Journal of Environmental Informatics 38(1) 56-67 (2021)

Journal of Environmental Informatics

www.iseis.org/jei

Evaluating Building Systems Energy Performance Superiority and Inferiority Ranking

M. Marzouk[1 *], I. Abdelbasset[1], and K. Al-Gahtani[2]

[1] *Structural Engineering Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt.*
[2] *Civil Engineering Department, College of Engineering, King Saud University, Riyadh 11362, Kingdom of Saudi Arabia.*

Received 17 August 2016; revised 02 May 2018; accepted 27 January 2020; published online 24 March 2021

ABSTRACT. Nowadays, the demand for sustainable buildings is increasing. The main purpose of buildings is to provide a comfortable living environment for their occupants, considering different aspects including thermal, visual, and acoustic comfort as well as Indoor Air Quality. Decreasing carbon footprint and energy consumption rates while increasing comfort level can help to achieve better living and working environment for building users. This research proposes a framework that aims at improving building system energy performance using building information modeling (BIM) during buildings' design stage by evaluating different alternatives for installed building systems. According to experts' opinions, evaluating buildings' energy performance by analyzing the energy consumption rates alone without including economic and environmental factors is insufficient. Therefore, in this paper, building systems are evaluated using four main criteria; operating cost savings, total energy consumption per year, Lifecycle cost savings, and carbon emissions. A Multiple Criteria Decision-making (MCDM) technique is applied using Superiority and Inferiority Ranking (SIR) to study the behavior of different alternatives. Sensitivity analysis is performed to detect the criticality and effectiveness of the different defined criteria that influence environmental concerns and building system energy performance. A case study is presented to demonstrate the use of the proposed framework on an academic building by considering four criteria which are Operating Costs, Life Cycle Cost, Energy Consumption, and Carbon Emissions. Sensitivity analysis is performed on the weights of the criteria to determine how critical each criterion is and how they affect the ranking of the alternatives. A total of 36 combinations are simulated, considering changing the weights and procedure (SAW vs. TOPSIS). The rank that has the top repetitive percentage is considered to identify the most dominating alternative.

Keywords: sustainability, building systems energy performance, multiple criteria decision-making, building information modeling, sensitivity analysis, superiority and inferiority ranking

1. Introduction

Construction industry has an immense negative impact on the environment. It consumes nearly 40% of the energy, 32% of renewable and non-renewable resources, 16% of water, 25% of timber and 40% of raw materials. Moreover, construction industry is responsible for approximately 35 ~ 40% of the carbon dioxide emissions. Sustainable building design, construction and operation require innovations in both engineering and management areas at all stages of a building's life. Inside this lifespan, essential requirements are generated from considerations of social, environmental, and economic issues for highly efficient energy-saving building systems in compliance with building codes and regulations. Energy consumed and greenhouse gas emitted during the buildings life cycle are considered of the most significant environmental problems.

The green building concept has been adopted by the construction industry as a response to the global environmental challenges and lead to successful results. Abbaszadeh et al. (2006) found that thermal comfort, air quality, furnishing, cleaning, and maintenance achieved higher rates of satisfaction in LEED-certified green buildings compared to non-green counter parts. On the other hand, clients are looking for the added benefits coming from applying the concept of sustainable buildings as they increase the capital cost invested to perform their projects (Paul and Taylor, 2008). Green buildings tend to reduce the harmful impacts of buildings on the environment and inhabitants, considering six main aspects: 1) efficient energy use, 2) healthy indoor air environment, 3) use of sustainable materials and resources, 4) efficient use of water, 5) lifecycle impact of different materials, and 6) minimum impact on both human health and environment. On the other hand, sustainable buildings consider broader aspects in addition to environment such as financial and social aspects over long periods of time. Previous research concluded that the aspect of sustainable and green buildings will become the most common among people when they are sure of the benefits and financial gains achieved from their projects as a result of the occupants' improved productivity (Zou and Zhao, 2014). This improved productivity is assigned to the comfortable and satisfying environment provided for their users. Interoperable Carbon Information Modeling (ICIM) provides an online tool to facilitate carbon assessment of a building by informing designers of their decisions and impact those decisions throughout the building life cycle (ICIM, 2011). Ac-

* Corresponding author. Tel.: +(202) 35678425; fax: +(202) 35723486.
E-mail address: mmarzouk@cu.edu.eg (M. Marzouk).

ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.202000448

cording to the norms of building automation, it was found that comfort is an important characteristic compared to the usual security and safety issues.

There are different definitions for the concept of BIM. BIM is the development and use of computer software model to simulate the construction and the operation of a facility (AGC, 2006). The resulting model, a building information model, is a data-rich, intelligent and parametric digital representation of the facility, from which data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility. A precise definition, proposed by the Royal Institute of Chartered Surveyors (Sawhney, 2014) is that "Building information modelling (BIM) gets people and information working together effectively and efficiently through defined processes and technology". BIM was also defined by the National Building Specification (NBS) to be "The process for generating and managing information" related to the building project throughout its life cycle. This information is updated and exchanged collaboratively during different project's stages. Using BIM is the corner stone for optimizing decisions to be made, actions to be taken and increasing "whole life value of assets" (McPartland and Mordue, 2016). Building Information Modeling (BIM) is considered one of the shining technologies developed to increase the efficiency of the construction industry. Its function was extended to help in the facility management process by using the As-built BIM model and it is also used in monitoring facility behavior over its life time as a way of increasing the level of control of buildings, even in operations or maintenance. These advantages are the results of the comprehensive information stored in the model during the construction process. Beazley et al. (2017) found that applying current industry BIM tools in embedding parameters in the data exchanges for thermal analysis would provide greater transparency of design intent and address coordination issues. Design decisions would be enriched with better information and that may lead to rapid iterative comparison of design alternatives, less chance of duplication in design effort to enhance the energy efficiency, and greater continuity of project data throughout project phases. The functional and physical characteristics of a facility can be modeled digitally using BIM (Marzouk and Abdelaty, 2014).

Thus, the main objective of the present study is evaluating buildings systems as per set of attributes that maximize the building sustainability. The present study assesses building's design using building information modeling considering several system design alternatives. Alternatives were studied with respect to preset objectives using SIR as a MCDM technique in order to aid with the decision of optimized design. The preset objecttives are limited to four main criteria; operating cost savings, total energy consumption per year, Lifecycle cost savings and carbon emissions. Also, a sensitivity analysis was performed on the problem criteria to detect the effectiveness of criteria and to support decision-making of alternatives with an increase in the efficiency of the resolution process. The effectiveness of criteria is meant to find how the weights used in the analysis may affect the results if they were slightly changed. Finally, this paper presents a case study of a university building located at King Saud University in Muzahimiyah campus which is close to Riyadh City, the capital of Saudi Arabia. The building is a multifunction consisting of offices, laboratories, and a lecture hall.

2. Literature Review

2.1. Multiple Criteria Decision-Making

Multiple Criteria Decision-Making (MCDM) techniques are used to model complex problems associated with different fields in the construction industry. Evaluating solutions usually require weighting factors in qualitative and quantitative manners. A number of decision methods have been developed to improve decision environments by providing objective modeling leading to subjective qualitative results. Multiple decision factors provide objectivity by cleaning out bias. Belton and Stewart (2002), Ergu et al. (2011), and Peng et al. (2011) portrayed some of these properties such as: (a) it seeks to take explicit account of multiple criteria, (b) it can put the management problem in a proper structured format, (c) it provides a model that can serve as a focus for discussion, and (d) it offers a process that leads to rational and explainable decisions. It was clear from literature review that MCDM has been applied in research forms and studies or in actual model forms to facilitate decision-making in different construction processes.

Superiority and Inferiority scores, as defined, are obtained by comparing different criteria values (Rebai, 1993, 1994). This method is performed due to the effect of uncertainty, indetermination, and imprecision in evaluating the criteria values and that is the reason for developing outranking methods to address such complex situations either by taking differences between values of criteria or introducing thresholds. The Superiority and Inferiority Ranking (SIR) technique was introduced by Xu (2001). Lv et al. (2012) indicated that the SIR method is considered an outranking method generalized for superiority and inferiority score notation taking into consideration the difference between types of generalized criteria and criteria values. This technique can also deal with data of different units and inexact environments. Several research efforts have been made to rank alternatives using multicriteria approaches. Marzouk (2008a) has proposed a generic tool for value engineering using the SIR ranking technique. This tool was developed with the aid of VBA. The tool requires inputs including: a) alternatives to be ranked, b) selected criteria, c) criteria weights (either to be defined or estimated), and d) ranking procedure (either Simple Additive Weighting [SAW] or Technique for Order of Preference by Similarity to Ideal Solution [TOPSIS]). For all selected criteria, it is required to define the criterion name, the selected generalized criteria and the preferred limit (the main objectives either to be minimized or maximized). The technique was also used by Tam et al. (2004) in concrete pump selection.

2.2. Building Energy Analysis

Simulation-based analysis related to energy management of buildings at design and operation have been performed in literature. Habibi (2017) introduced a strategy of combining building simulation tools and optimization methods with BIM. This resulted in some improvements not only at the construction process, but also in enabling exploration of alternative approaches. Jaggs and Palmer (2000) presented a methodology named EPIQR (Energy Performance Indoor Environmental Quality Retrofit) developed to help building owners who are deciding on refurbishment or upgrading their building stock. The EPIQR approach was developed through computer based programming that identifies the most appropriate retrofitting actions together with the initial cost estimate taking into consideration indoor and environmental quality. Horsley et al. (2003) designed a procedure for delivering energy efficient buildings by demonstrating environmental and economic benefits. A decision-support tool was developed to give guidance to the design teams at the early design stage where there is a lack of information regarding project specific energy performance issues, and their economic and environmental implications. Zurigat et al. (2003) simulated hourly cooling load for a public building under local climatic conditions using TRNSYS building computer simulation software. Different passive measures were investigated to reduce cooling loads which include space ventilation, envelope insulation, glazing, shading, artificial lighting, and evaporative cooling of the structure. These results are of high significance to building designers, architects, builders, contractors, and HVAC (Heat Ventilation and Air Conditioning) manufacturers.

Stephan and Stephan (2016) presented a quantification methodology for lifecycle energy and cost requirements for 22 different energy reduction measures. The introduced methodology helps in screening various energy reduction measures and identification of the most cost-effective measures. They took into consideration embodied, transport, and user-transport energy requirements. Embodied, operation, and transport energy was calculated over 50 years and lifecycle cost was calculated based on net present value methodology. They performed a sensitivity analysis for the inflation rates and discount rates. Moreover, they conducted sensitivity analysis for primary energy conversion factors of electricity.

AlAjmi et al. (2016) introduced a methodology to convert public buildings from inefficient energy consumers into net zero energy buildings (NZEB). The introduced methodology is achieved through cost effective energy efficient measures (EEMs) and integration with solar energy systems. They presented three scenarios that use the same roof area in order to convert buildings to net zero energy buildings. The implemented EEMs resulted in annual energy saving of 658.8 MWh and avoidance of 545.6 tons of carbon dioxide. Chau et al. (2015) illustrated different aspects of three streams of methods of lifecycle studies. The three streams are lifecycle assessment (LCA), lifecycle carbon emissions assessment (LCCO2A), and lifecycle energy assessment (LCEA). They compared the three streams against evaluation objectives, methodologies, findings and limitations of use of these streams as decision-making support tools. Chowdhury et al. (2008) conducted simulation of buildings' thermal-performances in order to forecast comfort of inhabitants in the buildings and to determine alternate cooling control systems. They concluded that systems that use chilled celling secure better thermal comfort for inhabitants during summer and winter in subtropical climate.

Djuric et al. (2007) performed optimization in order to determine the values of parameters that minimize the total cost and energy consumption where the thermal comfort aspect should be satisfied. The parameters were insulation thickness of building envelope, supply water temperature, and heat exchange area of radiators. They concluded that supply-water temperature greatly influences the time needed to reach desired indoor air temperature. Moreover, they concluded that the highest total cost is associated with the lowest supply-water temperature. Yeo and Gabbai (2011) illustrated the benefits of structural optimization of embodied energy in reinforced concrete structures. They concluded that optimization of structural member design for embodied energy results in a decrease of 10% in embodied energy and an increase of 5% in the cost. In addition to that, they concluded that embodied energy depends extensively on the value of the cost ratio (R) of steel reinforcement to concrete.

2.3. Research Gaps

Most of the previous studies focus on one perspective, as such, they are incapable to provide a comprehensive assessment of the building systems; including Operating Costs, Life Cycle Cost (LCC), Energy Consumption, and Carbon Emissions. Further, they lack the ability to combine such assessment criteria benefiting from the advantage of Multi-criteria decision-making (MCDM) and Building Information Modeling (BIM). The proposed framework is developed to enhance the process of building design and management of building systems based on economical and sustainability perspectives. The proposed framework proposes a comprehensive approach for applying energy analysis, compared to previous methodologies of energy analysis, where the framework allows the user to compare the performance of different building design systems. The proposed method tackles this issue by investigating different aspects that capture the sustainability of building systems. The framework takes into consideration the dynamic nature of external environmental changes over the year, whereas the proposed model considers a group of environmental and economic factors in order to evaluate a set of alternatives during the design phase. The assessment results are used to improve building system performance with respect to the consumption and usage of energy, and carbon emissions produced. Alternatives are studied with respect to preset objectives using SIR, combining economic, carbon Emissions, and energy related issues.

3. Proposed Framework

3.1. Model Development

The main objective of this research is to propose a framework that aims at improving building systems energy performance using BIM during buildings' design stage by evaluating different alternatives for the installed systems in buildings. The building systems are evaluated considering four main criteria; operating cost savings, total energy consumption per year, lifecycle cost savings, and carbon emissions. The framework consists of two main components; BIM Model and SIR Model. The designated procedure of the proposed framework is illustrated in Figure 1 and described in the sections below.

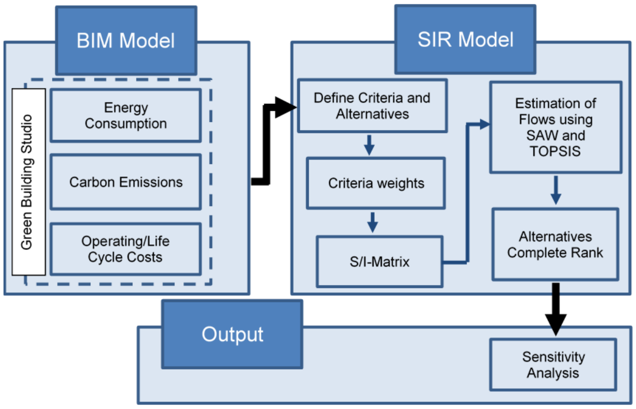

Figure 1. Propoased framework procedure.

The process of measuring temperature and humidity is required to be optimized by year-round tracking. In response to this problem, a thermal simulation was performed on the building using the developed BIM model with the help of the Revit and Green Building Studio software which was used to run an energy analysis. Energy consumption, carbon emissions, electrical cost, fuel cost and, other lifetime cycle cost issues were calculated to track the overall environmental performance for the building with respect to different types of costs. The analysis was first performed on Revit Software as all of the model spaces were defined and the model is exported in the GBXML format as shown in Figure 2.

After defining the space properties, the building was located on the map accurately using Google Earth. Then, the Riyadh city weather file was attached to the model and the solar path was defined according to the orientation of the building using Weather Tool (2017) as depicted in Figure 3. Temperature and Humidity effect on the building through the whole year is shown in Figure 4. The energy analysis process was performed to monitor the efficiency of the building behavior in dealing with energy usage and carbon emissions. This is important in judging the building's current design and in comparing it with alternative solutions. Each space in the building was defined according to its function (office, laboratory, lecture hall, etc.) and the settings were adjusted accordingly. The thermal properties of the building were selected and the HVAC system was defined along with its efficiency. Then, the thermostat range for environmental temperature comfort was defined, and lighting settings were set for each specified space. Finally, the operation schedule was defined according to the hours of operations of each zone.

The HVAC system Base case was set to be a Fan Coil System working on the concept of Constant Air Valve (CAV) with an assumed efficiency of 95%. Then, the first simulation experiment was conducted to study the impact of changing the HVAC system from Fan Coil System to Variable Air Valves (VAV) system. This change provided precise temperature control and improved system efficiency by providing low energy consumption. The simulation results of the alternatives listed in Table 1 were calculated using Green Building Studio software, considering the following inputs:

- The BIM model in the form of GBXML where some important data were embeded such as building area, space areas, volumes, material quantities, and types.
- The electric cost per KWH in Saudi Arabia was set to 0.09 SAR/KWH, considering average market rates.
- The fuel cost per MJ in Saudi Arabia was set to 0.007 SAR/MJ, considering average market rates.

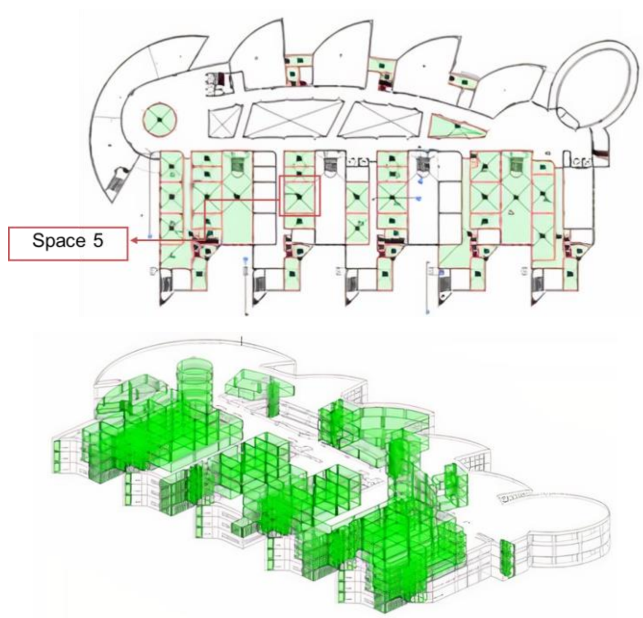

Figure 2. Defining spaces using Revit and exported GBXML file format.

3.2. SIR Model Criteria and Alternatives Definition

In order to improve the building design, several design alternatives were introduced then simplified into four main alternatives for the study based on the availability. These alternatives were inherited from the basic building design with some changes on the installed systems of HVAC and lighting. The basic design used a traditional HVAC system which is classified as a Constant Air Volume (CAV) system and the lighting system was a manual switching on/off system. Table 2 shows the variations in all alternatives. The basic design is referred to as Alternative 1.

The problem of improving the building design requires setting the main factors that can affect the decision-making process. After meeting with two domain experts who are specialized in energy performance in buildings, four objective criteria were chosen to be the most significant factors in the problem. These objective criteria are: 1) operating costs, 2) life cycle cost (LCC), 3) energy consumption, and 4) carbon emission. Operating costs were excluded from LCC because they have different significance as advised by experts. After setting the decision objectives to rely on for solving the problem, the relative importance

Table 1. Simulation Results of the Alternatives

Simulation	Original Case (RUP-BIM Model.xml)	Simulation Experiment 1 (VAV Alternative)	Simulation Experiment 2 (VAV and Lighting sensors)
Annual elec. cost (SAR)	138,807	134,804	133,254
Annual fuel cost (SAR)	691	691	691
Elec. demand (KW)	328.400	320.100	316.700
Annual elec. use (KWh)	1,478,242	1,435,616	1,419,110
Annual fuel use (MJ)	93,062	109,767	93,062
Energy use intensity (MJ/m^2/year)	767.700	748.300	737.500
Carbon emissions (MG)	537.000	522.500	515.700

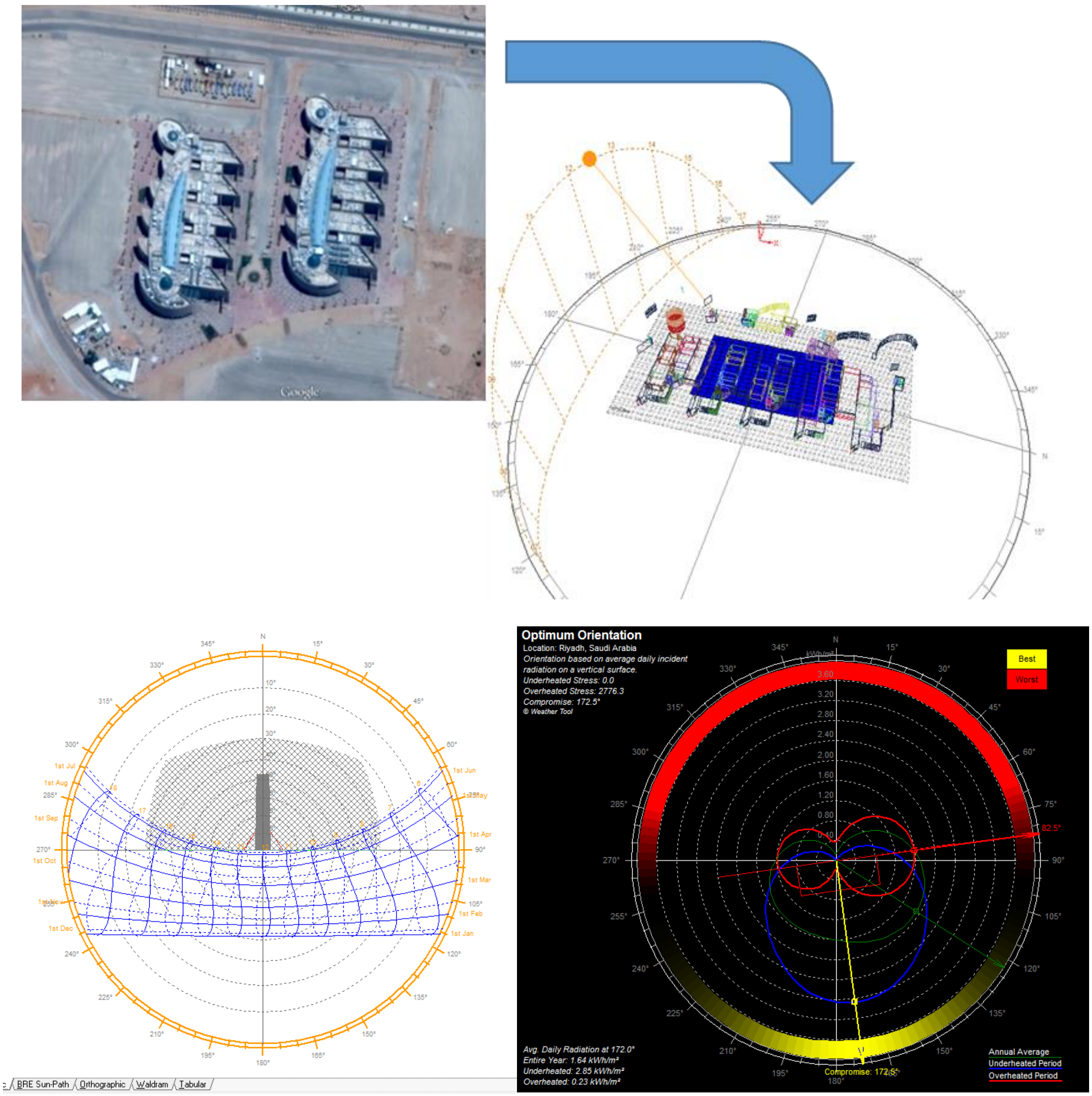

Figure 3. Locating the building with the proper orientation.

Table 2. Proposed Design Alternatives

Alternative	HVAC System	Lighting System
Alternative 1	CAV, Fan Coil Unit	Manual on/off switching
Alternative 2	VAV, ASHRAE 90.1-2007, COP 6.10 Chiller Electric Heat, 70F economizer	Manual on/off switching
Alternative 3	CAV, Fan Coil Unit	Day lighting sensors & controls
Alternative 4	VAV, ASHRAE 90.1-2007, COP 6.10 Chiller Electric Heat, 70F economizer	Day lighting sensors & controls
Alternative 5	VAV, ASHRAE 90.1-2004, COP 5.55 Chiller, Gas Boiler, 68F economizer	Occupancy/Day lighting sensors & controls

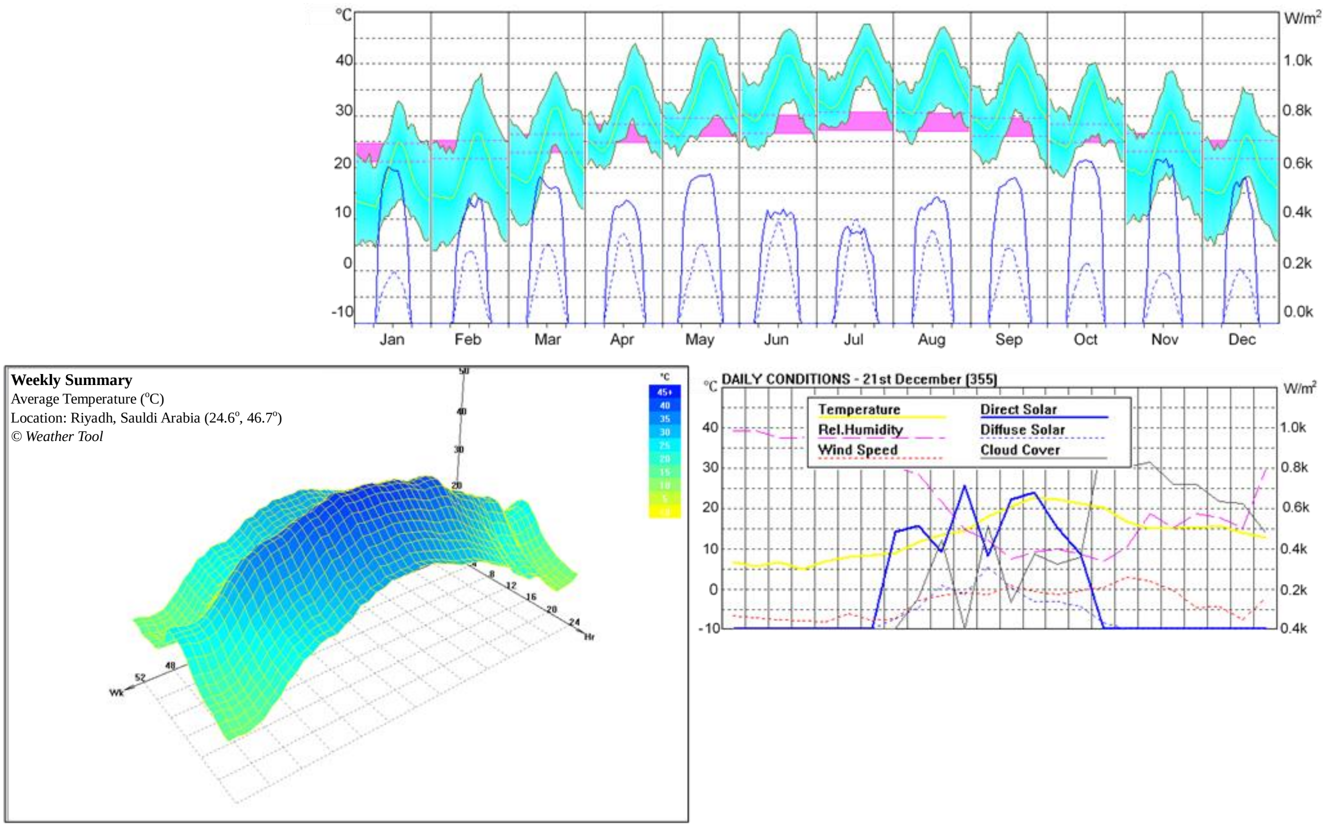

Figure 4. Temperature and humidity data throughout the year.

of objectives was estimated. This plays an important role in ranking the objectives and the alternatives later on. A questionnaire was conducted and distributed among experts to detect the relative importance of different objecttives. The questionnaire included the objectives hierarchy and their definition as well as the nine units scaling method developed by Saaty (1982) where 1 represented equal importance of the two alternatives, while 9 was used if one alternative was extremely important compared to the second one. Expert choice software was used in performing the questionnaire and in importing the questionnaire results where the Analytical Hierarchy Process (AHP) was applied in a simple way. This helped the user to indicate the priority of each factor. It also allowed the user to measure the overall consistency of the imported data. The criteria weights were imported from each questionnaire on a 1 ~ 9 scale. This scale is used on a pair wise comparison matrix which is composed of the four criteria in order to measure the relativeness between each criterion and the others. The four considered criteria were selected based on interviews that were conducted with two domain experts. The questionnaire survey was given to 10 respondents forming 10 pairwise comparison matrix then an average was calculated to reach a finalized matrix.

A consistency check was then applied to ensure the quality of fed data. The inconsistency was found to be 0.08 which is considered acceptable compared to the threshold limit 0.1 (Saaty, 1982). AHP helped the user synthesize the judgments performed in the pairwise comparison and the priority of each factor was indicated. It also allowed the user to measure the overall inconsistency of the imported data. The description and weights of criteria are listed in Table 3.

3.3. Superiority and Inferiority Ranking

The superiority and inferiority ranking (SIR) method, proposed by Xu (2001), is essentially an extension of superiority and inferiority scores defined by Rebai (1993) and Rebai (1994). It accounts for the differences between criteria values and allows the use of different types of generalized criterion. SIR provides the ranking of alternatives either in a form of complete ranking or partial ranking as described below.

3.3.1. Decision Matrix

The measured criteria (g_1, g_2, …, g_n) and alternatives (A_1, A_2, …, A_m) form a decision matrix, **D**:

$$\mathbf{D} = \begin{pmatrix} g_1(A_1) & g_2(A_1) & \cdots & g_n(A_1) \\ g_1(A_2) & g_2(A_2) & \cdots & g_n(A_2) \\ \cdots & \cdots & \cdots & \cdots \\ g_1(A_m) & g_2(A_m) & \cdots & g_n(A_m) \end{pmatrix} \tag{1}$$

Brans et al. (1986) proposed six generalized criteria which are True Criterion, Quasi Criterion, Criterion with Linear Preference, Level Criterion, Criterion with Linear Preference and Indifference Area, and Gaussian Criterion. The differences between criteria values are estimated using Equation (2):

$$P(A, A') = f(d) = f(g(A) - g(A')) \tag{2}$$

where $P(A, A')$ is the intensity of the preference of A over A'. f (difference between Alternatives) = f (Alternative 1 including criteria impacts – Alternative 2 including criteria).

3.3.2. Superiority and Inferiority Matrices

For each alternative A_i, the superiority index $S_j(A_i)$ and inferiority index $I_j(A_i)$ are estimated for criterion j of alternative i using Equations (3) and (4):

$$S_j(A_i) = \sum_{k=1}^{m} P(A_i, A_k) = \sum_{k=1}^{m} f_j(g_j(A_i) - g_j(A_k)) \tag{3}$$

$$I_j(A_i) = \sum_{k=1}^{m} P(A_k, A_i) = \sum_{k=1}^{m} f_j(g_j(A_k) - g_j(A_i)) \tag{4}$$

As such, superiority matrix (**S**-matrix) and inferiority matrix (**I**-matrix) can be formed using superiority and inferiority indexes as follows:

$$\mathbf{S} = \begin{pmatrix} S_1(A_1) & S_2(A_1) & \cdots & S_n(A_1) \\ S_1(A_2) & S_2(A_2) & \cdots & S_n(A_2) \\ \cdots & \cdots & \cdots & \cdots \\ S_1(A_m) & S_2(A_m) & \cdots & S_n(A_m) \end{pmatrix} \tag{5}$$

$$\mathbf{I} = \begin{pmatrix} I_1(A_1) & I_2(A_1) & \cdots & I_n(A_1) \\ I_1(A_2) & I_2(A_2) & \cdots & I_n(A_2) \\ \cdots & \cdots & \cdots & \cdots \\ I_1(A_m) & I_2(A_m) & \cdots & I_n(A_m) \end{pmatrix} \tag{6}$$

3.3.3. Estimation of Flows

The superiority and inferiority indexes (arranged in **S**-matrix and **I**-matrix, respectively) are aggregated into superiority flow (S-flow) φ > (.) and inferiority flow (I-flow) φ < (.). The S-flow and I-flow are basically the intensity of each alternative. The former flow measures how an alternative is globally superior to (or outranks) all the others, whereas, the latter flow measures how an alternative is globally inferior to (or is outranked by) all the others. Simple Additive Weighting (SAW) is an aggregation procedure that is used to obtain S-flow and I-flow. It should be noted that SAW procedure calculates the flows based on the weight of criteria (w_i) as per Equations (7) and (8):

$$\varphi^{>}(A_i) = \sum_{j=1}^{n} w_j S_j(A_i) \tag{7}$$

$$\varphi^{<}(A_i) = \sum_{j=1}^{n} w_j I_j(A_i) \tag{8}$$

where $\sum_{j=1}^{n} w_j = 1 (w \geq 0)$.

Then, net flow (n-flow) and relative flows (r-flow) are calculated utilizing S-flow and I-flow as per Equations (9) and (10):

$$\varphi_n(A_i) = \varphi^{>}(A_i) - \varphi^{<}(A_i) \tag{9}$$

$$\varphi_r(A_i) = \varphi^{>}(A_i) / (\varphi^{>}(A_i) + \varphi^{<}(A_i)) \tag{10}$$

3.3.4. Complete Ranking

Four complete ranking types are obtained from S-flow, I-flow, n-flow and r-flow. These are S-ranking ($\Re_>$), I-ranking ($\Re_<$), n-ranking ($\Re_n$) and r-ranking ($\Re_r$). The S-ranking ($\Re_> = \{P_>, I_>\}$) considering the descending order of $\varphi^{>}(A_i)$ as follows:

$$A_i p_> A_k \text{ iff } \varphi^{>}(A_i) > \varphi^{>}(A_k) \tag{11}$$

$$A_i I_> A_k \text{ iff } \varphi^{>}(A_i) = \varphi^{>}(A_k) \tag{12}$$

The I-ranking ($\Re_< = \{P_<, I_<\}$) considering the ascending order of $\varphi^{<}(A_i)$ as follows:

$$A_i p_< A_k \text{ iff } \varphi^{<}(A_i) > \varphi^{<}(A_k) \tag{13}$$

$$A_i I_< A_k \text{ iff } \varphi^{<}(A_i) = \varphi^{<}(A_k) \tag{14}$$

The n-ranking and r-ranking considering the descending order of n-flow and r-flow, respectively.

3.3.5. Partial Ranking

Partial ranking ($\Re$) is obtained by combining S-ranking ($\Re_>$) and I-ranking($\Re_<$) in a partial ranking structure as follows:

$$\Re = \{P, I, R\} = \Re_> \cap \Re_< \tag{15}$$

The intersection principle [13, 15] is used to compare any two alternatives, considering three options: 1) Preference relation (*P*), 2) Indifference relation (*I*), and 3) Incomparability relation *R*.

4. Case Study

4.1. Sensitivity Analysis

A university building located at King Saud University in Muzahimiyah campus, which is close to Riyadh City the capital of Saudi Arabia, was chosen for this case study. The building is multifunction, it has offices, laboratories, and a lecture hall. It consists of ground floor and two typical floors. The four objectives for the study were Operating Costs, Life Cycle Cost, Energy Consumption, and Carbon Emissions. Table 4 lists the estimated values of the criteria for five alternatives of the considered case study which essentially form the decision matrix. Subsequently, superiority and inferiority matrices can be formed, for simplicity, considering the first type of generalized criteria which is True Criterion as shown in Equations (16) and (17). Finally, SIR flows are calculated using SAW procedure and TOPSIS procedure for ƛ = 1 (the block distance), ƛ = 2 (the Euclidean distance) and ƛ = 10 (the distance with significantly large ƛ) as listed in Table 5. Detailed description of aggregation using SAW procedure and TOPSIS can be found elsewhere (Xu, 2001; Marzouk, 2008b).

$$\mathbf{S}-\text{Matrix} = \begin{bmatrix} 2 & 2 & 2 & 2 \\ 1 & 3 & 1 & 3 \\ 4 & 0 & 4 & 0 \\ 3 & 1 & 3 & 1 \\ 0 & 4 & 0 & 4 \end{bmatrix} \tag{16}$$

$$\mathbf{I}-\text{Matrix} = \begin{bmatrix} 2 & 2 & 2 & 2 \\ 3 & 1 & 3 & 1 \\ 0 & 4 & 0 & 4 \\ 1 & 3 & 1 & 3 \\ 4 & 0 & 4 & 0 \end{bmatrix} \tag{17}$$

It is worth noting that the results of SAW procedure and TOPSIS procedure (for ƛ equals 1, 2 and 10) are giving the same rank of the five alternatives as follows: A3 → A4 → A1 → A2 → A5.

Sensitivity analysis was performed on the weights of the criteria to determine how critical each criterion is and how they affect the ranking of the alternatives. Triantaphyllou and Sanchez (1997) proposed sensitivity analysis procedure to identify the most critical criterion that alters the existing ranking of the alternatives by slightly changing its weight. Four scenarios were worked out by considering equal weights of criteria, and random weights of specific criteria, adopting Triantaphyllou and Sanchez (1997) procedure.

4.2. Analysis of Scenarios

4.2.1. Scenario 1

In this scenario, all criteria were assumed to have equal weights; this means that all of them have the same weight of 25%. The new weights were substituted in the SIR model. Superiority and inferiority matrices were formed and SIR flows were calculated using SAW procedure and TOPSIS procedure and listed in Table 6. In this scenario, the alternatives are incomparable and cannot be ranked.

4.2.2. Scenario 2

In this scenario, the followed procedure was using random values for each criterion in order to substitute its original weights in the flow calculations. The procedure was applied considering random weights separately with incremental increase for each criterion. The increased percentage was deducted equally from the rest of the criteria in order to keep the summation of weights normalized at 100%. The incremental increase continued until one of two aspects were met either 1) a change in the ranking order of the alternatives occurred, or 2) negative weight value for any other criterion was reached. In this scenario, three experiments were conducted on three different criteria. Experiment 1 investigated energy consumption criterion as the original weight of 26% was substituted with random incremental values. A threshold of change in alternative ranking order was reached after increasing the original weight by 20%. Similarly, Experiments 2 and 3 investigated Carbon emissions and Life cycle cost savings criteria as the original weights of 21 and 27% were substituted with random incremental values for the two criteria, respectively. The new weights of the four criteria in the three experiments are shown in Table I1 - Appendix I. SIR flows were calculated using SAW procedure and TOPSIS procedure for the experiments of Scenario 2 and are listed in Table I2 - Appendix I. The rank of the five alternatives using SAW procedure and TOPSIS procedure (for ƛ equals 1, 2 and 10) are listed in Table I3 - Appendix I.

Table 3. Criteria Description and Weights

Criteria	Description	Weight
Operating cost savings (SAR)	Costs associated with all operating actions and maintenance in the whole building life time. Savings here is concerned with which alternative is consuming lower costs	0.310
Total energy consumption per year (MJ/m^2/year)	It is concerned with the total energy consumption by the building per year	0.260
Life cycle cost savings	All costs during the whole building life cycle (From the raw material stage to the demolition stage including initial costs and assumed life time of 20 years (operating costs are excluded)	0.230
Carbon emissions (MG)	It is concerned with the amount of carbon emitted by the building through its life cycle time	0.200

Table 4. Estimated Values of the Criteria for Five Alternatives

Criteria	Weight	Alternative					Objective
		A1	A2	A3	A4	A5	
Operating cost savings (SAR)	0.310	-	(3,803.98)	3,676.650	363.490	(9,792.120)	Increase
Total energy consumption per year (MJ/m^2/year)	0.260	767.700	747.020	787.680	769.680	717.810	Decrease
Life cycle cost savings (20 years)	0.230	-	(66,523)	105,126	27,942	(203,613)	Increase
Carbon emissions (MG)	0.200	537.000	522.400	551.100	538.400	500.200	Decrease

Table 5. SIR Flows Using SAW and TOPSIS Procedures

Procedure		Alternative	*S*-Flow	*I*-Flow	*n*-Flow	*r*-Flow
SAW		A1	2.000	2.000	0	0.500
		A2	1.923	2.077	-0.154	0.481
		A3	2.154	1.846	0.308	0.539
		A4	2.077	1.923	0.154	0.519
		A5	1.846	2.154	-0.308	0.462
TOPSIS	$\lambda = 1$	A1	0.500	0.500	0	0.500
		A2	0.481	0.519	-0.038	0.481
		A3	0.539	0.462	0.077	0.538
		A4	0.519	0.481	0.038	0.519
		A5	0.462	0.539	-0.077	0.462
	$\lambda = 2$	A1	0.500	0.500	0	0.500
		A2	0.469	0.531	-0.062	0.469
		A3	0.539	0.461	0.078	0.539
		A4	0.531	0.469	0.062	0.531
		A5	0.461	0.539	-0.078	0.461
	$\lambda = 10$	A1	0.500	0.500	0	0.500
		A2	0.456	0.544	-0.088	0.456
		A3	0.544	0.456	0.088	0.544
		A4	0.544	0.456	0.088	0.544
		A5	0.456	0.544	-0.088	0.456

Table 6. SIR Flows Using SAW and TOPSIS Procedures

Procedure	Alternative	*S*-Flow	*I*-Flow	*n*-Flow	*r*-Flow
SAW	A1	2.000	2.000	0	0.500
TOPSIS (λ = 1, 2 and 10)	A2	2.000	2.000	0	0.500
	A3	2.000	2.000	0	0.500
	A4	2.000	2.000	0	0.500
	A5	2.000	2.000	0	0.500

4.2.3. Scenario 3

The same procedures followed in Scenario 2 were applied except for the deduction step, where the increased percentage in the weight was deducted relatively from the other weights according to each criterion importance. The first experiment was applied on the energy consumption criterion, considering an increase of 30% as initial trial. Whereas, when the second experiment was carried out, a change in the rank of alternatives was observed with a change of 30% increase of the original weight of carbon emissions criterion (see Table I4 - Appendix I). SIR flows were calculated using SAW procedure and TOPSIS procedure for the Experiments of Scenario 3 and are listed in Table I5 - Appendix I. The rank of the five alternatives using SAW procedure and TOPSIS procedure (for λ equals 1, 2 and 10) are listed in Table I6 - Appendix I.

4.2.4. Scenario 4

The procedure followed in this scenario was considering an increase in the original weights of two combined criteria simultaneously. The increased amount in the weight value of the two criteria was relatively deducted from the rest of the criteria according to each criterion's weight. In Scenario 4, two experiments were also performed to detect the sensitivity of the criteria. The first experiment was applied on the energy consumption and the carbon emissions criteria together. It was found that after an increase of 10% on the two criteria the ranking of alternatives rank was changed as shown in Table I7 - Appendix I. In the second experiment, the random weight values were applied to energy consumption and life cycle cost saving criteria. At a 70% increase, the alternatives changed as shown in Table I7 - Appendix I. SIR flows were calculated using SAW

Table 7. Alternatives Rank for Base and Scenarios Cases

Scenario	Experiment	Procedure		Rank
Base	--	SAW		$Rank_{\_B}$
		TOPSIS	λ = 1	$Rank_{\_B}$
			λ = 2	$Rank_{\_B}$
			λ = 10	$Rank_{\_B}$
Scenario 1	--	SAW		$Rank_{\_IC}$
		TOPSIS	λ = 1	$Rank_{\_IC}$
			λ = 2	$Rank_{\_IC}$
			λ = 10	$Rank_{\_IC}$
Scenario 2	Experiment 1	SAW		$Rank_{\_B}$
		TOPSIS	λ = 1	$Rank_{\_B}$
			λ = 2	$Rank_{\_IC}$
			λ = 10	$Rank_{\_1}$
	Experiment 2	SAW		$Rank_{\_2}$
		TOPSIS	λ = 1	$Rank_{\_2}$
			λ = 2	$Rank_{\_IC}$
			λ = 10	$Rank_{\_B}$
	Experiment 3	SAW		$Rank_{\_B}$
		TOPSIS	λ = 1	$Rank_{\_B}$
			λ = 2	$Rank_{\_B}$
			λ = 10	$Rank_{\_B}$
Scenario 3	Experiment 1	SAW		$Rank_{\_2}$
		TOPSIS	λ = 1	$Rank_{\_2}$
			λ = 2	$Rank_{\_2}$
			λ = 10	$Rank_{\_1}$
	Experiment 2	SAW		$Rank_{\_2}$
		TOPSIS	λ = 1	$Rank_{\_2}$
			λ = 2	$Rank_{\_2}$
			λ = 10	$Rank_{\_1}$
Scenario 4	Experiment 1	SAW		$Rank_{\_2}$
		TOPSIS	λ = 1	$Rank_{\_2}$
			λ = 2	$Rank_{\_2}$
			λ = 10	$Rank_{\_1}$
	Experiment 2	SAW		$Rank_{\_2}$
		TOPSIS	λ = 1	$Rank_{\_2}$
			λ = 2	$Rank_{\_2}$
			λ = 10	$Rank_{\_1}$

Note: $Rank_{\_B}$: A3 → A4 → A1 → A2 → A5, $Rank_{\_1}$: A2 → A5→ A1→ A3 → A4, $Rank_{\_2}$: A5 → A2→ A1→ A4 → A3, and $Rank_{\_IC}$: Incomparable.

procedure and TOPSIS procedure for the Experiments of Scenario 3 and are listed in Table I8 - Appendix I. The rank of the five alternatives using SAW procedure and TOPSIS procedure (for λ equals 1, 2 and 10) are listed in Table I9 - Appendix I.

4.3. Results and Discussion

As refereed to earlier, the results obtained from the as-built BIM model was used to monitor system behavior and occupant's comfort levels. The BIM model was developed to estimate: 1) operating costs, 2) life cycle cost (LCC), 3) energy consumption, and 4) carbon emissions. Then, the simulation results of the alternatives were obtained.

Alternatives were studied with respect to present objectives using SIR, combining economic, carbon emissions, and energy related issues. Sensitivity analysis was performed to detect the uncertainty in model's outputs that can be apportioned to uncertainty associated with model inputs. Sensitivity analysis is considered useful when facing complex decision-making because of inherent instability. Different scenarios were generated in which the priority of alternatives was changed to reach a consensus. The outputs obtained from the Base case and the considered four scenarios are summarized in Table 7. Overall, three ranks of alternatives have been obtained; $Rank_{\_B}$, $Rank_{\_1}$, and $Rank_{\_2}$. There are few situations where the alternatives cannot be ranked (i.e., $Rank_{\_IC}$) such as in scenario 1 and few instances in Scenario 2. For SAW procedure and TOPSIS procedure at λ = 1, $Rank_{\_2}$ is the most frequent rank which was repeated five times compared to $Rank_{\_B}$ reoccurred three times. $Rank_{\_2}$ was obtained in the second experiment of Scenario 2 in addition to the different experiments of the second and third scenarios. Rank_B, on the other hand, was obtained in the base scenario, and the first and third experiments in the second scenario.

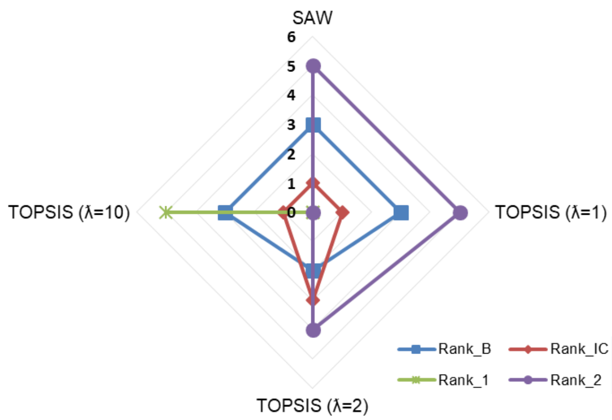

Figure 5. Sensitivity analysis ranks at different procedures.

For TOPSIS procedure at ƛ = 10, Rank_1, which was repeated five times, is the most frequent rank compared to Rank_B that was repeated three times. Incomparable rank (Rank_IC) was repeated three times with TOPSIS procedure at ƛ = 2 and occurred once in the remaining procedures. For TOPSIS procedure at ƛ = 2, the frequency for Rank_B and Rank_2 are two and four, respectively. Figure 5 summarizes the frequency of the different ranks (Rank_B, Rank_IC, Rank_1 and Rank_2) in the different procedures. It is worth noting that SAW procedure and TOPSIS procedure at ƛ = 1 provide the same results with respect to the alternatives ranks in all Scenarios and Experiments.

Overall, 36 combinations were simulated, considering changing the weights, procedure (SAW vs. TOPSIS), and the ƛ value of TOPSIS procedure. These combinations provide a systematic and comprehensive assessment for the different scenarios may be encountered during the assessment process. The percentage of different ranks and incomparable situation can be summarized as follows:

- Rank_B occurs 11 times representing 30.6% of combinations.
- Rank_1 occurs 5 times representing 13.8% of combinations.
- Rank_2 occurs 14 times representing 38.9% of combinations.
- Rank_IC occurs 6 times representing 16.7% of combinations.

As such, Rank_2 (A5 → A2 → A1 → A4 → A3) has top repetitive percentage which indicates that A5 is the most dominating alternative; i.e., A5 alternative outperforms the remaining alternatives. Since it is the best alternative, the HVAC system (VAV, ASHRAE 90.1-2004, COP 5.55 Chiller, Gas Boiler, 68F economizer) along with Occupancy/Day lighting sensors & controls lighting system are the best combination alternative for the considered case study to assure a high energy performance system and consequently maximize sustainability.

As such, it is important to conduct sensitivity in order to identify the dominating alternative since the critical criterion is not necessarily to be the one that has the highest weight. Also, it is worth to note that the rank of alternatives depends on the considered decision-making techniques and the utilized procedure/parameters in these techniques. Therefore, the same problem needs to be examined in different decision-making techniques to identify the robust one.

5. Conclusions

This research presented a framework for evaluating building design using BIM by considering several design of system alternatives. Alternatives are studied relatively with respect to preset objectives using SIR as a MCDM technique in order to help designers reach an optimized solution. A case study was presented to illustrate the proposed framework. Sensitivity analysis was performed on the decision-making problem to identify the most critical criterion that alters the existing ranking of the alternatives by slightly changing its weight. Four scenarios that detect the criticality of the problem objectives as well as the effectiveness of inputs in getting outputs were presented. The outputs obtained from the Base case and the four scenarios were investigated. Three ranks of alternatives were obtained, although there were situations where the alternatives could not be ranked. Sensitivity analysis was performed on the weights of the criteria to determine how critical each criterion is and how they affect the ranking of the alternatives. It is worth noting that the most weighted criteria is not necessary to be the critical one. The most critical criterion that alters the existing ranking of the alternatives by slightly changing its weight. For the considered case, four objectives were considered (Operating Costs, Life Cycle Cost, Energy Consumption, and Carbon Emissions). The rank of alternatives that has top repetitive percentage which indicates that is the most dominating alternative. This rank considers the HVAC system (VAV, ASHRAE 90.1-2004, COP 5.55 Chiller, Gas Boiler, 68F economizer) along with Occupancy/Day lighting sensors & controls lighting system are the best combination for the case study to assure a high energy performance system.

Acknowledgments. This research was funded by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (11-BUI2090-02).

References

Abbaszadeh, S., Zagreus L., Lehrer, D., and Huezenga, C. (2006). Occupant Satisfaction with Indoor Environmental Quality in Green Buildings. *Proc. of Healthy Buildings*, Lisbon, Portugal, III, 365-370.

AGC (2006). *The Contractors' Guide to BIM*. Ed. 1. The Associated General Contractors of America. Available at http://www.agc.org/

AlAjmi, A., Abou-Ziyan, H., and Ghoneim, A. (2016). Achieving annual and monthly net-zero energy of existing building in hot climate. *Appl. Energy*, 165, 511-521. https://doi.org/10.1016/j.apenergy.2015.11.073

Beazley, S., Heffernan, E., and McCarthy, T.J. (2017). Enhancing energy efficiency in residential buildings through the use of BIM: The case for embedding parameters during design. *Energy Procedia*, 121, 57-64. https://doi.org/10.1016/j.egypro.2017.07.479

Belton, S. and Stewart, T. (2002). *Multiple Criteria Decision Analysis: An Integrated Approach*. Boston (MA), USA: Kluwer. https://doi.org/10.1007/978-1-4615-1495-4

Brans, J.P., Vincke, P., and Mareschal, B. (1986). How to select and how to rank projects: The PROMETHEE method. *Eur. J. Oper. Res*., 24(2), 228-238. https://doi.org/10.1016/0377-2217(86)90044-5

Chau, C.K., Leung, T.M., and Ng, W.Y. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Appl. Energy*, 143, 395-413. https://doi.org/10.1016/j.apenergy.2015.01.023

Chowdhury, A.A., Rasul, M.G., and Khan, M.M.K. (2008). Thermal-comfort analysis and simulation for various low-energy cooling-technologies applied to an office building in a subtropical climate. *Appl. Energy*, 85, 449-462. https://doi.org/10.1016/j.apenergy.2007.10.001

Djuric, N., Novakovic, V., Holst, J., and Mitrovic, Z. (2007). Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools. *Energ. Buildings*, 39(4), 471-477. https://doi.org/10.1016/j.enbuild.2006.08.009

Ergu, D., Kou, G., Yi, P., and Yong, S. (2011). A simple method to improve the consistency ratio of the pair-wise comparison matrix in ANP. *Eur. J. Oper. Res*., 213(1), 246-259. https://doi.org/10.1016/j.ejor.2011.03.014

Habibi, S. (2017). The promise of BIM for improving building performance. *Energ. and Buildings*, 153, 525-548. https://doi.org/10.1016/j.enbuild.2017.08.009

Horsley, A., France, C., and Quatermass, B. (2003). Delivering energy efficient buildings: a design procedure to demonstrate environmental and economic benefits. *Construct. Manag. Econ*., 21(4), 345-356. https://doi.org/10.1080/0144619032000073 505

ICIM (2011). iCIM (Interoperable Carbon Information Modelling). https://sites.google.com/site/openbimtoolkit/case-studies/interoperable-carbon-information-modelling

Jaggs, M. and Palmer, J. (2000). Energy performance indoor environmental quality retrofit - a European diagnosis and decision making method for building refurbishment. *Energ. Buildings*, 31(2), 97- 101. https://doi.org/10.1016/S0378-7788(99)00023-7

Lv, Y., Huang, G. H., Li, Y.P., and Sun, W. (2012). Managing water resources system in a mixed inexact environment using superiority and inferiority measures. *Stoch. Env. Res. Risk A*., 26(5), 681-693. https://doi.org/10.1007/s00477-011-0533-1

Marzouk, M. (2008a). SIR-VE: *A Generic Tool for Value Engineering. 5th International Engineering and Construction Conference* (IECC' 5), ASCE, Irvine, California, U.S., pp. 663-672.

Marzouk, M. (2008b). A superiority and inferiority ranking model for contractor selection. *Constr. Innov*., 8(4), 250-268. https://doi.org/10.1108/14714170810912644

Marzouk, M. and Abdelaty, A. (2014). BIM-based Framework for Managing Performance of Subway Stations. Automation in Construction. *Automat. Constr*., 41(1), 70-77. https://doi.org/10.1016/j.autcon.2014.02.004

McPartland, R. and Mordue, S. (2016). What is BIM? Retrieved May 18, 2018, from https://www.thenbs.com/knowledge/what-is-building-information-modelling-bim.

Paul, W. and Taylor, P. (2008). A Comparison of occupant comfort and satisfaction between a green building and a conventional build- ing. *Build. and Environ*., 43(11), 1858-1870. https://doi.org/10.1016/j.buildenv.2007.11.006

Peng, Y., Kou, G., Wang, G., Wu, W., and Shi, Y. (2011). Ensemble of software defect predictors: An AHP-based evaluation method. *Int. J. Inf. Tech. Decis*., 10(1), 187-206. https://doi.org/10.1142/S0219622011004282

Rebai, A. (1993). BBTOPSIS: A bag based technique for order preference by similarity to ideal solution. *Fuzzy Set. Syst*., 60(2), 143-162. https://doi.org/10.1016/0165-0114(93)9034 3-G

Rebai, A. (1994). Canonical fuzzy bags and bag fuzzy measures as a basis for madm with mixed noncardinal data. *Eur. J. Oper. Res.*, 78(1), 34-48. https://doi.org/10.1016/0377-2217(94)90120-1

Saaty, T.L. (1982). *Decision Making for Leaders*. California, USA, Wadsworth.

Sawhney, A. (2014). International BIM implementation guide. *Royal Institution of Chartered Surveyors.*

Stephan, A. and Stephan, L. (2016). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Appl. Energy*, 161, 445-464. https://doi.org/10.1016/j.apenergy.2015.10.023

Tam, M., Tong, T.K.L., and Wong, Y.W. (2004). Selection of concrete pump using the superiority and inferiority ranking method. *J. Constr. Eng. M. Asce*., 130(6), 827-834. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:6(827)

Triantaphyllou, E. and Sanchez, A. (1997). A sensitivity analysis approach for some deterministic multi-criteria decision making methods. *Decis*., 28(1), 151-194. https://doi.org/10.1111/j.1540-5915.1997.tb01306.x

Weather Tool (2017). Weathercloud. https://weathercloud.net/info/weathertool

Xu, X. (2001). The SIR method: A superiority and inferiority ranking method for multiple criteria decision making. *Eur. J. Oper. Res*., 131, 587-602. https://doi.org/10.1016/S0377-2217(00)00101-6

Yeo, D. and Gabbai, R.D. (2011). Sustainable design of reinforced concrete structures through embodied energy optimization. *Energ. Buildings*. 43, 2028-2033. https://doi.org/10.1016/j.enbuild.2011.04.014

Zurigat, Y., Al-Hinai, H., Jubran, B., and Al-Masoudi, Y. (2003). Energy efficient building strategies for school buildings in Oman. *Int. J. Energy Res*., 27(3), 241-253. https://doi.org/10.1002/er.871

Zou, J. and Zhao, Z.Y. (2014). Green Building Research Current Status and Future Agenda: A Review. *Renew. Sust. Energ. Rev*., 30(C), 271-281. https://doi.org/10.1016/j.rser.2013.10.021