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CONCEPTUAL COST MODELS FOR ENERGY SIMULATION IN BUILDING PROJECTS

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Abstract: Economic analysis has been known as one of the major challenges for energy consultants in early phases of design, when project characteristics are not clear enough. One source of the challenge is to obtain cost data for elements based on their energy performance (rather than the product information). Therefore, quantitative economic analyses are usually postponed to later phases, when changing the decisions (which are already made) is costly and challenging. In response to this need, the present study aims to develop conceptual cost estimation models which can be used by energy simulation tools in early phases of projects (i.e. Schematic Design). These parametric cost models can assist energy simulator engines to estimate installation costs of building elements, based on parameters indicating their energy efficiency performance. In this study, three main categories of design parameters which significantly influence building energy consumption were considered: envelope (walls/roof insulation and windows/fenestration); lighting systems; and heating, ventilation and air conditioning (HVAC). For each component, cost databases such as RSMeans, and other commercial vendor databases were used for analysis based on physical parameters governing the energy performance of each element. Those parameters include R-value for insulation; U-Value and Solar Heat Gain Coefficient (SHGC) for windows; Lighting Power Density (LPD) for lighting; and efficiency for HVAC systems. To assist in recording and updating values for the cost model, a database was developed based on building energy performance parameters. The database is used in a life cycle cost analysis software and integrates well with Building Information Modeling (BIM), which can help energy consultants to start quantitative life cycle cost analyses during early design phase.

1 INTRODUCTION

Along with the rise in environmental concerns during the past decades, building sector around the world was found to be one of the major contributors to energy use and greenhouse gas emissions (Asif, Muneer, and Kelley 2007; Bribián, Usón, and Scarpellini 2009). In efforts to decrease buildings' footprints, more sustainable designs have become more popular in the industry. These buildings are known to consume less energy than conventional buildings however, they are also known to have a greater construction cost (Jalaei 2015).

When making decisions to develop a sustainable design, it is essential for building owners to know how much more investment will be needed during the construction phase, and what is the return on such investment. An ideal way to answer such questions is to compare the life cycle costs (LCC) of a conventional building with its sustainable design variant (Alshamrani 2012).Lifecycle cost assessment of the building depends on construction, operation and maintenance costs. When it come to the construction costs, models available for conceptual design phase, normally relate the costs to some 'parameters' of building components (such as size, volume and count). However, energy efficiency of the components is normally ignored by these parametric models. Considering such details is currently pushed forward to the later phases of design.

Energy conservation measures are known to decrease energy consumption throughout the life cycle of buildings but, they were also found to be significant cost parameters in the construction cost of a building (Tatari and Kucukvar 2011; Marszal and Heiselberg 2011). Although there are many existing methods to estimate construction cost of buildings, most only focus on structural characteristics of the building. Not enough emphasis is given on capital costs related to energy conservation measures, such as window types, insulation, lighting and mechanical systems. These parameters have great influence in the energy consumption of a building during its lifetime, therefore designers cannot take informed decisions when talking about these measures and its financial impact during the early design period.

The objective of this study is to explain the structure of the developed cost model that is used to estimate the premium capital costs related to the adoption of energy efficient components in building designs. The cost model is designed to work with energy-related parameters, and is applied with the assistance of a database, which is structured to support an LCC analyzer software in calculating construction costs related to energy conservation measures. The remaining of this paper is organized as follows. First, a review of existing methods for early building design cost estimation. Next, the methodology used for each component of the model. Then, the structure of the model and the method for keeping the database up-to-dated is highlighted. And finally, the summarized contribution of this study along with its limitations and future works.

2 LITERATURE REVIEW

Literature shows an evolution in early design cost estimation methods over the years. Until the early 2000s, commonly used methods were based on 2-dimensional CAD drawings to create a Quantity Takeoff (QT) model which include the number of items and materials needed for the project. This drawing use to define the dimension of the selected items and adding the quantities for the QT model (Jalaei 2015). That process limited them from being able to use detailed information about the quantity and material of items used in a building when estimating cost. Such methods were known as constructed area method; quantity of work and elementary price; construction cost index and complex nature; estimation based on work breakdown structure (Pettang, Mbumbia, and Foudjet 1997); and others that followed a quantity take off or were under a questionable linear relationship (Günaydın and Doğan 2004). During that time almost the whole process was done manually, so not only errors were frequent, but it was also very time consuming (Jalaei 2015).

Starting in the early 2000s, with the rise of artificial intelligence (AI), neural network approaches were possible for cost estimation in the construction business (Tatari and Kucukvar 2011; Arafa and Alqedra 2011; Günaydın and Doğan 2004). By using the AI method called artificial neural networks (ANN), building cost estimates began to show very successful estimate accuracy thanks to its ability to investigate non-linear and multilinear relationships between building cost parameters (Günaydın and Doğan 2004; Arafa and Alqedra 2011). ANN also showed promise in when selecting the key-parameters to be investigated in the data analysis section (Arafa and Alqedra 2011). A great downside to this method, however, is its dependency on a large quantity of quality data. The method requires a great selection of data points to train the built network, and a different selection to go through the testing phase (Tatari and Kucukvar 2011; Arafa and Alqedra 2011; Günaydın and Doğan 2004).

Later, when building information modeling (BIM) started to gain strength in the market, new methods for calculating construction cost using BIM started to merge (Cheung et al. 2012). BIM itself can select appropriate components among many existing alternatives to minimize cost of a building. Integrating BIM with the cost evaluation can lead to more precision, and both cost and time efficiencies during early stage design projects (Jalaei 2015). One analyzed example was developed by Cheung et. al. as a plug-in to the 3D design tool SketchUp (Cheung et al. 2012). The goal of the module is to be able to estimate the cost of the model and continuously update as designer moves forward. This tool takes into consideration five major groups of elements: substructure, superstructure, finishes, fitting and furnishing, and services (Cheung et al. 2012). Another example of cost estimation using BIM and "Sage Timberline" was offered by (Jalaei 2015). This plug-in calculates construction cost by analyzing structural components of the building as it is

designed in BIM, the components are then matched to a cost database in order to find the buildings construction cost. This product database contains a limited variation of components based on their physical structure no emphasis on their performance.
Even though it was found that parameters in the LEED's (leadership in energy and environmental design) energy and atmosphere category are highly influential in the cost estimation process of a sustainable building(Tatari and Kucukvar 2011), the analyzed literature does not show details concerning cost estimation of energy conservation attributes based on their performances.

3 METHODOLOGY

The present study aims to develop cost models which receive different components' energy performance parameters as inputs and provide the associated cost (of installation and operation) as the output. The cost models are meant to be easy to update and implement in life cycle energy analyses. To assist in the application of such model, we developed a database to record cost and/or unit costs for various building elements (of envelope, lighting and HVAC) and apply the cost models to feed an LCC Analyzer system. The LCC Analyzer makes changes to building models, creates new design alternatives and performs energy simulation and evaluates construction and life cycle costs accordingly. This system relies on OpenStudio as its building energy simulation tool. Energy conservation attributes are applied through OpenStudio measures, which are programs that can access and make changes to a model automatically (rather than manually by the user and through the user interface). Most costs can be applied through these measures, which will then be included in the energy simulation; however, some rely on post simulation data to accurately estimate construction costs.
The system in question focuses on three main areas of energy conservation, including envelope, lighting and HVAC. The methods for acquiring cost data and developing cost models for each item are presented in the following.

3.1 Envelope

3.1.1 Wall and Roof Insulation

The estimation cost model covered by this study focuses on two types of insulation, for wall and roof. Costs for these two are mainly based on three parameters: material, thickness and R-value, which is the metric used to represent a material's resistance to heat flow. When applying a change in desired R-value of insulation to a model, two measures are responsible; one for walls ("Increase R-value of insulation for exterior walls to a specific value"), and one for roof ("Increase R-value of insulation for roofs to a specific value"). The desired change in each component brings its respective cost inputs through the measures as well, in the form of cost per area.
To assist in the calculation of cost per area based on R-value to be inputted into the measures, the first approach considered was to form a database with insulation cost data collected from major suppliers in the Canadian market (such as Home Depot and Rona). The idea was to gather information for different insulation materials such as fiberglass and polystyrene, which were listed based on their thickness and R-value. However, these data showed complete dependency on market demand and producer.
The next approach was to use RSMeans data (RSMeans, 2018 a) instead of market suppliers. RSMeans is a reliable and up-to-date database used for cost estimation in worldwide. With its data, we were able to develop an insulation cost model based on material's unit cost (i.e. cost per area of insulation) based on the desired R-values. To calculate the model's desired input (cost per area for desired R-value), three options were considered constant, step-wise, and best fit line methods. In the constant method, the unit cost of each product of the same material (where thicknesses are different) was divided by their R-value to achieve unit cost per R. The average unit cost of R of these products (all with the same material) is then calculated to have a single value to be used in the model calculations. In step-wise method, the data is classified based on different ranges of R-values, and for each class, a unit cost per R is allocated. Finally, in the best fit line method, a linear regression was generated based on the available data, this regression enables the calculation of unit cost per R based on chosen R-value.
The materials found in RSMeans are available in four different thickness, which directly affect their R-value. After presenting these materials and calculation methods to the industry partner, fiberglass board insulation with 1.5-pound weight for each cubic foot was selected for wall, and unfaced fiberglass blanket was selected

for roof. And, since materials for each insulation type are the same, the constant method was selected for developing a unit cost per R model during early stage of projects.

3.1.2 Windows

Cost of windows is affected by two main parameters, window type and size. Type includes frame material, frame type and glazing characteristic. In the system, the cost of a window is dependent on two OpenStudio measures, one that sets the window type ("Replace exterior window constructions with a different construction from the model") and applies its respective unit cost, and one that sets the size of the window ("Set window to wall ratio by facade"). In order to apply the window cost in the cost model, a database was developed to enable the input of unit costs of different window types into the measures. The applied unit cost (cost per squire foot) of a window type is calculated by the sum of glazing and framing unit costs. Then, the total cost of windows is calculated when the size of windows is applied through the set window to wall ratio measure.

Each window type, based on its glazing material, will bring its respective U-value, which is the main parameter making the difference in the energy consumption of the building. All analyzed window glazing types are available in Building Component Library (BCL) and DOE2 library (DOE-2 2019). They are categorized based on glazing layers (single, double, triple); U-value, which indicates the rate of heat transfer through the window; solar heat gain coefficient (SHGC), which determines the fraction of solar radiation that enters a building through the window assembly; gas filing and gap thickness. To find cost to the items in the libraries, two sources of data were first considered, market suppliers and RSMeans. Each method has its own benefits and limitations. Market price can not be updated directly, and the price depends on the market demands, brands etc. On the other hand, RSMeans cost data, in section 08, is related to opening type and window material. As a result of these different categorization methods, matching costs with window types from DOE2 library was not simple. In addition to that, RSMeans does not cover triple glazing. To overcome such limitations, a combination of data from RSMeans and market suppliers was found to be the solution for a database that can cover all desired window types.

From different frame materials, aluminum as one of the most common materials and sliding window and curtain wall window as the common window type in buildings were selected in a consultation with our industry partner. Since in the RSMeans, curtain wall cost information limited to average cost of single and double glazed and investigating in the market show that the cost of curtain walls varies by the brands and company. As a result, finding the logical relationship between single, double and triple glazed curtain wall was narrowed our decision to the sliding window type. Moreover, in the RSMeans the cost of a window frame includes the glazing as well, and there is not any information about the glazing specification; as a result, our choice limited to the items which not include the glazing; the 'aluminum sash' item, which does not include the glazing in its cost, was selected to derive the unit cost of framing.

For having the glazing cost portion, the DOE2 glass library was matched with RSMeans based on the glass thickness, gap thickness and gap filling gas. However, a comparison between windows with the same glazing type and different gas fillers (such as air and argon) in the market, showed that gas type does not affect the price of glazing. Therefore, the cost model input for window glazing remained limited to glazing type and number of layers. As previously mentioned, triple glazing is not available in the RSMeans database. To overcome this limitation, the growth in the market price from double glazing to triple glazing for the same windows type was considered to extrapolate prices for triple glazing, from double glazing RSMeans data.

3.2 Lighting System

In the case of the building's lighting system, the main design parameter for energy simulation is Lighting Power Density (LPD) and LPD reduction resulting from the use of energy conservative lighting systems. LPD is a metric used to measure lighting energy use, and is defined as watts of lighting per square foot of floor area. Thus, the purpose of our cost model was to estimate the cost, based on LPD and LPD reduction units. There are two measures responsible for setting the cost of the system: one which sets the baseline cost and one which reduces that cost by using energy conservative lighting systems. Therefore, if the building does not have any energy efficient lights then only one measure would suffice. The objective of the cost database is to store the information required to calculate inputs for both baseline and reduced lighting systems. The measure applying baseline lighting load ("Set Lighting Loads by LPD") is responsible for setting the LPD for a standard building type (ASHRAE 2007) and its respective cost. The main challenge here was the fact that the same level of LPD (and accordingly, LPD reduction) can be virtually provided by a wide range of different lighting systems, each of which is associated with a different level of initial and life cycle costs. In a consultation with building energy consultant, we selected a basic/common set of fluorescent lighting system types (that use either T8 or T5 bulbs) as the main sources of lighting for baseline buildings. System types considered consist of troffers, surface ambient and high-bay/low-bay. To support the set lighting load measure, a few tables were added to the database entailing frame cost data and lighting bulb cost and useful life data for the standard fluorescent systems. The frame and lighting bulb costs were extracted from the Home Depot product database and the useful life data for the bulbs comes from the manufacturer specifications.

The second aspect of building lighting is to reduce the lighting load, by using energy conservative lighting technologies. This is applied in OpenStudio via the measure “Reduce Lighting Loads by Percentage” which is responsible for the efficiency increase from the previously set lighting system, as well as to add its respective cost increase. The efficiency of lighting load reduction in this measure is represented as LPD reduction percentage which basically is the process of taking one type of lamp out to add a similar one that consumes less energy but keeps the same lighting comfort for the building user. The cost model required must link each percent of LPD reduction into the expenses associated with it. We created a table for efficient lighting systems data, which focus on all three previously mentioned types, but this time only with light-emitting diode (LED) technology. The table includes all needed systems’ information, such as cost, power (in watts), expected life (in hours), and specific store and its web address (since frames and bulbs are sold together in this case). In the database, we developed another table to assist in the calculation of cost increase for the more efficient system. In this table, total cost of baseline systems is calculated by combining cost data from fluorescent systems’ tables. The total cost and power data from all energy efficient systems is also assembled there to combine information of two technologies for one lighting type, which will then enable the cost increase calculations from a fluorescent system to more energy efficiency of the same type.

Based on the research performed during this study, cost of lighting systems can depend on factors such as technology (fluorescent, LED, etc.), type (troffers, surface ambient, high-bay, etc.), model, brand, store location and other specifications. To keep the database complete yet consistent, we limited the available lighting technologies and types to the most common ones. Models of each technology in the market were matched to find closest equivalent model while keeping brand, store and location consistent. Details of the lighting systems considered by our database can be seen in Table *1*.

The building’s standard lighting cost is then calculated by multiplying the unit cost of the fluorescent light (frame plus bulb) with the standard LPD. This cost is used in the first OpenStudio measure (i.e. Set Lighting Loads). After that, the premium cost for the efficiency increase is calculated by Equation 1, to be introduced to the simulation, through the second measure (Reduce Lighting Loads), for evaluating the final system’s cost.

[1] $Iuc = \frac{UCred}{UCn}(1 - reduction) - 1$

In the equation, *Iuc* is the percentage increase in unit cost, *UCred* is the unit cost of the reduced design, *UCn* is the unit cost of standard lighting and *reduction* is the desired percentage reduction in LPD that is manually inputted to the measure.

Table 1: Summary of lighting system details

Lighting type	**Technology**	**Watt**	**Are light bulbs included?**	**Bulb type (quantity)**
Troffers	Fluorescent	96	No	T8 (3)
Surface Ambient	Fluorescent	64	No	T8 (2)
High-Bay/ Low-Bay	Fluorescent	216	No	T5 (4)
Troffers	LED	59	Yes	-
Surface Ambient	LED	35	Yes	-
High-Bay/ Low-Bay	LED	112	Yes	-

3.3 HVAC

When it comes to the HVAC systems, the application of associated costs to energy simulations works differently than all the previously mentioned components. For HVAC, instead of introducing costs (or unit costs) as an input through the OpenStudio measure (prior to the simulation); they must be calculated after the simulation is completed, and based on the specifications (i.e. count and capacity) of different components of the system. In terms of varying system types, HVAC also works differently than the other components; instead of being able to input a variable through one or two measures, the variable inputs to a model are the measures themselves. Each OpenStudio measure that applies HVAC systems represents a different type of system (e.g. rooftop package, water source heat pump, etc.). These measures add to the model a set of components characteristics of that system; however, the quantity and capacity of each type of component will be an output of the energy simulation and will depend on the characteristics of the building in question.

Based on RSMeans data (RSMeans, 2018 b), the costs of studied systems are calculated as the summation of partial costs of existing components in the system, and the cost of each component will vary mainly depending on its capacity. Both the unknown quantity and capacity of components make the costing procedure impossible to happen prior to the building simulation. Once the building simulation is finished, its output must be parsed and matched with the components from RSMeans.

To support the costing procedure for HVAC systems, we provided links to RSMeans cost database, for all components used by the OpenStudio measures. All varieties of capacities available in the RSMeans items were targeted, so that the post processing for evaluating components' costs can find the cost for the closest capacity to the design output. The components modeled in our database are divided into 6 main groups (one table created for each): HVAC packages; geothermal; terminal units; fan coil; heating and cooling; and pumps and heat exchangers. Also, each table is further divided into the subcomponents; e.g. heating and cooling table encompasses chillers, boilers, cooling towers and radiant heaters of different types and capacities.

4 RESULTS AND DISCUSSION

Conceptual cost models created in this study were applied via a cost database. The product database is divided into four major categories of products: window, insulation, lightning and HVAC. Each of these sections has its own specific set of tables, format and relations. In the window database, data is broken down into window glazing, framing, additional coefficients that enable the implementation of market prices that are unavailable in RSMeans, and finally, window catalogue which is where all parts of a window come together, enabling for total unit cost calculations for a window type to be performed. The inter-relation between window parts can be visualized in the database entity relationship diagram (ER) (Figure 1), where it is noticed that, to form one window type, only one item of each table is used (One to one connection line). In the other words, each value of these entity set is related to at most "one" entity of the other set.

Insulation, as a major category, supports two different types: insulation for wall and roof. Wall insulation database contains a list of four different products of the same insulation material (rigid un-faced fiberglass board insulation), products differ only in their thicknesses. A regression is derived from this table, enabling a linear model to find the value for wall insulation cost based on the desired R-value. Same method is used to create database for roof, but with a different material, blanket un-faced fiberglass. Each of these insulation sections are disconnected from each other without any sort of relationship, and that can be seen represented in Figure 1 as well.

The lighting system itself has separated two main sections, the fluorescent lighting data and energy efficient lighting data. Both have information on three lighting types, which are then compared to enable the cost calculations. The fluorescent lighting consists of two different tables: table with lighting frame data and table for light bulb data. Each lighting frame may contain one or more light bulbs to complete the system, the unit cost of this system is then calculated in the lighting catalog. The energy efficient lighting, however, consists of only one table, as its frames and bulbs are always sold together. The unit cost of this system is also calculated in the lighting catalog where both systems can also be compared to find cost increase of energy efficient system. This relationship in the lighting database is represented in Figure 1.

The section of HVAC components, in this database are divided into 6 categories: HVAC packages, geothermal HVAC, terminal units, fan coil, heating and cooling, and pumps and heat exchangers. All these components are dependent on a set of components and their capacities read from the simulation report.

The cost of an entire system is calculated as the sum of all components existing in the given system. Each component is just dependent on its own capacity, making them all unrelated to each other in the product database. Such relationship can be seen in Figure 1.

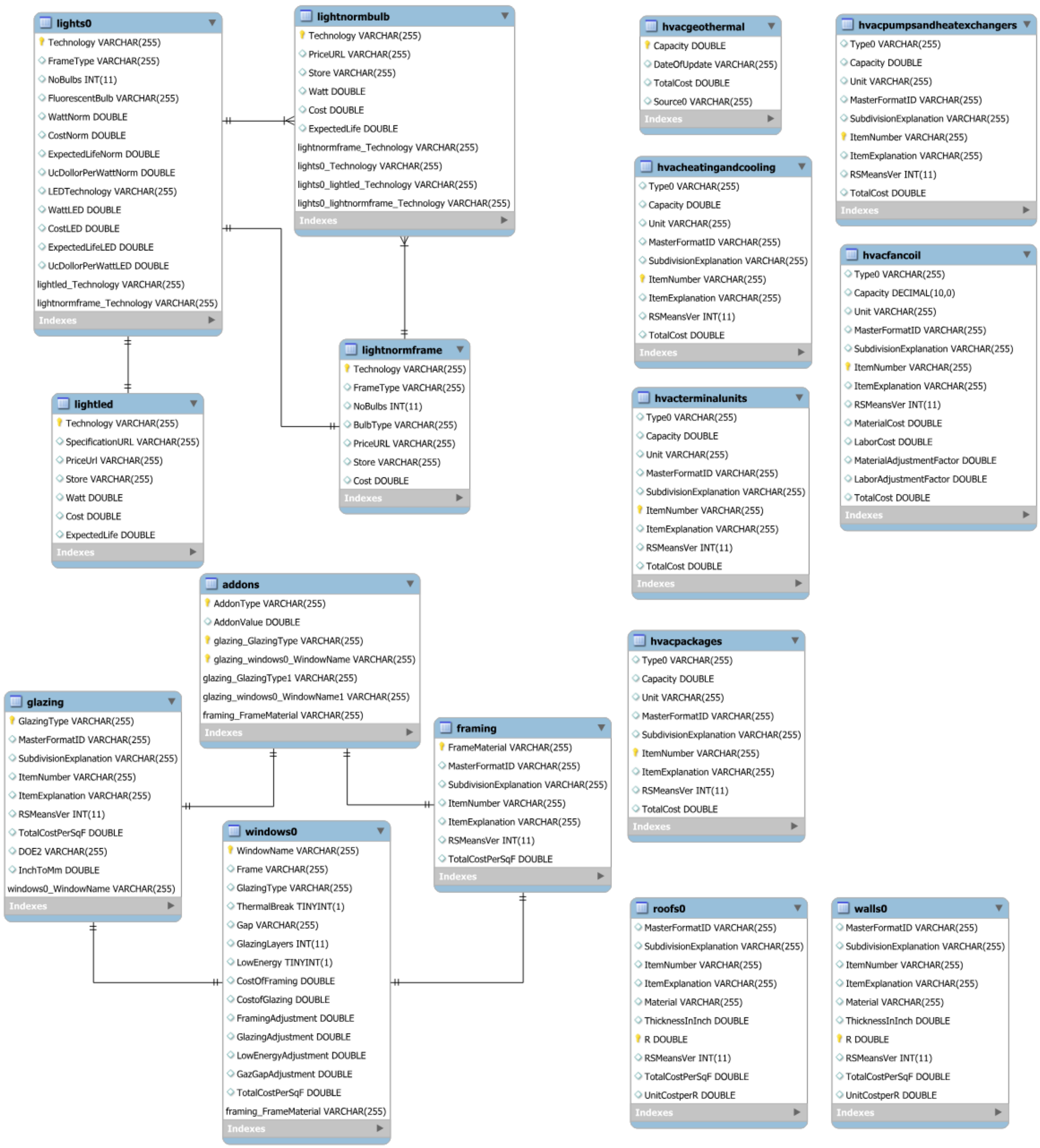
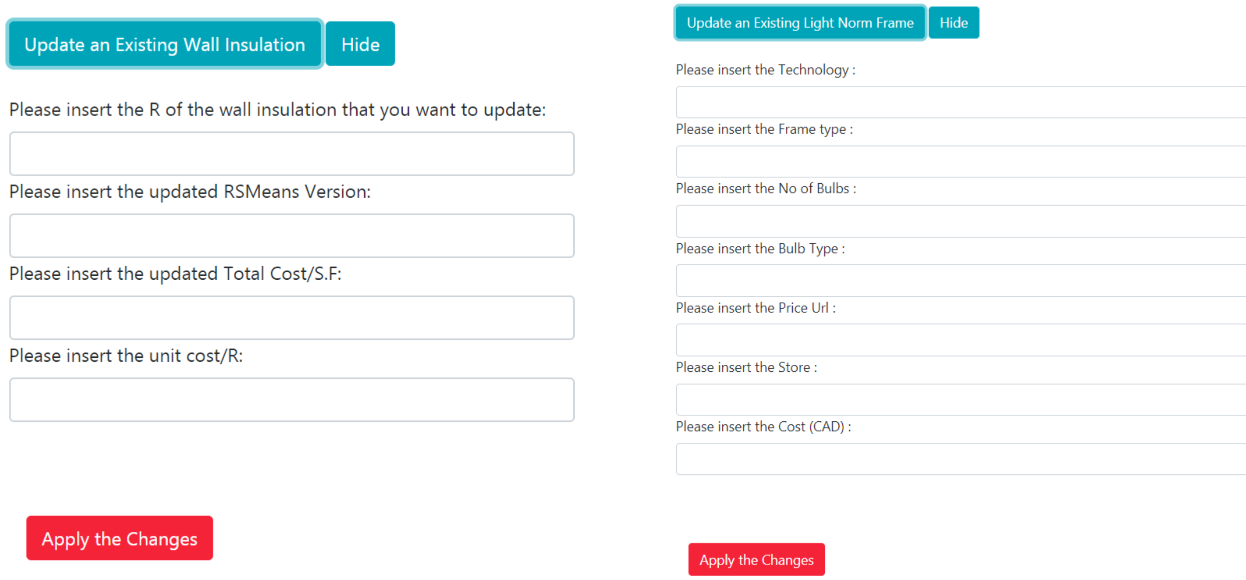


Figure 1: Entity Relationship diagram of the developed product database

While this database is developed so that it can be linked with applications running through OpenStudio (so that they can automatically pull the cost information from the database); keeping the cost information up-to-dated or adding new items (as required) needs the interaction of an administrator. We developed an



(a) Updating wall insulation cost

(b) Updating lighting frame cost

Figure 2: Sample screenshots of the user interface developed for management of the created cost database

admin interface for managing the database and the information listed in it. For instance, items that use RSMeans as their source of cost information need to input their RSMeans product ID (as the key) to let the system know which item is being updated. After updating (or adding new) cost information, the updated information will be stored back in the database as a new version. Depending on the component, more RSMeans-related fields might be needed, for example the insulation R-value of the material. An example of the admin interface section for updating an RSMeans component can be found in Figure 2(a), where the wall insulation data can be updated.

In items that use other sources, such as lighting system components, some fields are asking for some specific details of each component to be able to match the correct item to be updated. The main difference compared to RSMeans items is the need to add the source web address and the store location to which the price was found. An admin interface example for update of a lighting system component can be found in Figure 2(b). The reason to which the store field is needed is because the price of components can vary depending on location and over time. While these changes (if being minor) can be applied through location and time indexes; they may need major update when applied to a new context (i.e. location or time) for which the indexes are not available.

RSMeans cost data is the main source of data for most components in this database. However, they only have a limited number of variants for each component, which limits in the applicability of the database. In the windows database for example, RSMeans does not cover different gap sizes; and the window glazing options are limited to single and double glazing. To bridge this gap, other sources of cost are needed, which will in-turn complicate the process of updating the database. The same difficulty exists when it comes to window framing, insulation material, and HVAC components.

When it comes to lighting, RSMeans was not used since the available data were not relevant to the inputs needed by an energy simulation system. Hence, the entire lighting section had to be taken from a different source, which also complicates the updating process even more.

5 CONCLUSION

Current methods for estimating construction costs have showed that creating a product database is the most efficient way to estimate such costs. However, even though energy saving parameters are known to be important factors when calculating construction costs, previous studies have not focused on the product's capacities for saving energy during a building life cycle. To try to fill that gap, this study is presenting a cost model that enables the comparison of different versions of a building model based on their energy performance attributes as inputs. Such model is designed to help both energy consultants and architects in early stages of building conceptual design with respect to energy conservation.

To assist the developed model, a database was created based on RSMeans and market cost data for components like windows, insulation materials, lighting and HVAC systems products. Those were the only components being considered by this model and, with the assumption that operation and maintenance costs do not change with a component's change in performance, this model results in an accurate comparison between alternative designs of the same building against one another, but it is not able to provide accurate absolute costs. To overcome this limitation in the model, in future works, the application of more components as well as operation and maintenance costs can be implemented. Lastly, apart from the system's current limited variety of components, the database (and the cost models it is running based upon) shows great promise in providing reliable and up-to-dated information for life cycle cost estimation. Future works for this matter includes the expansion in the quantity of items and components of each category for more advanced cost models, their respective operation and maintenance costs and times, as well as the automation of the process of importing cost data from the different sources through their API.

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