A BIM-based Life Cycle Cost (LCC) Method to Reduce the Operation Energy Costs in Buildings

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Abstract

The rapid and continuous rise in the energy costs dictates significant cost control efforts during buildings' operation phase, despite the fact that achieving remarkable energy cost reductions are highly governed by the decisions taken during earlier phases of the construction project. As a solution, researches attempt to present workflows that include Life Cycle Costs (LCC) techniques in the evaluation of building assemblies. Some managed to integrate it with Building Information Modelling (BIM), while others focused on including the operating energy costs in the evaluation without the BIM integration. This paper aims to propose a more structured method that both combines the capabilities of BIM and energy simulations with the LCC can be developed employing the available efforts made. A case study is used to apply the proposed method, and the results show that around 17% LCC savings can be achieved when including the energy costs in roof assemblies. The proposed method can be used by facility managers or building design team to select the most cost-effective building envelope assembly.

Introduction

Background

In the past 10 years operation energy costs have more than doubled in the building sector in countries with subsidized energy prices such as Saudi Arabia, while it will continue to increase to reach international energy rates in the near future (ECRA, 2019; MoWE, 2007).

Currently, the general practice favours sustainable buildings designs, known as green buildings, which use minimal energy to operate (EPA, 2016; Jones & Barnett, 2018). This trend aids in keeping the operational energy costs controlled despite the rapid increase in electricity rates. However, the governing factor upon selecting building materials remains the construction project budget, not the targeted operational budget. Construction projects are usually constrained by a predefined budget, which compels decision-makers to select materials based on their initial costs and is mostly affected by personal judgements which may or may not be reliable (Marzouk, Azab, & Metawie, 2018).

Although the facility management (FM) phase is the construction projects phase with the longest duration and also takes over 80% of the total cost (Liu, Stumpf, Kim, & Zbinden, 1994; Teicholz, 2004), little attention is given to favour it in terms of the choices of envelope materials.

Nonetheless neglecting the effect of the selection of the material on the operation phase leads to escalated running costs and hence great efforts to control them. Nonetheless, achieving remarkable operational energy cost reductions is highly governed by the decisions and choices made concerning the building envelope during the early stages of the project, Karaguzel et. al. conducted a study to optimize the LCC and found out that changing the building envelope can induce up to 28% savings in the total operating costs (Karaguzel, Zhang, & Lam, 2014). Ultimately, reducing the building's operation energy costs is a task often solely assigned to the facility manager, which implies the importance of involving him in the envelope materials selection process, during the design and the retrofitting phases (Roper o. & Rechar d p., 2014) through a collaboration platform.

The collaboration platform that is currently used and shows promise in successfully achieving the various construction project goals is Building Information Modelling (BIM).

Building Information Modelling (BIM)

Building Information Modelling (BIM) is a digital process that facilitates the roles of different stakeholders through managing the various building project elements and processes. According to the National BIM Standard (NBS) national BIM report for 2018, BIM is the main process used by 75% of the building and construction industry (NBS, 2018).

The BIM processes are defined by different levels of details or information, which can be also translated to "dimensions". The third dimension (3D) is where information about the building's geometry in the 3D space is found. While the fourth dimension (4D) introduces the different project stages and the fifth dimension (5D) includes the cost data. The sixth and seventh dimensions (6D & 7D) are usually perceived as the sustainability dimension and facility management dimension interchangeably.

BIM has the potential to be used by the construction team members during all the project stages, thus coupling it with an economic evaluation technique is capable of offering a practical decision-making method.

Life Cycle Cost (LCC)

Many of the available economic evaluation techniques can be used for buildings or building system to compare their economic performance and reach the best cost-

effective decision. The most commonly used methods include life-cycle cost (LCC) analysis, the benefit-to-cost ratio or the savings-to-investment ratio, internal rate of return, net benefits, and payback period (ASTM E917-13, 2015). Utilizing an evaluation technique that considers the entire life cycle costs is specifically important when comparing building envelope assemblies, because it considers all the associated costs from purchasing and installation, operation and maintenance, and end-of-life costs (William East, Nisbet, & Liebich, 2013). Another research carried out by Assad (2011) utilizes LCC for building envelope components, mainly the roof, walls and windows, as an optimization criterion to reach a customized green building design.

Integration of LCC and BIM

Since LCC is used in evaluating buildings and building systems, the possibility of integrating such a technique with BIM has been tested by a number of researchers and showed great promise. Dawood (2016) presents a framework to achieve an optimal or near optimal design for residential buildings. The optimum design is identified as having the least energy consumption and LCC. Kehily, Woods, & McDonnell (2013) explore the possibility of exploiting the BIM data in carrying out whole LCC calculations using a cost estimation software. The aim is to attach whole LCC relevant data, such as interest rates, to the BIM data in order to obtain a faster real-time whole LCC analysis. Marzouk et al., (2018) proposed a decision-making framework that combines BIM, Monte-Carlo simulation and Genetic Algorithm as an optimization method to reach the best materials for a certain building, economically and environmentally. The sustainability aspect relies on the Leadership in Energy and Environmental Design (LEED) rating system as a judging criterion, while the economic aspect is addressed through a stochastic LCC methodology.

Nonetheless, there are several problems that make utilizing LCC in evaluating buildings and building systems and specifically in integrating it with BIM challenging. Some of the drawbacks found in the LCC studies as reported by Schmidt & Crawford (2017) include, not providing transparent input and calculations, not including operational energy, absence of graphical outputs, and the inapplicability during the design phase.

Analysing the Existing Methods

Through examining various workflows in previous researches, the different strengths and weaknesses in each are concluded. Some of the limitations and gaps that are available include the type of the building addressed, as several workflows are specifically tailored for residential buildings (Assad, 2011; Dawood, 2016; Hasan, Vuolle, & Sire'n, 2008; Nassar, Thabet, & Beliveau, n.d.; Sandberg et al., 2019). Also, the size of the project may present a challenge to some workflows as the level of complexity and details increase. Other workflows focus on a very specific commercial building type as school buildings, therefore applying the workflow in a different context it would need some changes in the criteria of the workflow (Alshamrani, 2012). In other cases, the method presented

targeted a specific element in the building envelope, thus applying it to other elements needs to be tested (Tarabieh, Mashaly, & Rashed, 2017).

Another important note is that several workflows didn't utilize BIM (Alshamrani, 2012; Assad, 2011; Hasan et al., 2008; Schmidt & Crawford, 2017), even though this is not considered a drawback, it certainly limits the use of the workflow. Nonetheless, some of the workflows that made use of BIM did not utilize its full potential as exploiting its energy simulation capabilities (Marzouk et al., 2018).

A number of the workflows examined did not include the operational energy costs in the LCC calculations, and hence is useful only when the operational phase of the building is not targeted (Dawood, 2016; Kehily et al., 2013; Marzouk et al., 2018; Schmidt & Crawford, 2017). There are two possible LCC calculation techniques to consider upon comparing several building envelope alternatives and both are used by a number of the discussed workflows. LCC can be calculated for the whole building, whereas the lowest LCC can be achieved by a certain combination of different building envelope elements: a certain wall, roof, and/or glazing type (Alshamrani, 2012; Assad, 2011; Kehily et al., 2013; Marzouk et al., 2018; Sandberg et al., 2019). Using that specific combination will result in the calculated LCC. The other technique is to calculate the LCC for different alternatives of a certain element, for example, wall types, whilst studying its effect on the building's running costs, the lowest LCC in this case belongs to that specific wall type (Dawood, 2016; Hasan et al., 2008; Tarabieh et al., 2017). Although both techniques are beneficial, they do not offer the same flexibility upon selecting the most convenient building envelope assembly. Being restricted by a certain combination of elements to achieve savings may be impractical as in some cases a trade-off may be preferred.

Finally, in a number of workflows, the LCC calculations need more elaboration; the method of calculation is not specified and the inputs/outputs are not discussed. In a number of workflows, it is not mentioned how the needed inputs can be obtained or extracted, either from the BIM model or other sources. As a number of workflows rely on optimization (Dawood, 2016; Hasan et al., 2008; Marzouk et al., 2018; Sandberg et al., 2019), the applicability of such workflow in the commercial AEC industry may be hindered due to its complexity. Utilizing a workflow that depends on optimization, especially if programming software has to be involved, may be limited to researchers, therefore may not be practical to facility managers or designers.

From the previous literature, various researches proposed workflows or methods to calculate the LCC of building components. A number of those methods included BIM in calculating the LCC, and others focused on optimizing the assembly choices to result in less LCC. Whereas a few frameworks included the operational energy costs in the LCC of building components. A more structured method that both combines the capabilities of BIM and energy

simulations with the LCC can be developed employing the available efforts made.

Table 1 shows a summary of the examined workflows and methods.

Table 1: Examined workflows and methods.

Author	Year	BIM	Operation Energy	LLC calculations		Optimization	Workflow Presented	Systems Targeted					Case Study	Targeted Building Type	
				Per Element	Whole Building			Walls	Glazing	Roof	Orientation	Other		Residential	Commercial
Hasan et. al.	2008		•	•		•	•	•	•	•		•	•	•	
Assad	2011		•		•	•	•	•	•	•	•		•	•	
Alshamrani	2012		•		•		•	•	N/A	•		•	•		•
Kehily et. al.	2013	•			•			N/A	N/A	N/A	N/A	N/A	•		•
Dawood	2016	•				•	•	•	•		•			•	
Schmidt et. al.	2017					N/A	•	N/A	N/A	N/A	N/A	N/A			
Tarabieh et. al.	2017	•	•	•					•				•		•
Marzouk et. al.	2018	•			•	•	•	•	•	•		•	•		•
Sandberg et. al.	2019	•	•		•	•	•	•	•	•			•	•	

* N/A: Data not available

Methodology

The method proposed targets the facility manager, focusing on the opportunities BIM offers to reduce the operation cost of the building, specifically the energy costs. For the development of this method, existing workflows and methods are examined and compared in the previous section. This comparison allows identifying the strengths and drawback in the available literature in order to construct a more comprehensive up-to-date method.

A case study is then carried out for the implementation and validation of the developed method. The details of the case study are explained in depth to better explain the method and to demonstrate its applicability.

Method Development

Based on the observation of previous literature and analysing the gaps, a method that integrates the BIM process with the LCC is constructed. The method's main objective is to assist building facility managers as well as designers to refine the material selection of building elements to ensure the choice is cost-effective for the long run. The workflow consists of 3 main phases: the initial phase, the BIM phase, and the LCC phase.

Initial Phase

Firstly, in the initial phase, an aim and scope for the study have to be defined in order to be able to obtain the relevant data afterwards. One of the key issues this workflow addresses is the complexity of the methods available, mainly because it requires optimization and risk assessments that can only be performed by a few specialists. To overcome that issue the aim required here

is to be narrowed down to one building envelope assembly type at a time.

BIM Phase

This phase will include the BIM-related processes that will enable semi-automated and efficient data extraction. The first process is the BIM model development and the 3D-modelling process. Afterwards, the possible scenarios will be defined, and two versions of the model are created for different purposes. The first version is a 5D BIM model that is created for quantity take-off and the other one is an Energy BIM model for energy analysis.

Main BIM Model Development

The development of a BIM model is necessary for obtaining accurate data for the quantity take-off and energy analysis. The importance of having a BIM model lies within the data centralization process, which enables every team member to access, view and add different data to the main project.

The main BIM model is created in this step, this model typically has a medium to high Level of Development or Level of Detail (LOD) across the crucial elements. This model is constructed using the project's architectural plans with the actual project's orientation and location data. However, the definition of the materials can be made to match the basic standards available, to suit the common materials used in this location, or to reflect the specific materials that are used in this project. All the defined materials, excluding the envelope material to be studied, are fixed throughout the entire study, thus will not affect the comparative analysis carried out. Nonetheless, to obtain realistic values or near-actual values, the actual materials for the fixed elements need to be used in this

model. Several copies of the main model are created afterwards, the number of copies depends on the number of alternatives compared, whereas each copy of the model belongs to one alternative.

Defining the Scenarios

In this step, the different scenarios are represented by creating multiple copies of the BIM model while changing the assembly or material that is under study. Afterwards, each copy will have two versions of the model; a 5D BIM model version and an Energy BIM model version. The data for the different alternatives can be replaced manually or using a scripted algorithm coded within the BIM authoring tool.

5D BIM Model

The 5D BIM model will include cost data to perform quantity surveying and produce Bill of Materials (BOQ) for certain elements. When creating a BIM model, the level of development of elements should be defined. The LOD of the various BIM model elements is determined by the function and intent of the element within a certain process. In other words, the LOD for the geometric elements in the 5D BIM model has to be accurate enough for extracting realistic BOQs, so a range of LOD 200-400, for example, can be considered.

Quantity Take-off

The cost of materials or building assemblies is entered to the BIM model and the initial cost of assemblies can be extracted directly based on the volume or surface area of the geometry of the assembly. The initial costs of assemblies are calculated from the cost per unit item and the quantity of the item in the BIM model. The quantity of a certain item is referenced back to the 3D geometry of the modelled item. Therefore, it is crucial to accurately model the 3D geometry of the BIM model while considering the different elements' hierarchy whenever there is an intersection or a connection. Moreover, it is crucial to prevent overlapping and/or double counting of certain elements. Therefore, it is important to perform a clash detection to ensure accurate modelling. Also, based on user-defined equations and assumptions, the operation and maintenance costs can be obtained as well as the resale or salvage values. Those values can be calculated predefined equations in schedules inside the BIM authoring tool.

Energy BIM Model

The second version of the model is the Energy BIM model. Contrarily to the 5D BIM model, the energy model's geometry requires a lower LOD, since the energy model only requires space boundaries to be defined as well as openings. Having a model with a higher level of geometry details may result in inapplicability with the energy simulation software requirements to convert the building geometry to energy geometry. However, more details are required for the building and spaces information. The building's location and orientation, occupancy schedule and spaces' activities have to be provided in order to perform an accurate energy analysis. More importantly, the thermal properties of the building's

envelope are crucial inputs to the energy model, such as the U-value of materials and SHGC of window systems.

Energy Analysis

The operational energy use is the main output of the energy analysis stage, it can be translated afterwards to operation energy costs. In order to perform an energy analysis for a BIM model, interoperability between the BIM authoring software and the energy simulation software is needed. The BIM model file may be extracted and used as an input to the energy analysis software. Nonetheless, in this workflow, it is recommended to utilize an energy analysis plug-in for the BIM authoring tool of choice. This will help eliminate any interoperability issues between the two software, save time and provide a more flexible and practical method to obtain the energy analysis results. There are several extensions or plugins that can be used with the different BIM authoring tools or have direct interoperability with it. Calquin (2017) summarized the different BIM authoring tools and the possible extensions and plugins that run energy simulation and analysis.

LOD Validation

In order to validate the LOD needed for each model a simple check list with the type of data needed for the targeted assemblies. The type of data that will affect the energy simulation such as the thermal information and the type of data that will affect the BOQ such as accurate dimensions of assembly layers should be included.

BIM integration with LCC Phase

The outcomes of this phase for each scenario can be summarized as follows; the annual energy consumption of the building, the assembly's materials costs, and materials quantities. Thereupon, this data is to be used to perform the LCC calculations. Firstly, the platform used to carry out the calculations has to be defined and then the output format of the data can be adjusted accordingly. Generally, there is not a standardized tool to perform the LCC and it is mostly carried out using spreadsheets. Therefore, extracting the assembly's materials costs and quantities in schedules format is a convenient way to obtain this data from the BIM model and use it in the LCC calculations. As for the energy analysis, it is usually given in the form of a report and the values required can be extracted and used for the LCC calculations. This process can either be semi-automated, and it is neither time consuming nor complicated, or a tool can be used to fully automate the data transfer from BIM to the software calculating the LCC. Another solution can be performing the LCC calculations within the BIM authoring tool. Similarly, several solutions have been offered in the literature to facilitate the interoperability between BIM and Life Cycle Assessment (LCA) (Najjar, Figueiredo, Palumbo, & Haddad, 2017; Soust-Verdaguer, Llatas, & García-Martínez, 2017), the suggested methods can be tailored for the BIM and LCC integration as well.

Finally, in the LCC phase, the LCC calculations are carried out using the LCC elements, interest rates, and cost data collected in the initial phase. There are several economic evaluation techniques which consider the

whole life cycle costs, some of which have been mentioned in the literature. Any technique can be used in this step; however, the choice of the proper technique depends on the scope and the available data. The LCC elements considered in the evaluation can include, but not limited to the initial cost of the assembly, and running costs or benefits, repair and maintenance costs, and the salvage or resale cost. In order to carry out LCC calculations correctly the time value of money has to be considered, an economic rate, or a combination of rates should be used. An example of the rates that can be considered is; discount rate, inflation rate, escalation rate, and/or the investment rate.

Afterwards, the results are analysed and a decision can be made accordingly. The selection is governed by the scope of the study, and the constraints defined like the project budget or certain investment goals. Figure 1 illustrates the different steps in the method explained above.

Case Study

The aim of this case study is to compare different building envelope assemblies based on their LCC, focusing on their effect on the operation energy costs of the building. The building envelope assemblies in the scope of this

study are the external wall assemblies, roof assemblies and glazing assemblies for the external windows.

The case study is a school complex in Jubail, Kingdom of Saudi Arabia (KSA). The building space type for all the buildings in this case study is a school which has a regular K-12 school schedule. The school in the case study presented here is the Intermediate Boys School in Mutfah Sector F1, which is shown in Figure 2. The part of the case study presented here focuses on the roof assemblies.

Jubail is located in zone 0B according to the ASHRAE world climate zones map from the ASHRAE standard 169:2013 (ASHRAE, 2013). Zone “0B” is considered an extreme hot dry climate (desert climate) with temperatures ranging from 38 °C in summer days to 11 °C in winter nights, a variation of 19 °C.

The selected construction materials are commonly used materials in the Saudi Arabian construction industry. The construction type and structure system of the school’s building is a standard concrete skeleton type. And the building envelope materials are concrete based materials. Expanded Polystyrene is usually the preferred type of insulation for walls and roofs.

Figure 1: The proposed method for including energy operational costs in the LCC of buildings envelope assemblies.

Figure 2: A 3D view from the BIM model for the Intermediate Boys School in Mutrafiah Sector F1, Jubail, KSA.

LCC Calculations

The study period used in this analysis is 30 years, and the economic evaluation technique of choice is the Present Value for LCC (PVLCC). The main equation used to calculate the PVLCC is in ASTM E917-13 (2015)

$$PVLCC = \sum_{i=0}^N \frac{C_t}{(1+i)^t} \quad (1)$$

Where:

C_t = sum of all relevant costs occurring in year t ,

N = length of the study period in years, and

i = the discount rate.

However, instead of using the simple discount rate utilized in equation (1), a modified version is used here to account for the energy escalation rate (e_{energy}), inflation rate (e), and discount rate (i) (Fuller & Petersen, 1996).

$$\text{real interest rate } r = \frac{i-f}{1+f} \quad (2)$$

$$\text{effect of escalation of energy prices } r_e = \frac{r-e}{1+e} \quad (3)$$

$$\text{discount factor for energy } a = \frac{1-[1+r_e]^{-n}}{r_e} \quad (4)$$

$$\text{discount factor } f_r = (1+r)^{-n} \quad (5)$$

Where:

i = nominal interest rate

f = inflation rate

e = escalation in energy price

The depreciated resale value is calculated using the Sum of Digits method at year 30. The life time of the roof assembly is assumed to be 100 years, and there is no end-of-life salvage value. The maintenance and repair costs for all roof types can be assumed to be the same, therefore, it is safe to omit this specific type of costs from the study and LCC analysis. A similar approach has been adopted by Hasan et. al. (Hasan et al., 2008), whilst evaluating the building envelope assemblies through life cycle costing.

Therefore, the modified version of the PVLCC for Roof x = PV difference in initial construction and material cost + PV difference in resale value. The energy escalation rate (e_{energy}) is assumed to be 15% based on the energy prices data pattern in the last 10 years in the KSA (ECRA, 2019). As for the discount rate (i), it is assumed to be 3%, and the inflation rate (e) is assumed to be 2.8% according to

the current statistics by the Saudi Arabian Monetary Authority (SAMA, 2019).

Cases

The full case study included evaluating different wall, roof and window assemblies, however, for the sake of this paper, only the roof assemblies' comparison is displayed. The total roof surface area is 6042m². The following table shows the different roof types tested and their thermal properties as well as the estimated total cost of each type based on previous projects in the KSA.

Table 2: Roof Assembly Types.

Name	Layers			U-value	Cost/ m ²	Total Cost	R-US
	1	2	3	W/m ² .k	SAR	SAR	
Type 1 (Basic Type)		No Insulation		3.45	208	1,310,870	R-2
Type 2	Gravel 50mm	Inverted roof insulation, 50 mm thick.	Concrete 160mm	0.53	256	1,613,030	R-11
Type 3		100 mm thick extruded polystyrene insulation		0.26	248	1,562,670	R-22
Type 4 (Design)		150 mm thick extruded polystyrene insulation (R=30)		0.18	268	1,688,570	R-32
Type 5		2x 150 mm thick extruded polystyrene insulation (R=60)		0.09	328	2,066,270	R-62

Results & Discussion

Figure 3: LCC savings for roof assemblies compared to the base case assembly (type 1).

The chart in Figure 3 demonstrates the LCC savings of all roof types compared to type 1 (Base design). The chart also shows the LCC savings as well as the difference in initial costs and present value annual operation energy savings. The LCC savings range from 26.3 million SAR for type 2 (R-11) and up to 30.4 million SAR savings for type 5 (R-62). Whereas the savings in operational energy costs range from 26.6 million SAR for type 2 (lowest R-value) to 31.1 million SAR for type 5 (highest R-value). LCC savings are mainly governed by the PV annual operation energy savings per type, rather than the initial costs. The highest savings in operational energy costs achieved the best LCC savings as shown for type 5. The

design case assembly (Type 4) achieved remarkable results compared to the base case with total savings of 30 million SAR and 30.3 million SAR savings in annual operation energy. However, it is neither considered the most economical alternative in terms of total LCC nor energy savings.

Figure 4 illustrates the annual cumulative net present value for the different wall types. The charts show the rate of each type compensates the extra initial cost paid to increase the insulation for more energy savings. The payback period ranges from 3.24 years to 6.61 years, where type 5 ranks as the fastest type to compensate for the initial cost and start saving money through the operational energy savings. While types 2 and 4 nearly have the same payback period around 6 years, even though they have different initial costs and different potential energy savings. The difference in initial costs and energy savings between type 2 and 4 is illustrated in Figure 4. Type 5 has the highest payback period, as shown in Figure 4, due to its higher difference in initial cost, which means even though with its high annual operation energy savings it needs 6.61 years to reach a break-even point. Moreover, as indicated in Figure 4, type 5 surpasses types 2 and 3 at 14 years and type 4 at 22 years respectively indicating the significance of the energy savings induced by the thermal performance of this type even though it is after a longer period of time.

Figure 4: Annual cumulative net present value for roof types.

Overall, although the difference in LCC savings between type 4 and type 5 is insignificantly higher for type 5, we are inclined to recommend type 4 for it achieves higher initial cost savings. On the other hand, the payback period results, shown in Figure 4, offers a means to rank the alternatives. The shown results of the payback period basically describe how fast the alternative will return all the extra investments, made in its initial cost, in the form of operation energy cost savings. Type 3 scores the lowest payback period of just 3.24 years and oppositely type 5 has the highest payback period of 6.61 years. This proves that type 3 is a safer and less risky investment in a short time. However, when analyzing both the payback period and the total LCC savings, type 3 on the long term is around 3 million SAR short in LCC savings than type 5. But when considering type 4, we can find out that it gives

a trade-off between the LCC savings and payback period, making it an optimal choice in this case.

Conclusion

LCC integration with BIM and energy simulation tools proves to be an effective decision-making approach for the building envelope selection. Accounting for the whole building life cycle validates the need to relocate and redistribute the budget to permit the use of the more energy efficient option, despite the increase in the initial investment. The economic aspect is justified through the LCC calculations that show the possible energy cost savings during the operation phase of the project.

The method proposed utilizes vastly used tools to achieve a cost-effective selection for the building envelope assemblies. It has been observed that when approaching LCC in the building context it is more practical and faster to narrow the scope. This makes the decision-making process dependant on fewer assumptions, and hence more accurate. It also eradicates the need to use complex optimization techniques since it studies each element independently. Even though it is not conventional to choose building envelope assemblies based on their LCC, it is fairly doable and leads to a more informed economical selection. Unlike most existing contributions this workflow is not tailored for researches and hence it does not require programming knowledge nor experience in optimization techniques to be applied, but it rather makes use of common commercial tools to obtain the most suitable selection. This makes the workflow fast, simple and reliable and more likely to be used by facility managers and other construction team members. Last but not least, this workflow considers the whole life cycle of the building envelope assembly and includes the operation energy costs in order to achieve an economic selection.

This method presents a means for the facility manager to take a part in the building envelope material selection either early on in the project during the design phase, or in the retrofitting phase. The facility manager can utilize BIM in forecasting the operation costs of different building elements and can take decisions to make recommendations in the design/retrofitting phase, supported by the LCC for more justifiable choices. Nonetheless, all building team members can use this tool to have a prediction on the effect a certain building assembly on the operation energy costs of the building as well as the possible savings.

The applicability of this method is demonstrated through implementing it on a case study, a school complex in Jubail, Kingdom of Saudi Arabia (KSA). The case study shows that despite the roof of choice is with the high initial cost, the energy saving resulting from that choice can lower its LCC and hence making it the most cost-effective option. Ultimately, the selected option is a trade-off between the least LCC as well as operational energy costs, initial costs and payback period.

As part of the limitations, the workflow has been tested only on school type building in one climate. Further applications and case studies should be tested. Another

limitation is the number of roof assembly types, which was limited to 5 different types, making the comparison and selection process limited.

Future research would work on enhancing the workflow based on experts' opinion through interviews and testing and modifying the workflow based on a wider variety of case studies. As a next step, creating a tool that automates the material selection method to include the operational energy cost in its LCC would be investigated.

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