# EVALUATION OF BUILDING LIFE CYCLE COST (LCC) CRITERIA IN EGYPT USING THE ANALYTIC HIERARCHY PROCESS (AHP)

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**ABSTRACT**

Recently, life cycle cost (LCC) has gained a wide acceptance in the field of industrial building construction, where it is categorized under economic sustainability in the overall sustainability of buildings. Hence, it is necessary to think about the categories and criteria that affect the building's cost over its lifespan. In this study, the Analytical Hierarchy Process (AHP), a multi-criteria decision-making methodology, is employed to evaluate and weight four categories which are building blocks of the LCC of industrial building construction. The assessment model applies seventeen criteria which are distributed under the following four categories: initial cost, operating or maintenance cost, environmental impact cost, and the end of life. These are evaluated by thirty-seven civilian experts responding to a pair wise questionnaire. The results are significant as they reflect the viewpoints of the civilian experts and can aid in the development of a building's economic sustainability by illuminating the impact factors of the life cycle cost of buildings. To the best of our knowledge, this is the first study to handle criteria evaluation of LCC for sustainable building using the AHP multi-criteria decision-making (MCDM) methodology.

**Keywords**: Life Cycle Cost (LCC); LCC categories; LCC criteria; sustainable building in Egypt; economic sustainability; Analytic Hierarchy Process (AHP)

## 1. Introduction

There has been a growing need to consider building costs and develop methods to evaluate life cycle costs (LCC). Prior to 1970, the initial capital cost was the only investment choice considered for many clients. A number of reports have upheld the necessity of thinking through the long-term cost of project choices, which is called a life cycle cost assessment. Presently, sustainable projects support the implementation of LCC methods since they can deliver an evaluation of the long-term cost of industrial building construction. This study will launch an initiative to apply economic sustainability of industrial buildings construction using a life cycle cost assessment.

A systematic methodology is applied to evaluate LCC selection criteria of industrial buildings construction in Egypt by establishing an AHP questionnaire to achieve high performance in economic sustainability for the new buildings. Civilian experts evaluated the selected criteria from the previous literature. The relative importance weights were calculated by the Analytic Hierarchy Process (AHP), a pair-wise comparison method. These criteria were developed under the following categories of LCC (NRM 1, 2012; NRM 3, 2014; RICS, 2016): initial cost, operating and maintenance cost, environmental impact cost, and end of life cost. The questionnaire was divided into three sections; the first section provided the selected life cycle costs criteria and definitions; the second section provided the calculated relative weights based on the pair-wise matrix and the scale ranges between one and nine provided by civilian experts; and the third section determined the consistency of the responses.

The main problem was to determine the LCC categories and criteria and evaluate them in order to make a decision from amongst the long-term cost of industrial buildings construction choices. Therefore, this study presents an AHP model to evaluate and weight the selected categories and criteria of the LCC of industrial buildings construction by civilian experts responding to a pair-wise questionnaire. The AHP is a systemic technique that helps make complex decisions. The method supports decision makers in choosing the optimal option for their needs based on their comprehension of the problem. It represents an organized and thorough framework for structuring a problem, representing and quantifying its aspects, connecting the identified aspects to goals, and evaluating alternate solutions.

The objective of this research is to develop a multi-criteria decision-making (MCDM) methodology by creating an AHP model of the four LCC categories, and seventeen criteria for industrial building construction. This will allow the discussion of mechanisms for achieving sustainable economic development dimensions, and the application of the true concept of LCC management for the construction of industrial projects to achieve economic recovery in the real estate market.

## 2. Literature review

### 2.1 Life cycle cost concept and analysis of the construction of industrial buildings

In the process of creating a building, early decisions have the greatest impact, hence the need for life cycle costing (NRM 1., 2012; NRM 3., 2014; RICS, 2016; ISO/TC59, B.C. ISO, 2017)). Life cycle costing is an economic quantitative estimation method (*ISO/TC59, B.C.* ISO, 2017; Reisinger et al., 2022). This method evaluates the entire cost of a building over its operating life (Zhang et al., 2018; Noshadravanet al., 2017). The operating life includes initial capital costs, maintenance costs, operating costs and the ultimate disposal of the asset at the end of its life (Noshadravanet al., 2017).

Determination of the economic effects of the alternatives is an important step in a LCC analysis study. A literature review was conducted to extract and coordinate common independent variables related to LCC analysis (Tu& Huang, 2013; Tu, Taur & Lin C., 2016; Ahmed & Arocho, 2021; Marreroet al., 2022). The variables that are applied for LCC are building area, floor height, number of floors, structure and envelope type, building age, and year built.

A previous study in Egypt aimed to evaluate the effects of façade retrofit measures in residential buildings in Cairo using life-cycle cost analysis (Medhat et al., 2021). In Egypt, despite the high initial cost, the High-Performance Glazing Systems (HPGSs) are supposed to be economically feasible in the LCC. Youssef (2022) investigated and compared the economic feasibility of three HPGSs for an office building in New Cairo with the help of MHUC (Ministry of Housing, Utilities & Urban Communities). In terms of life cycle cost (LCC), the Low-E, Electro chromic, and Photovoltaic glazing systems were compared to Clear Double-Glazing as a conventional system (Youssef et al., 2021). In the operation phase of LCC, the rapid and continuous rise in energy costs dictates significant cost control efforts despite the fact that achieving remarkable energy cost reductions is highly governed by the decisions made during earlier phases of the industrial construction project (Yussra et al., 2019).

### 2.2 Objectives of the AHP process

Thomas L. Saaty, a mathematician, developed the AHP method (Saaty,1990; Saaty, 2000; Saaty, 2013; Ferretti, & Saaty, 2014). This method is a framework for operative decision-making of complex problems by simplifying the decision-making process while dividing the issues into sections. These sections or variables are arranged in a hierarchical order with the importance of each variable assigned numerical values which are used to determine which variable has the highest priority and ability to influence the outcome (Saaty, 2005; Ferretti, & Saaty, 2014; Alitaneh, 2019). The AHP method helps solve complicated problems by developing a framework hierarchy of criteria. The AHP also integrates the strengths of the various issues of reasoning, and then aggregates the results that are consistent with our estimates as previously presented (Salgado, et al., 2012). Saaty solved the problem of how to stimulate and discuss the key characteristics of multicriteria analysis techniques and work through the conceptual lens of decision processes in the field of urban and territorial transformations with the AHP according to three principles: the framework of the hierarchy, the principle of prioritization, and the logical consistency principle (Ferretti & Saaty, 2014). The AHP sets up a hierarchy of issues to be resolved, taking into account the criteria that support the accomplishment of the objectives (Garuti& Salomon, 2012; Akman & Dagdeviren, 2018; Karaman & Akman, 2018). It is important to carefully choose the criteria in the AHP objectives process to avoid problems.

## 3. Methodology

We used a two-phase research methodology in this study to determine LCC criteria priorities of sustainable buildings. In phase I, we identified the categories and criteria of LCC that are more effective in sustainable buildings with the help of a comprehensive literature review. Then, we formed an expert panel (EP). The LCC categories and criteria were determined through discussions and the support of the EP. In phase II, the priorities of the sustainable building's LCC categories and criteria were evaluated via the widely recognized AHP methodology by surveying civil professionals. We present a systematic research methodology in Figure 1.

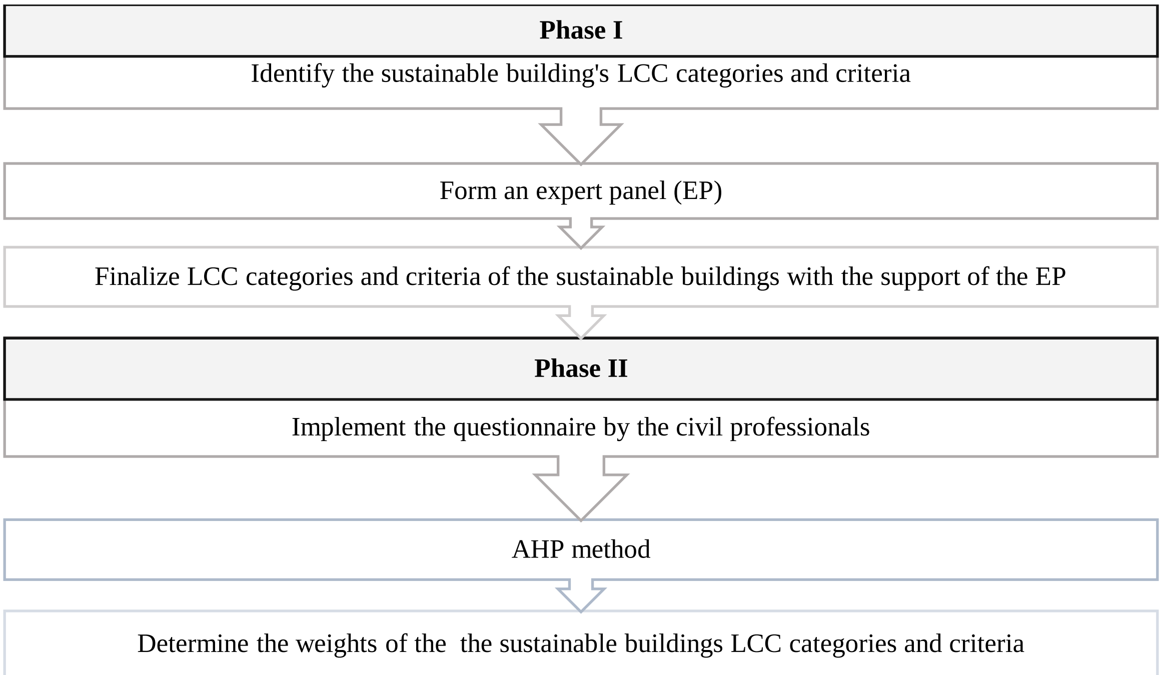


Figure 1 Systematic two-phase research methodology

**3.1 Phase I - Criteria selection**

During the criteria selection stage, it is important to ensure that all aspects utilized in making the decision are covered in order to obtain the required objectives. Each of these criteria should be defined in order to help decision-makers appreciate the suggested alternatives. Criterion that have the same meaning should be avoided which is why we set disciplined standards based on the desired goal (Garuti & Salomon, 2012; An, 2014).

The defined categories and criteria for LCC of industrial building construction included in this research are a result of a combination of information from the existing literature and civil experience. Detailed information about what is included under each category of selected criteria is given. The descriptions and references of the selected LCC categories and criteria are summarized in Table 1.

Table 1
Categories and criteria description and references related to building life cycle cost

| Category | Selected Criteria | Descriptions | References |
|---|---|---|---|
| **Initial cost** | | **Construction industrial cost** | Tu K. J. & Huang Y. W. (2013); Medhat K., Sherif E.& Osama T., (2021); Tu K., Taur Y. &Lin C. (2016); Domenico A.N., Hitapriya S. & Tri Joko W. A. (2020); Kaming Peter F. (2017); Youssef O., Mona G. I., Koji T.& Ahmed M. A. (2021). |
| | Building area | The total area of building which is one of the basics of the building footprint | |
| | Floor height | The height of each building story in unit length which is one of the basics of the building footprint | |
| | Numbers of floors | Number of stories (e.g. 1,2,3….) which is one of the basics of the building footprint | |
| | Structure & envelope type | Includes steel, concrete, wood, and precast concrete in various combinations | |
| | Building age | The study period in years (e.g. 15, 25, 30 years) | |
| | Location city | Cost index of a location varies in different cities | |
| | Year of industrial construction | This parameter includes the projects that are built within the study period | |
| **Operating and Maintenance** | | **Refers to hard facilities management costs including operating costs such as cleaning and energy costs, maintenance costs, and other costs.** | ISO/TC59, B.C. ISO (2017); RICS (2016); NRM 1, (2012); Gao X. & Pishdad-Bozorgi P. (2018); Ibrahim A. (2001); Medhat K., Sherif E.& Osama T., (2021); NRM 3 (2014); Yussra M. R., Ibrahim N. , Khaled N., Islam A. M.&Meshary G. (2019); Kaming Peter F. (2017); Yussra M. R., Ibrahim N. , Khaled N., Islam A. M.& Meshary G. (2019). |
| | Energy cost | Energy used for heating and lighting. | |
| | Catering and services | General support services, communications and security services, letting fees, facilities management fees, caretaker and janitorial services, service transport, IT services, and laundry and linen services, e.g. internal deliveries. | |
| | Cleaning | Waste management and disposal. | |
| | Major repairs | Redecoration, renovation, rehabilitation, replacement. | |
| | Periodic maintenance | The cost of contractors who perform skilled jobs, such as sanitation and HVAC services. | |
| | Rent and insurance | Insurance rates and other local taxes and charges. | |
| **Environmental impact cost** | | **Environmental cost is a reference to the cost of greenhouse gas (GHG) emissions, which are produced during industrial construction of concrete and which has effects on the environment.** | ISO/TC59, B.C. ISO (2017); NRM 3, (2014); ISO 15686 Part 5, (2013); RICS, (2016); Kaming |

| Category | Selected Criteria | Descriptions | References |
|---|---|---|---|
| | Structure and envelope material waste cost | Waste gathered from all stages such as production of raw materials, manufacturing concrete, placing concrete in the location, and demolition. | (2017); Zhang, C., Cao, L. W., & Romagnoli, A, (2018); Point carbon website. |
| | Market price of resultant $CO_2$ | Cost of controlling gas emissions. | |
| **End of life** | | **This includes disposal and demolition, but specifically includes the worth of alternatives at the end period of LCC analysis.** | ISO/TC59, B.C. ISO (2017); Yussra M. R., Ibrahim N. , Khaled N., Islam A. M.&Meshary G. (2019); RICS, (2016); Domenico A.N., Hitapriya S. & Tri Joko W. A. (2020); Noshadravan A., Miller T. R. & Gregory J. G., (2017). |
| | Salvage and recycling | Recycling, the conversion of building waste into new objects. | |
| | Demolition cost | Building demolition waste such as materials, aggregate, concrete, wood, and metal. | |

Life cycle cost components for buildings can be broken down into several elements in a hierarchy structure, as shown in Table 1. The first level contains the four cost categories of initial costs, operating and maintenance costs, and end of life cost (salvage value & demolition cost). Since parties in the Kyoto Protocol committed to reach their targets through reducing GHG emissions over the 2008-2012 commitment period and since the Protocol allows countries that have emission units to sell the extra capacity to countries that are over their targets (United Nations, 2011), the environmental impact costs are added as future costs based on the prices and quantities of GHG converted into $CO_2$ and structure and envelope material waste costs.

The second level consists of the seventeen criteria, which can be broken down into the four categories. For example, initial costs include building area, floor height, numbers of floors, structure & envelope type, building age, location city, and year of industrial construction, while operating and maintenance costs includes energy cost, catering and services, cleaning, major repairs, periodic maintenance, and rent and insurances.

**3.2 Phase II – AHP**

Comparative judgment means building judgments about the proportional weight of two criteria at a given level in relation to the above levels. This evaluation is the core of the AHP, as it will influence the preference of the criteria. We used a pair wise comparison matrix to establish the evaluation results (An, 2014). To achieve effective metrics when comparing two criteria, we needed to understand the general purpose. The benchmark reference in Table 1 was used to complete the scale of comparative importance in pairs according to Saaty.

We applied an AHP survey to develop the selected criteria of LCC for buildings; this survey proposed the effective execution of LCC implementation for new buildings. Therefore, we looked for the most effective LCC criteria from the latest literature. In order to choose the best priorities of the selected criteria, thirty-seven civilian experts evaluated the chosen criteria using Saaty's 1-9 scale. The main objective of the applied survey was to collect the decision makers' opinions and then calculate the relative weights for the selected criteria by using the AHP pairwise comparison method (Ferretti, & Saaty, 2014; Alitaneh, 2019). In this context, the AHP hierarchy for the effective categories and criteria of industrial building construction LCC are given in Figure 2.

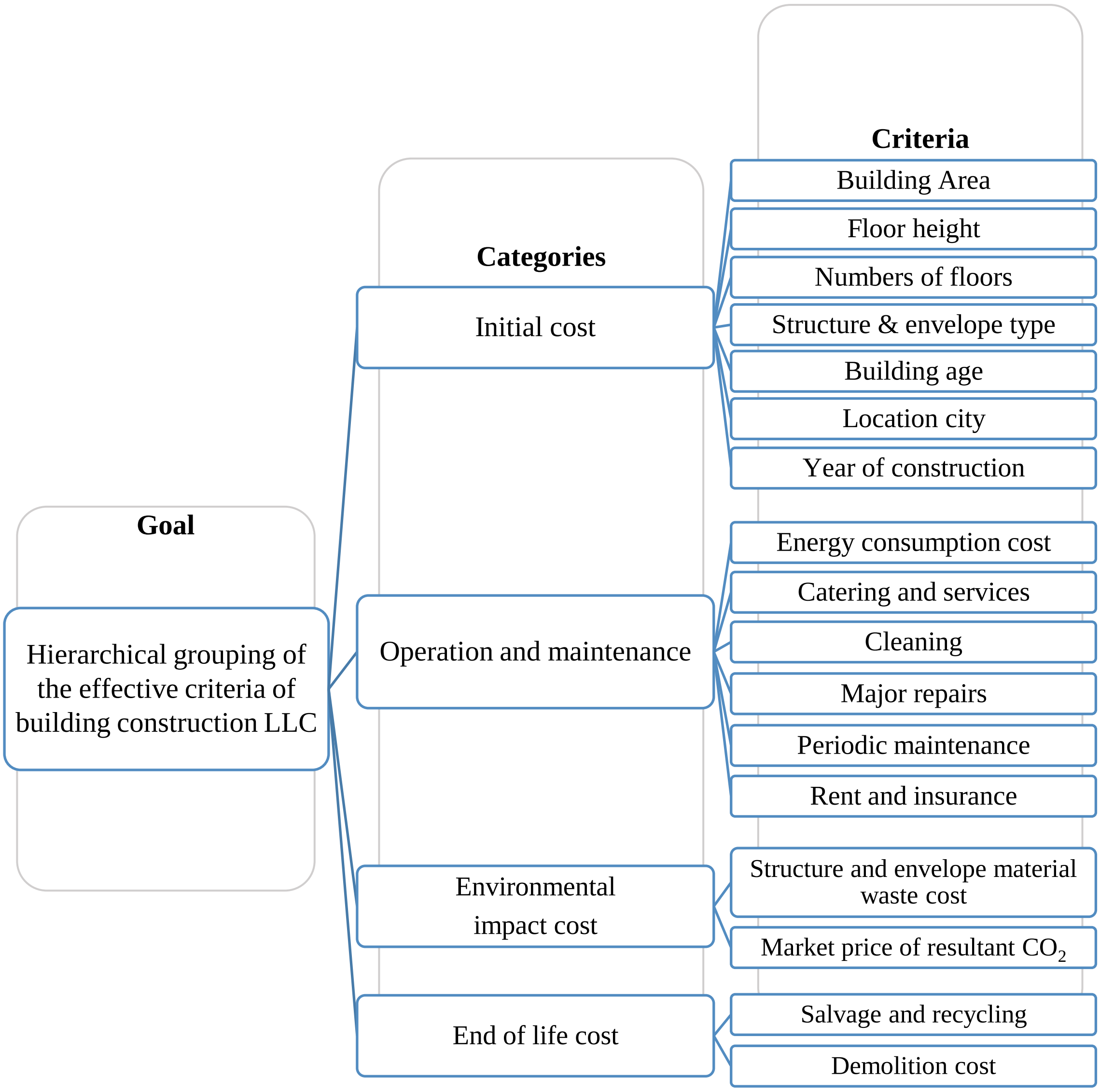


Figure 2 Hierarchy of the AHP model

### 3.2.1 Calculations of sample size

We can statistically calculate the required sample size according to Equation (1) (Montgomery, 1998). Where, n is sample size, $Z\alpha/2$ is a critical value from statistical tables, P is a percentage of the target sample population to the total population, and d is the accepted error percentage.

$$n = \frac{\left(z_{\alpha/2}\right)^2 * p * (1-p)}{d^2} \tag{1}$$

For a target sample population of 10,000 and 22,729 for contractors and consultants respectively, and a total population of 182,703 civil engineers (all registered civil engineers in all departments of the Egyptian Engineers Syndicate), the assumed accepted error percentage in this method is 10% ; $Z\alpha/2 = 1.645$ and the minimum sample size is calculated to be 15. Thirty-seven civilian experts participated in the research.

### 3.2.2 Survey study

A web-based survey was applied based on pilot study feedback. It was distributed to about tens experts including building managers, consultants, academics, and contractors both in and out of Egypt. This study was conducted in English. We received 37 responses and excluded five of them. The responses were collected electronically through the web-based system and the Egyptian Engineers Syndicate. The questionnaires were scanned many times and discussed with certain civilian experts.

### 3.2.3 Evaluation of selected criteria by the civilian experts

Once the hierarchy of a problem has been established, the decision makers must evaluate and compare its different elements to each another. In making the comparisons, the decision makers can use their judgments about the elements or they can use real data, or a combination of both. The main attribute of the AHP is that human judgments, and not just the underlying information, can be used to perform the evaluations.

We started by asking the experts to fill out half of a $\boldsymbol{n \times n}$ matrix $\boldsymbol{A}$ of criteria, $\boldsymbol{i}$ and $\boldsymbol{j}$ about a preference numerical value, $\boldsymbol{a_{ij}}$ from the 1 to 9scale as in Table 2.The matrix $\boldsymbol{A}$ is written below in Equation (2).

Table 2
Saaty’s fundamental rating scale (Saaty, 1990, 2000)

| Scale | Definition | Explanation |
|---|---|---|
| **1** | Equal importance | Two activities contribute equally to the objective |
| **3** | Moderate importance of one over another | Experience and judgment moderately favor one activity over another |
| **5** | Essential or strong importance | Experience and judgment strongly favor one activity over another |
| **7** | Very strong importance | Activity is very strongly favored and its dominance demonstrated in practice |
| **9** | Extreme importance | Evidence favors one activity over another is of the highest possible order of affirmation |
| **2, 4, 6, 8** | Intermediate values between the two adjacent judgments | Compromise is needed |

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad (2)$$

Other entries of matrix $\boldsymbol{A}$ are determined by $\boldsymbol{a_{ii}=1}$, $\boldsymbol{aji=1/ a_i}$, assuming $\boldsymbol{a_{ij}\neq 0}$. After that, we reversed the values in the other half of matrix. This method evaluates and quantifies the relative weights of each matrix *A* dividing the entries into the columns to the respective column sums for the selected categories and criteria. The relative weights are normalized and calculated based on the pair-wise matrix and the scales provided by experts as below in Equation (3).

$$\boldsymbol{Aw=\lambda_{max}w} \qquad (3)$$

Where $\boldsymbol{w}$ is the principal eigenvector corresponding to the largest eigenvalue $\boldsymbol{\lambda max}$.

Tables 3 to 7 represent the average of the pair-wise comparison matrix for 32 experts of the selected categories and criteria.

Table 3
Pair-wise comparison matrix of LCC categories

| **LCC categories** | Initial costs | Operating and maintenance | Environmental impact cost | End of life cost |
|---|---|---|---|---|
| Initial costs | 1.00 | 2.00 | 2.00 | 3.00 |
| Operating and maintenance | 0.50 | 1.00 | 2.00 | 2.00 |
| Environmental impact cost | 0.50 | 0.5 | 1.00 | 4.00 |
| End of life cost | 0.33 | 0.50 | 0.25 | 1.00 |


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Table 4
Pair-wise comparison matrix of initial cost criteria

| **Initial cost Criteria** | Building area | Floor height | No. of floors | Structure & envelope type | Building age | Location city | Year built |
|---|---|---|---|---|---|---|---|
| Building area | 1 | 2 | 1 | 2 | 6 | 5 | 3 |
| Floor height | 0.5 | 1 | 0.5 | 2 | 3 | 4 | 2 |
| No. of floors | 1 | 2 | 1 | 3 | 4 | 6 | 3 |
| Structure & envelope type | 0.5 | 0.5 | 0.33 | 1 | 4 | 5 | 2 |
| Building age | 0.167 | 0.33 | 0.25 | 0.25 | 1 | 0.33 | 0.5 |
| Location city | 0.2 | 0.25 | 0.167 | 0.2 | 3 | 1 | 0.5 |
| Year built | 0.33 | 0.5 | 0.33 | 0.5 | 2 | 2 | 1 |

Table 5
Pair-wise comparison matrix of operating and maintenance cost criteria

| **Operating and maintenance criteria** | Energy consumption cost | Catering and services | Cleaning | Major repairs | Periodic maintenance | Rent and insurance |
|---|---|---|---|---|---|---|
| Energy cost | 1 | 3 | 1 | 2 | 3 | 4 |
| Catering and services | 0.33 | 1 | 1 | 0.33 | 0.5 | 4 |
| Cleaning | 1 | 1 | 1 | 0.5 | 0.33 | 2 |
| Major repairs | 0.5 | 3 | 2 | 1 | 2 | 4 |
| Periodic maintenance | 0.33 | 2 | 3 | 0.5 | 1 | 4 |
| Rent and insurance | 0.25 | 0.25 | 0.5 | 0.25 | 0.25 | 1 |

Table 6
Pair-wise comparison matrix of environmental impact cost criteria

| **Environmental impact cost criteria** | Structure and envelope material waste cost | Market price of resultant $CO_2$ |
|---|---|---|
| Structure and envelope material waste cost | 1.00 | 2.00 |
| Market price of resulted $CO_2$ | 0.50 | 1.00 |

Table 7
Pair-wise comparison matrix of the end of life cost criteria

| **End of life cost criteria** | Salvage value | Demolition cost |
|---|---|---|
| Salvage and recycling | 1.00 | 3.00 |
| Demolition cost | 0.33 | 1.00 |

The AHP utilizes five pair-wise comparison matrices consisting of various factors. The previous pair-wise comparison matrices provided the importance ratio for each pair of alternatives. Each matrix is a mutual matrix in which the main diagonal elements are 'one' and the values above the diagonal are the reciprocal of those below. The relative importance of each category and sub category are based on a 1-9 scale with the interpretations presented in Table 2. The AHP converts each different evaluation to a numerical value that can be easily processed and compared over the whole range of the problem. In the next step, a numerical weight is determined for each element of the hierarchy, which often allows incommensurable and varied elements to be compared to each other in a rational and consistent way. This feature distinguishes the AHP from other techniques. Next, numerical priorities are estimated for each alternative in the final step of the process. These numbers represent the alternatives' relative ability to achieve the main goal, which allows a simple consideration of the various courses of action.

### 3.2.4 Consistency analysis of the responses

All responses are submitted to a consistency test. The consistency ratio is calculated by dividing the consistency index value ***CI*** by the random consistency ***RI*** index value as below in Equation (4). We calculated the ***CI*** using Equation (5), while the ***RI*** value was obtained from Table 8, and this value depends on a size ***n*** matrix. If ***CI*** equals ***0***, the matrix is consistent. Where the ***CR*** value of any matrix is less than ***10%,*** the inconsistency of the responses is still considered acceptable (Ergu, Kou, Peng & Shi, 2011). We obtained 37 responses, and excluded five due to their high consistency ratio. Table 9 represents the value of λmax, calculated by dividing the vector weight by the relative weight of each criterion, the consistency index value ***CI***, and consistency ratio ***CR*** for all the previous matrixes.

$$CR = CI / RI \quad (4)$$

$$CI = (\lambda_{max} - n)/ (n - 1) \quad (5)$$

Table 8
Random inconsistency index (RI) for n=1, 2…10

| ***n*** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ***RI*** | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.27 | 1.32 | 1.41 | 1.54 | 1.49 |

There are different consistency ratios ***CR,*** and the value of $\lambda_{max}$ and ***CI*** for all the previous matrices are shown in Table 9. When the consistency ratio of the responses for LCC categories, initial cost criteria, operating and maintenance criteria are 0.082, 0.042, 0.077, respectively, which less than 0.1 (Ergu, Kou, Shi & Shi, 2011), the consistency is considered acceptable. When the ***CR*** was decreased to zero, the comparison matrix was completely consistent as in the environmental impact cost criteria and end of life cost criteria comparison matrix.

Table 9
Value of $\lambda_{max}$, ***CI, CR*** for all the previous matrices

| Matrix name | LCC categories | Initial cost criteria | Operating & maintenance criteria | Environmental impact criteria | End of life criteria |
|---|---|---|---|---|---|
| $\lambda_{max}$ | 4.22 | 7.33 | 6.49 | 2 | 2 |
| ***CI*** | 0.074 | 0.55 | 0.098 | 0 | 0 |
| ***CR*** | 0.082 | 0.042 | 0.077 | 0 | 0 |

## 4. Results and discussion

### 4.1 Results of AHP weights and ranking

LCC is a sustainable economic tool to evaluate the cost performance of industrial building construction. It aims to make choices between different categories to achieve the client's goals when those categories are not only in their initial costs but also in their subsequent operation and maintenance costs, environmental impact costs, and end of life costs. The AHP allows the weighting and ranking of the alternatives of categories and criteria to be compared on the same basis. It is used for option appraisal by the weighting of LCC categories and criteria. The first comparison of the study (shown in Table 10) includes initial costs, operation and maintenance cost, environmental impact cost, and end of life cost.

Table 10
AHP weights and rank of the LCC categories

| **LCC categories** | Weight | Rank |
|---|---|---|
| Initial costs | 0.40 | 1 |
| Operating and maintenance | 0.27 | 2 |
| Environmental impact cost | 0.23 | 3 |
| End of life cost | 0.10 | 4 |
| sum | 1.00 | |

The second AHP ranking of the study was applied for the paired matrix criteria of each category. As shown in Table 11, the initial cost criteria were weighted and ranked. The civilian experts ranked number of floors and building area at the top of the initial cost criteria with 27% and 26%, respectively. Whereas, floor height and structure & envelope type ranked lower with 16% and 14%, respectively. At the bottom of the ranking, was year built, followed by location (city) then building age.

Table 11
AHP weights and rank of the initial cost criteria

| **Initial cost criteria** | Weight | Rank |
|---|---|---|
| Building area | 0.26 | 2 |
| Floor height | 0.16 | 3 |
| No. of floors | 0.27 | 1 |
| Structure & envelope type | 0.14 | 4 |
| Building age | 0.04 | 7 |
| Location city | 0.05 | 6 |
| Year built | 0.08 | 5 |
| sum = | 1.00 | |

In Table 12, weighting and ranking of the operating and maintenance cost criteria reveal that the energy cost (30%) has the top priority in sustainable building followed by major repairs (23%), periodic maintenance (18%), cleaning (12.4%), catering and services (11%), and rent and insurance (4.8%). RICS (2016) discusses that lower expenditure on building fabric or insulation might lead to higher energy expenditure and a more expensive cladding system might lead to savings on frame and foundation costs; however, this will also cost more to renew and using a cheaper component might be less durable and require replacement or maintenance more frequently. The logic behind our results may be a result of the emphasis on the professional civilian experts and the value of the collected data.

Table 12
AHP weights and rank of the operating and maintenance cost criteria

| **Operating and maintenance criteria** | Weight | Rank |
|---|---|---|
| Energy cost | 0.30 | 1 |
| Catering and services | 0.11 | 5 |
| Cleaning | 0.124 | 4 |
| Major repairs | 0.23 | 2 |
| Periodic maintenance | 0.18 | 3 |
| Rent and insurance | 0.048 | 6 |
| sum = | 1.00 | |

The experts evaluated structure and envelope material waste cost as 67% of the environmental impact cost criteria, whereas market price of the resultant $CO_2$ was 33% as shown in Table 13. This means that the cost of controlling $CO_2$ gas emissions is about 7% of all the LCC for sustainable buildings, and waste gathered from all stages such as production of raw materials, manufacturing concrete, placing concrete at the location, renewal and replacement and demolition is about 11% of all the LCC for sustainable building.

Table 13
AHP weights and rank of the environmental impact cost criteria

| **Environmental impact cost criteria** | Weight | Rank |
|---|---|---|
| Structure and envelope material waste cost | 0.67 | 1 |
| Market price of resultant$CO_2$ | 0.33 | 2 |
| sum = | 1.00 | |

The weight of salvage value and recycling at the end of life cycle criteria is about 75% (Table 14). As shown in Table 10 the end of life cost takes 10% of the LCC. Therefore, it is logical that it would be 7.5% yield cost of the LCC (salvage and recycling) because it has 75% of the end of life cost (Table 14). Building demolition waste costs, such as materials, aggregate, concrete, and wood, are 2.5% of the LCC because it has 25% of the end of life cost (Table 14).

Table 14
AHP weights and rank of the end of life cost criteria

| **End of life cost criteria** | Weight | Rank |
|---|---|---|
| Salvage and recycling | 0.75 | 1 |
| Demolition cost | 0.25 | 2 |
| sum = | 1.00 | |

### 4.2 Discussion

Since the LCC models in previous studies were varied in terms of categories of LCC and methods, Figure 3 presents the LCC categories including initial cost, operation & maintenance cost, and energy cost that were obtained and compiled from green government office buildings in Indonesia (Domenico, Hitapriya & Tri Joko, 2020).

Kaming (2015, 2016, 2017) presented three types of buildings which are hostels, universities, and commercial buildings in three different studies with the same categories including initial construction industrial cost, operational cost, and maintenance and replacement costs. Figure 4 shows the distribution of LCC categories of commercial buildings found in his studies.

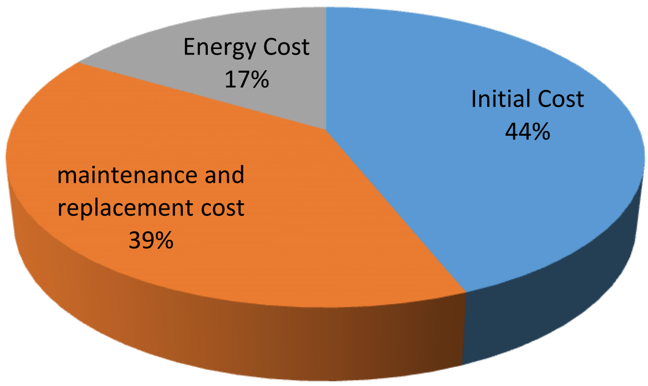


Figure 3 Distribution of LCC categories of green government office buildings in Indonesia (Domenico, Hitapriya & Tri Joko, 2020)

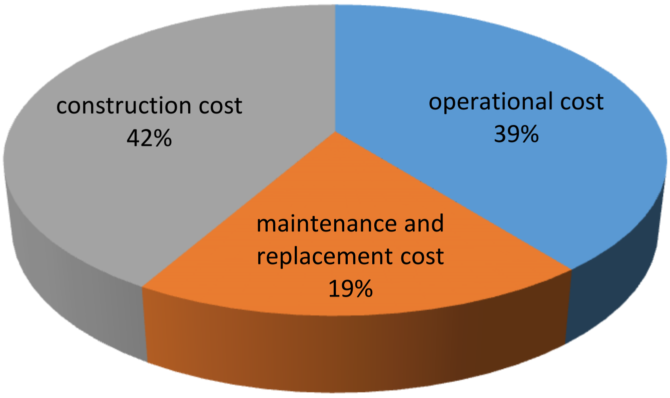


Figure 4 Distribution of LCC categories of commercial buildings (Kaming, 2017)

In this study, the civilian experts viewed initial cost as important with 40% of all of the life cycle cost followed by operation and maintenance cost and environmental impact cost, then end of life cost with 27%, 23%, and 10%, respectively as shown in Figure 5. This means that the running costs are significantly more important, since they are more than 50% of the LCC of industrial building construction in Egypt. Whereas the operation and maintenance cost criteria revealed that the energy cost (30%) had a top priority in sustainable building followed by major repairs (23%), periodic maintenance (18%), cleaning (12.4%), catering and services (11%), and rent and insurance (4.8%), respectively (Figure 6).The expert's evaluated the structure and envelope material waste cost as 67% of the environmental impact cost criteria, whereas market price of resultant $CO_2$ was 33% as shown in Figure 7. Salvage value and recycling at the end of life cycle criteria is about 75% and building demolition waste cost is about 25% as shown in Figure 8.

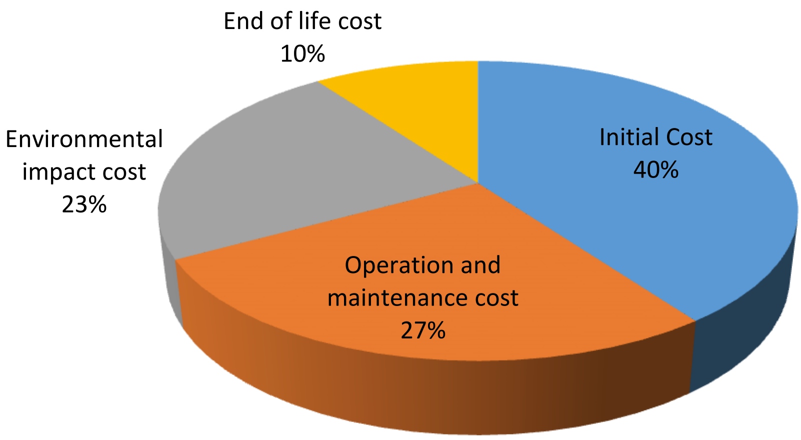


Figure 5 Distribution of LCC categories of industrial building construction in Egypt


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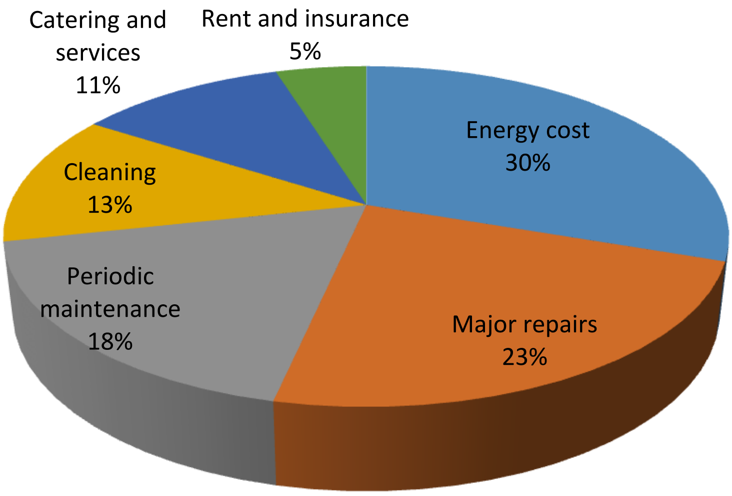


Figure 6 Distribution of the operation and maintenance cost criteria of industrial building construction in Egypt

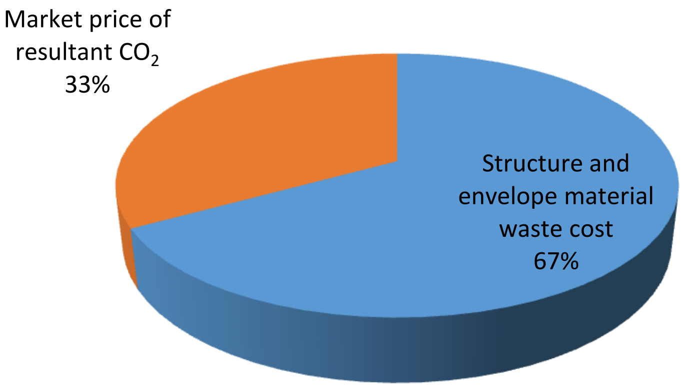


Figure 7 Distribution of the environmental impact cost criteria of industrial building construction in Egypt

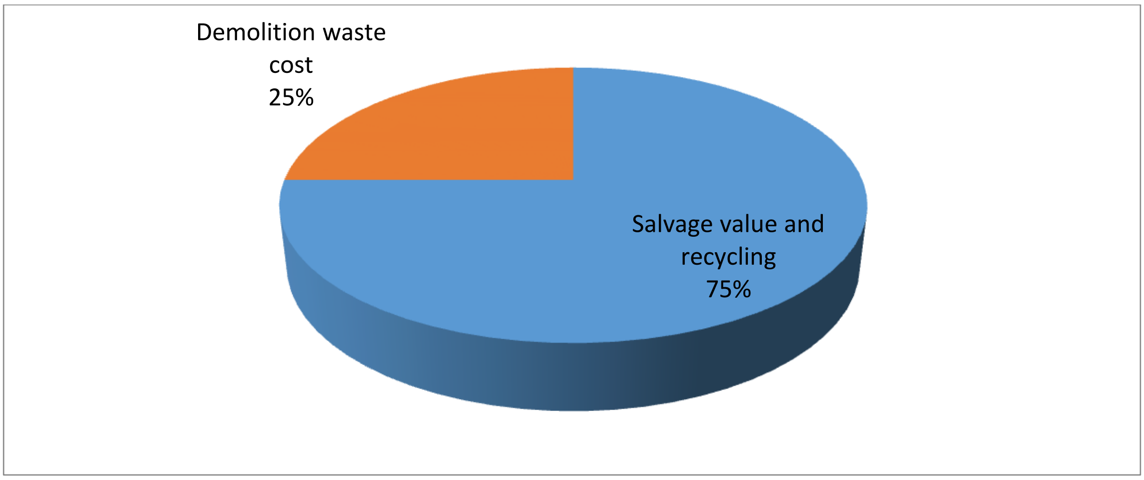


Figure 8 Distribution of the End of life cycle cost criteria of industrial building construction in Egypt

## 5. Conclusion

- The AHP methodology was proposed to rank life cycle cost (LCC) categories and criteria of industrial buildings in Egypt. This methodology is a Multi-Criteria Decision-Making process. In this study, we collected data from previous reviews, and then formed an experts' panel (EP). Next, we developed a hierarchical structure with LCC categories and criteria of construction buildings.
- A web-based AHP questionnaire was distributed to civilian experts inside and outside of Egypt. Only 37 responses were received with five responses excluded due to their high consistency ratio.
- The consistency was checked for each paired matrix by dividing the consistency index value CI by the random consistency RI index value; the indication of consistency ratios (CR) for LCC categories, initial cost criteria, operating and maintenance criteria matrices are 0.082, 0.042, 0.077, respectively, which are all less than 0.1. The comparison matrix for environmental impact cost criteria and end of life cost criteria is completely consistent, as the CRs equal zero.
- The assessments made so far reflect that the experts' opinions to the LCC categories and criteria in general define a roadmap for building construction. The civilian expert evaluations clarified that the running costs are significantly important, as this criterion is more than 50% of the LCC, whereas initial cost is about 40% of LCC.
- The civilian experts provided responses for the paired matrix criteria under each category. In the matrix of initial cost criteria, the number of floors and buildings are at the top of the initial cost criteria ranked 27% and 26%, respectively. Whereas, floor height and structure & envelope type are less important with 16% and 14%, respectively. At the bottom of the ranking, we find year built, followed by location (city) then building age.
- In the operating and maintenance cost criteria AHP matrix, energy cost (30%) has a top priority in sustainable building followed by major repairs (23%), periodic maintenance (18%), cleaning (12.4%), catering and services (11%), and rent and insurance (4.8%), respectively.
- The assessment of environmental impact cost criteria clarified that structure and envelope material waste cost is rated 67% and market price of resultant $CO_2$ is 33%.
- The AHP rank shows that the salvage value and recycling of the end of life cycle criteria is about 75%, accordingly demolition cost is 25% of the end of life cost criteria. The experts' views can enable clients or researchers to assess the current building's LCC, and plan for economic sustainability of buildings in coming projects and investments.

The study limitations are as follows:

- The developed AHP model and selection framework are limited to industrial building construction in Egypt.
- The gathered data used are from previous studies related to LCC categories and criteria.
- The results are based on civilian expert's views, such as civil engineers in the Egyptian engineers syndicate and engineering civilian services that were gathered by an electronic survey.

Recommendations for future research:

- Collect additional data points for life cycle components such as initial costs of business practices and more criteria related to energy costs, environmental impact cost criteria, and end of life cycle cost criteria.
- Gather additional experts' opinions regarding the weighting of selection criteria and the preferred range of each criterion.
- Provide another approach for a future study such as modeling the historical costs and forecasting costs of industrial buildings in Egypt, based on an artificial intelligence model.

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## APPENDIX

### AHP questionnaire survey for sustainable industrial buildings construction based on life cycle cost

Please perform a pair-wise comparison of importance using the following 1 to 9 scale:

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Equally Preferred | | ← | Stongly Preferred | | → | | Extremely Preferred | |

The information extracted from this questionnaire will be compiled and will be used as a part of the research. Your contribution towards this study is greatly appreciated since it will significantly add to the value of this research.

### SECTION 1: GENERAL INFORMATION

**This section contains general information about you and your firm to identify the various responses received.**

- Name:
- Phone number:
- Email address:
- Experience in green and sustainable construction industrial industry:
- Company name:
- Position:
- How would you classify your firm?

☐ Owner Representative
☐ Consultant firm
☐ Contractor
☐ Other, please specify:

### SECTION 2: DEFINITION OF SELECTED DIMENSIONS

| Selected Dimensions | Definition |
|---|---|
| **Initial cost** | **Construction industrial cost** |
| Building area | The total area of building which is one of the basics of building foot print |
| Floor height | The height of each building story in unit length which is one of the basics of building foot print |
| Numbers of floors | No. of building stories (e.g. 1,2,3….) which is one of the basics of building foot print |
| Structure & envelope type | These include steel, concrete, wood, and precast concrete in various combinations |
| Building age | The study period in years (e.g. 15, 25, 30, ….. year ) |


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| | |
|---|---|
| Location city | The cost index of a location varies in different cities |
| Year of construction industrial | This parameter includes the projects that are built within the study period |
| **Operating and Maintenance** | **Referred to as hard facilities management costs, these costs include operating costs such as cleaning and energy costs, maintenance costs, and other costs.** |
| Energy cost | Energy used for heating and lighting. |
| Catering and services | General support services, communications and security services, letting fees, facilities management fees, caretaker and janitorial services, service transport, IT services, and laundry and linen services, e.g. internal deliveries. |
| Cleaning | Waste management and disposal. |
| Major repairs | Redecoration, renovation, rehabilitation, replacement. |
| Periodic maintenance | The cost of contractors who perform skilled jobs, such as sanitation and HVAC services. |
| Rent and insurance | Insurance rates and other local taxes and charges. |
| **Environmental impact cost** | **Environmental cost references the cost of greenhouse gas (GHG) emissions, which are produced during the industrial construction of concrete and which has effects on the environment.** |
| Structure and envelope material waste cost | Waste gathered from all stages such as production of raw materials, manufacturing concrete, placing concrete in the location, and demolition. |
| Market price of resultant $CO_2$ | Cost of controlling gas emissions. |
| **End of life** | **This includes disposal and demolition, but specifically includes the worth of alternatives at the end period of LCCA.** |
| Salvage and recycling | Recycling, the conversion of building waste into new objects. |
| Demolition cost | Building demolition waste such as materials, aggregate, concrete, wood, and metal. |

## SECTION 3: AHP QUESTIONNAIRE

| The pair-wise comparison matrix of LCC categories | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| Initial costs | | | | | | | | | | | | | | | | | | Operating and maintenance |
| Initial costs | | | | | | | | | | | | | | | | | | Environmental impact cost |
| Initial costs | | | | | | | | | | | | | | | | | | End of life |
| Operating and maintenance | | | | | | | | | | | | | | | | | | Environmental impact cost |
| Operating and maintenance | | | | | | | | | | | | | | | | | | End of life |
| Environmental impact cost | | | | | | | | | | | | | | | | | | End of life |

| The pair-wise comparison matrix of initial cost criteria | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| Building area | | | | | | | | | | | | | | | | | | Floor height |
| Building area | | | | | | | | | | | | | | | | | | No. of floors |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Building area | | | | | | | | | | | | | | | | | | Structure & envelope type |
| Building area | | | | | | | | | | | | | | | | | | Building age |
| Building area | | | | | | | | | | | | | | | | | | Location city |
| Building area | | | | | | | | | | | | | | | | | | Year of built |
| Floor height | | | | | | | | | | | | | | | | | | No. Of floors |
| Floor height | | | | | | | | | | | | | | | | | | Structure & envelope type |
| Floor height | | | | | | | | | | | | | | | | | | Building age |
| Floor height | | | | | | | | | | | | | | | | | | Location city |
| Floor height | | | | | | | | | | | | | | | | | | Year of built |
| No. of floors | | | | | | | | | | | | | | | | | | Structure & envelope type |
| No. of floors | | | | | | | | | | | | | | | | | | Building age |
| No. of floors | | | | | | | | | | | | | | | | | | Location city |
| No. of floors | | | | | | | | | | | | | | | | | | Year of built |
| Structure & envelope type | | | | | | | | | | | | | | | | | | Building age |
| Structure & envelope type | | | | | | | | | | | | | | | | | | Location city |
| Structure & envelope type | | | | | | | | | | | | | | | | | | Year of built |
| Building age | | | | | | | | | | | | | | | | | | Location city |
| Building age | | | | | | | | | | | | | | | | | | Year of built |
| Location city | | | | | | | | | | | | | | | | | | Year of built |

| The pair-wise comparison matrix of operating and maintenance cost criteria | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| Energy cost | | | | | | | | | | | | | | | | | | Catering and services |
| Energy cost | | | | | | | | | | | | | | | | | | Cleaning |
| Energy cost | | | | | | | | | | | | | | | | | | Major repairs |
| Energy cost | | | | | | | | | | | | | | | | | | Periodic maintenance |
| Energy cost | | | | | | | | | | | | | | | | | | Rent and insurances |
| Catering and services | | | | | | | | | | | | | | | | | | Cleaning |
| Catering and services | | | | | | | | | | | | | | | | | | Major repairs |
| Catering and services | | | | | | | | | | | | | | | | | | Periodic maintenance |
| Catering and services | | | | | | | | | | | | | | | | | | Rent and insurance |
| Cleaning | | | | | | | | | | | | | | | | | | Major repairs |
| Cleaning | | | | | | | | | | | | | | | | | | Periodic maintenance |
| Cleaning | | | | | | | | | | | | | | | | | | Rent and insurance |
| Major repairs | | | | | | | | | | | | | | | | | | Periodic maintenance |
| Major repairs | | | | | | | | | | | | | | | | | | Rent and insurances |
| Periodic maintenance | | | | | | | | | | | | | | | | | | Rent and insurances |

| The pair-wise comparison matrix of environmental impact cost criteria | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| Structure and envelope materialwaste cost | | | | | | | | | | | | | | | | | | Market price of resulted $CO_2$ |

| The pair-wise comparison matrix of the end of life cost criteria | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| Salvage and recycling | | | | | | | | | | | | | | | | | | Demolition cost |