A Holistic methodology for lifecycle energy consumption of heritage buildings

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Abstract. Heritage buildings are historically exceptional in their landscape and specific attention must be paid to their architectural element and components. Recently, the techniques that are utilized for the study and protection of cultural heritage have been on the rise in the research field. Studies have shown that project life cycle phases can be implemented to determine the performance of a given building in general. However, heritage buildings and their need were not considered. The project life cycle phases include: 1) planning, 2) manufacturing, 3) transportation, 4) construction, 5) operation and 6) maintenance phases. In addition, there is a need for an encompassing rating system that is capable of determining the most optimal pathway for rehabilitating heritage buildings. Hence, this article aims to present a comprehensive life cycle energy analysis model that optimizes expenditure over all building components by optimizing the budget. Furthermore, as a proof of concept, two case studies are applied in this research - GN in Canada and MP in the KSA.

1. Introduction
In 2018, the WHL (World Heritage List) encompassed 1092 sites worldwide, 77% of which are cultural and the remaining natural [1]. Heritage buildings are unique structures with a historical and cultural value. Such buildings need special care to maintain their unique architectural elements. The protection and use of heritage buildings is gaining greater attention from researchers recently, specifically preservation. A study of existing literature displays a variety of rating systems that are utilized to assess the performance of buildings on the level of sustainability [2-4]. Yet most existing models tend to combine three main criteria: the environmental, physical, and social aspects. Prominent examples include LEED, CASBEE, BREEAM, and ITACA. Each of the presented examples have their respective assessment metrics and attributes yet none of them presents a well-defined guideline for decision makers to chooses the most sustainable yet affordable rehabilitation option for heritage buildings [5]. Usually, the project life phases are divided into six phases with the last one being the demolition phase. However, since this work focuses on Heritage Buildings, we consider only 6 phases of the project life cycle as described.
2. Literature review

Literature for this review was mainly obtained from heritage-related organizations e.g. UNESCO, International Council on Monuments and Sites (ICOMOS) and other governmental organizations that focus on the conversation, restoration and rehabilitation of their heritage buildings. Through reviewing the literature, five key points have been pointed out concerning the heritage buildings: criteria and factors related to the identification and technology of the building; multi-criteria decision-making techniques, sustainability models, rating systems and rehabilitation as well as renovation methods as shown in Figure 1.

![Figure 1. Framework of the literature review analysis](image-url)

Some previous studies were carried out to evaluate and predict energy consumption and environmental emissions in different infrastructure systems. Fu et al. [6] developed a model that predicts daily electrical load of service systems in public buildings using support-vector-machines (SVMs). This included ventilating, lighting, power, and air-conditioning systems. The inputs of the models comprised weather predictions and historical electricity usage data. The developed model outperformed the decision tree (DT), artificial neural network (ANN) and autoregressive moving average with exogenous input model (Arimax). In this regard, the support vector machine model achieved normalized root mean squared error (RMSE) of 15.2% and normalized mean bias error (NMBE) of 7.7%. Ye et al. [7] adopted a generalized regression neural network to simulate energy-related carbon dioxide emissions in office buildings. The input variables of the model were occupied floor area, gross regional production, building floors, heating degree days, cooling degree days and energy consumption membership. It was found that the developed model performed well in predicting the carbon dioxide emissions such that it accomplished mean absolute percentage error (MAPE), relative error, RMSE and index of agreement of 2.53%, 5.4%, 0.4 and 0.9, respectively.

Jovanović et al. [8] used various ANN models for forecasting the energy consumption due to heating of a university campus. They utilized adaptive neuro-fuzzy inference system (ANFIS), radial basis function neural network (RBNN) and feed forward back propagation neural network (FFNN). An ensemble of neural networks was proposed, whereas it was found that the ensemble model improved the prediction accuracies regarding single neural networks. Yu et al. [9] utilized decision tree modelling to develop an approach for simulating the demand of energy in a given building. Ten input variables were determined which were annual average air temperature, floor area, construction type, space heating, number of occupants, hot water supply, etc. Results demonstrated DT model had
successfully classified and predicted the demand of energy in a building with a training accuracy and testing accuracy of 93% and 92%, respectively.

Monfet et al. [10] presented an approach for simulating energy demand of commercial buildings using case-based reasoning. In this context, the developed model was evaluated based on monitored data captured from existing buildings in Quebec. It was derived that the proposed approach accomplished coefficient of variance of RMSE and normalized mean absolute error below 13.2% and 5.8%, respectively. Dagdougui et al. [11] developed an ANN model for short term and very short-term load predicting in district buildings. The authors found that increasing the number of the hidden layers significantly affects the learning process and computational efficiency of the neural network. It was also found that the Bayesian regularization back propagation algorithm provides less prediction error when compared against the Levenberg-Marquardt algorithm.

Ashtiani et al. [12] proposed regression and ANN models that are capable of predicting indoor thermal comfort in urban heat islands. In the conducted study, different building characteristics and environmental parameters were tested. It was found that the artificial neural network model surpassed the regression models in predicting the indoor bulb-temperature. Li et al. [13] compared a set of machine learning models for the simulation of hourly cooling loads in buildings. The comparative analysis encompassed back propagation neural network, radial basis function neural network, generalized regression neural network and SVMs. Results demonstrated that SVMs and general regression neural network provided better results than other models.

Mohammed Abdelkader et al. [14] compared and analysed multiple machine learning models in their capability of evaluating heating and cooling loads in buildings. The input variables encompassed glazing area, glazing area distribution, roof area, wall area, surface area, overall height, orientation, and relative compactness. Results demonstrated that radial basis outperformed other machine learning models accomplishing MAPE, RMSE, and mean absolute error of 1.016%, 0.5363 and 0.2133, respectively in the prediction of heating loads. Liu et al. [15] proposed a support vector machines-based model for the sake of emulating energy consumption of public buildings. The input variables encompassed climate information, historical energy consumption profile, and time-cycle information. It was found that the developed model attained maximum prediction error of 1013 kwh.

Zeng et al. [16] utilized Gaussian process regression for simulating building electricity consumption. It was found that Gaussian process regression provides short processing time of 0.02 seconds per prediction. It was also concluded that the developed model could achieve average deviation below 15%. Moon et al. [17] investigated different architectures of ANN models for predicting building energy consumption. The performance comparison was carried out according to coefficient of variation of RMSE and MAPE. Experimental results highlighted that ANN with five hidden layers and scaled exponential linear units, achieved the lowest prediction error. In view of previous studies, it can be inferred that there are lack of models which can look at energy consumption of heritage buildings alongside its different phases. In this context, most of the developed models focused on evaluating energy consumption in residential buildings and they overlooked heritage buildings.

3. Assessing the sustainability of heritage buildings

The perception of environmental sustainability of heritage buildings has results in a wide variety of views regarding their energy performance. Researchers can be divided into two main categories: conservationists and modernists. Conservationists believe that the embodied energy within heritage buildings is of high value and must be preserved. On the other hands, modernists believe that in spite of the value of the embodied energy of heritage buildings they should be upgraded to energy efficiency requirements. Conservationists believe that heritage buildings are more environmentally friendly than modern buildings. That is mainly due to the fact that the energy required to for their construction has already been expended during their construction. This energy, also referred to as embodied energy, is defined as all the required energy to extract, process, deliver, and install a given structure [14-17]. This claim can be further reinforced by the fact that embodied energy does not contribute to an existing building’s present-day energy performance nor cost of operation. Therefore,
reusing an existing building results in zero waste generation or waste of additional energy when compared to constructing a new building.

Additional arguments highlight the fact that heritage buildings were constructed using more traditional and environmentally friendly materials, such as stone and wood, which had little to no manufacturing footprint [18]. In case any forms of manufacturing were required, the manufacturing would not have relied on fossil fuels and other pollutant inducing materials and processes. Additionally, heritage sites were usually constructed using materials that are readily available and in close proximity, thus minimizing the impact of any transportation required. Therefore, the energy required to construct older buildings is much lower when compared to modern structures [19]. In conclusion, conservationists believe that the environmental cost of energy required for constructing or demolishing any new structures is much higher than repurposing, rehabilitating, and reusing existing structures. As a result, it is more environmentally sensible to preserve and reuse existing buildings because of their embodied energy. This way, natural resources are conserved in a cost-effective fashion that allows for long term energy savings as well.

4. Research methodology

Figure 2 depicts a detailed abstraction of the framework we followed for the heritage building life cycle. In a broader view, the life cycles described consists of three main phases, each modeled as a system of input, process and output. The methodology can be broken down as follows:

1. Identifying the criteria, factors and indicators: In this phase, the main objective is to identify the quantitative and qualitative factors and indicators. For that, the literature review and answers from the questionnaires are compiled together and processed. This results in identifying the different environmental, physical, economic and social factors and indicators.

2. Computing of Energy (Electricity + Gas) Consumption: The objective is to calculate the energy consumption of the heritage buildings considered in both case studies; Murabba Palace (MP), Saudi Arabia and Grey Nuns (GN) Building, Canada. A model for each building was built and the energy consumption was calculated accordingly and cross-validated with the actual energy consumption obtained from Concordia University facility management department and Royal Commission of Riyadh.

3. Survey analysis: this involves the evaluation of the proposed life cycle phases in terms of their significance and rankings. In order to achieve that, the answers from the questionnaires were used to validate the proposed model of the life cycle assessments.
Literature Review
Identify criteria, factors & indicators
Identify life cycle cost phases
Compression between phases
Qualitative/quantitative criteria, factors, & indicators

Input
Calculation

Data collection
Survey Analysis

Figure 2. Framework of the developed research methodology.

5. Lifecycle assessment of heritage buildings
A project, by definition, is a set of tasks carried out individually or collaboratively to achieve a specific target. As a result, a project has to go over multiple phases before reaching its complete form as shown in Figure 3. Generally, the project life phases are divided into six phases with the last one being the demolition phase. However, since this work focuses on Heritage Buildings, considering only 6 phases of the project life cycle which are: 1) planning phase; 2) manufacturing phase; 3) transportation phase; 4) construction phase; 5) operation phase; and 6) Maintenance phase.
5.1 Planning phase
It is highly critical to outline what are the main components of any given project and what tasks are required to reach the end goal of the project. Thus the first phase of the project lifecycle is planning. The planning phases focus on identifying the scope of a given project. The main components of the project scope are primarily emphasizing on, the available resources, and the entities that will work towards completing a set of requirements to reach the goal. The concept of handling the scope and its components is called scope management [5]. The scope presents an overview of the whole project. Based on the scope, the project would be divided into milestones and activities. Each activity would have a set of resources assigned to its completion. Once the milestones and activities are identified, the required resources can be clearly planned and accordingly the overall project budget can be developed. The milestones and budget provide a guideline that would aid in tracking progress. Afterwards, the scope and quality management plans can be developed to facilitate future implementations of the developed plan [6].

5.2 Manufacturing phase
The manufacturing phase commences once the planning phase is finalized. The main goal of the manufacturing phase is to determine the energy levels that are embodied within the manufacturing materials. This is done by means of a rigorous data collection process that investigates the properties of the materials to be used in the project. The cost and the intensity of said materials are also taken into consideration. The collected data is then cross-checked and validated using an EIO-LCA model. The developed model allows the calculation of the total initial embodied energy per material. This is determined by multiplying the sectoral intensity contributions of the material by its national average price and its net quantities (accounting for waste) delivered to the site. The data for wastage factors was provided by Concordia University and the Royal Commission for Riyadh [1].

5.3 Transportation phase
After finishing the manufacturing phase, the transportation phase commences. In this phase, materials would be transported to the site where the construction will take place. During the transportation, the impact of the transportation of the materials on the environment is determined. Yet, current assessment methods possess certain drawbacks such as using emissions only or operations only estimates. To overcome such limitations Life-Cycle Assessment (LCA) was utilized. LCA provides a

**Figure 3.** An illustration of project lifecycle phases.
more comprehensive overview of the transportation process. Furthermore, LCA can take into consideration a variety of factors including Greenhouse gas emissions and energy consumption [20].

5.4 Construction phase
In the construction phase, the project is put together. This includes site preparation, envelope installation, equipment installation, and finishing. The execution of construction activities can be formalized using a process based LCA. The required documents include drawings, specification, site data, contractor data, equipment data and manufacturer data. Another important factor to assess is the construction energy, which represents the electricity utilized by the project and the diesel fuel used by the equipment for construction activities and the transportation of materials [20].

5.5 Operation phase
In the operation phase, the operating energy requirements are calculated. The main approach relies on a Process-based LCA to calculate the building’s operating energy requirements. For each project, the design specifications of mechanical and electrical equipment were utilized to determine the energy consumption patterns of those devices. This information is coupled with the predicted energy consumption pattern of the building to develop a global understanding of the overall energy consumption of the whole structure [21]. The investigation is expected to cover the electrical consumption for heating, ventilation, lighting, operational equipment, water supply, and any other equipment with an energy demand. This approach is verified by cross validating collected data with electricity records. The cross validation has shown high correlation between the two datasets [22].

5.6 Maintenance phase
The last phase of a project’s life cycle is the maintenance phase. Energy consumption assessments during the maintenance phase rely on techniques that resemble the approaches utilized in computing the energy requirements for the manufacturing of building materials. Yet, in this scenario the user must also consider the estimated lifespan of the materials of the building [2], [23-25].

6. Data reliability
Is it critical to examine the reliability of the collected data from respondents. The data must possess an acceptable degree of confidence in order to have an accurate implementation and analysis. Cronbach’s alpha is a method that can be utilized to check the consistency of a given dataset. There are different ways to calculate the Cronbach’s alpha, e.g. the ANOVA method. First, the Anova: Two factor without replication tool in Excel® has been used on the raw data collected. Then, the following formula was applied to get the Cronbach’s alpha as shown in Eq. 1 [24], [26-28]:

\[ \alpha = 1 - \frac{\text{MSE}}{\text{MSR}} \]  

Where:
MSE = Mean Squares Error
MSR = Mean Squares Rows

After that, given that some commercially available software like Minitab® have built-in functions to calculate the Cronbach’s alpha, it was further used as a second-stage validation process of the data collected. The tables for inputs, outputs and Cronbach’s alpha values calculated using Excel® sheets.

7. Model implementation
The conducted questionnaire survey was distributed to 150 experts, whereas 40 experts responded which results in a response rate of 26.67%. The respondents encompassed experts from Saudi Arabia and Canada who are fully aware of heritage buildings, construction practices and sustainability measures. The questionnaire comprises four main modules which are: area of expertise, location of experience, percentage of energy consumption in each phase and percentage of carbon emissions in each phase. A sample of the questionnaire survey of lifecycle phases of heritage buildings is presented.
in Figure 4. After ensuring the reliability and consistency of the data obtained from the answers to the questionnaire, the results are highlighted. The questionnaire results are depicted in Figures 5 and 6 to illustrate energy consumption, gas consumption and cost, respectively, for both case studies. The operation phase had the highest energy and gas consumption for both buildings, with energy consumption of almost 150,000 kWh per area and 20,000 kWh per area for the Grey Nuns (GN) and Murabba Palace (MP), respectively. Similarly, the cost of the operation phase was also the highest among all the different phases, with values of CAD 222.085/m² and CAD 142.134/m² for (GN) and (MP), respectively. On the other hand, the planning phase had the lowest energy and gas consumption as well as cost in both (GN) and (MP), with costs of CAD 5,768/m² and CAD 3,692/m², respectively. The energy savings produced from using mud envelope material rather than the current stone envelope material is 1,052,598 kWh per year in GN building.

Heritage Buildings Life Cycle Phases
The main purpose of this survey is to obtain based on your experience the contribution of the below listed phases on the parameters of energy consumption per year and carbon dioxide emissions.

The phases are:
- Planning phase
- Manufacturing phase
- Transportation phase
- Construction phase
- Operation phase
- Maintenance Phase

Thank you for your cooperation

* Required

1. What is your name? *

2. Area of expertise *
   - Architect
   - Civil Engineer
   - Mechanical/Electrical Engineer
   - Project Manager
   - Other

3. on which location is your experience based on? *
   - Riyadh - KSA
   - Montreal - Canada

4. How much percentage of energy consumption do you think the each phase accounts for in the total life cycle? [Mark only one option per row]

| Phase            | 0-10% | 10-20% | 20-30% | 30-40% | 40-50% | 50-60% | 60-70% | 70-80% | 80-100% |
|------------------|-------|--------|--------|--------|--------|--------|--------|--------|---------|
| Planning phase   |       |        |        |        |        |        |        |        |         |
| Manufacturing    |       |        |        |        |        |        |        |        |         |
| Phase            |       |        |        |        |        |        |        |        |         |
| Transportation   |       |        |        |        |        |        |        |        |         |
| Phase            |       |        |        |        |        |        |        |        |         |
| Construction     |       |        |        |        |        |        |        |        |         |
| Phase            |       |        |        |        |        |        |        |        |         |
| Operation Phase  |       |        |        |        |        |        |        |        |         |
| Phase            |       |        |        |        |        |        |        |        |         |
| Maintenance Phase|       |        |        |        |        |        |        |        |         |
| Phase            |       |        |        |        |        |        |        |        |         |

5. How much percentage of carbon emission do you think the each phase accounts for in the total life cycle?

[Mark only one option per row]

Figure 4. A sample of the conducted questionnaire survey
Figure 5. Energy consumption of the life cycle phases

Figure 6. Gas consumption of the life cycle phases
Table 1. Cost of life cycle phases of GR and MP

| Project life cycle phases | GR ($) | MP ($) |
|--------------------------|--------|--------|
| Planning                 | 5,768  | 3,692  |
| Manufacturing            | 17,305 | 11,075 |
| Transportation           | 14,421 | 9,230  |
| Construction             | 11,537 | 7,384  |
| Operation                | 222,085| 142,134|
| Maintenance              | 17,305 | 11,075 |

8. Conclusion
In this research, a life cycle cost (LCC) of energy analysis for heritage buildings is developed. The project life cycle phases include planning, manufacturing, transportation, construction, operation, and maintenance phases. A model was developed and validated based on sensitivity analysis and case studies. Saudi Arabian and Canadian experts completed questionnaires to attribute a percentage of importance to each of the aforementioned phases with respect to energy consumption. Two case studies – Murabba Palace (MP), Saudi Arabia and Grey Nuns Building (GN), Canada – were then evaluated. The operation phase appeared to be the most energy consuming phase in both case studies. For GN, energy consumption per year is 3,303 MWh and carbon emission is 31,492.8 kg CO$_2$. As a result, the cost per year is 288,422.09 $ per m$^2$. For MP, energy consumption per year is 2,114 MWh and the carbon emission is 49,2070 kg CO$_2$. As a result, the cost per year is 184,590.14 $ per m$^2$. Thus, the operation phase has the highest impact on the energy consumption, gas consumption and cost of the building in both case studies. The findings from this study will aid facility managers in having more efficient rehabilitation projects.

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