or uncertain risks, LCC forecasting models were developed by applying Monte-Carlo Simulation to determine the cost effectiveness of optimum building material scenario. LEED-rating system was used for determining the degree of the environmental sustainability of building according to the use of traditional and green materials in construction. The assessment has been carried out through proposing a framework that integrated Building Information Modeling (BIM) with two different models; Optimization model and Monte-Carlo Simulation model. BIM model has been used to represent the geometrical information and the other properties of the building such as building elements properties and material properties. The different materials quantities such as concrete, plastering, painting, bricks, flooring and doors & windows materials have been extracted from the model and then exported to the optimization and the simulation models. Monte-Carlo Simulation model has been used as a fitness function for the optimization model. For each generation during the GA optimization process, the fitness function is retrieved from the simulation model. The optimization model utilizes NSGA-II genetic algorithm to select the optimum building materials that minimizes the LCC of building materials scenario.

According to the sensitivity analysis of the optimum solution, the paper concluded that the building systems have different effects on each component of the LCC of building. Also, considering green-building materials instead of conventional building-materials through materials selection process enhances building performance, which has a crucial role in the formation of a sustainable building.

The proposed framework aids the decision makers in the construction industry to choose the appropriate building materials that achieve minimum LCC and maximum number of LEED-Credits Points taking into consideration uncertainty of costs through the analysis. The paper concluded that integrating BIM with Optimization Modeling, and Monte-Carlo Simulation helps the decision maker in selecting the optimum building materials that achieve the environmental and economic sustainability of the building.

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