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A Systematic Approach to Embodied Carbon Reduction in Buildings

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Abstract. The eminence of climate change and global warming has received considerable international awareness in recent decades. Construction industry sector consumes a substantial amount of natural resources and leads to the emissions of million tonnes of carbon into the environment. Consequently, Malaysia is one of the countries with the highest level of carbon emissions in the world. The commercial sector has been identified as one of the major contributors to carbon emission by energy consumption. Building developers should take action in promoting sustainable building practices to reduce carbon emission and energy consumption. Selection of appropriate building materials can lead to significant reduction in greenhouse gases emission. In this paper, an absolute quantification and estimation of embodied carbon emission are presented. Furthermore, this paper investigates the amount of energy consumed. It also presents a novel optimization model for embodied carbon emission which has been developed by evolutionary Genetic Algorithm (GA). GA evaluation has been rarely used to address environmental performances of construction projects, particularly in Malaysia. In this regard, the adoption of the ISO 14040 framework and evolutionary GA were used to evaluate the office project. This paper presents an assessment model that can be beneficial for carbon emission management. According to findings, the developed GA model can be used in practice which has been validated by an application to the building.

INTRODUCTION

Human activities have led to the increase in the concentration of greenhouse gases (CHGs) in the atmosphere. Carbon dioxide (CO₂) is believed to be one of the most significant contributors to CHGs [1]. Global warming is the consequence of the increase in CO₂ emission level which has been stated to be about 70% of greenhouse effects to date [2]. Malaysia is listed as one of the countries with the highest CO₂ production in the world [10] which place this country as 26th on the list of countries with the highest volume of carbon emission in the world [3]. From 1990 to 2004, carbon emission in Malaysia has grown approximately 221%, one of the highest rates in the world [4]. In response, Malaysia is taking initiatives to decrease the emission of CO₂ by organising a national mitigation and intergovernmental mechanism which targets the decrease of about 40% of the carbon emitted into the atmosphere by 2020.

In this regard, one of the biggest culprits is the construction sector as it is known to produce a substantial amount of wastes and CO₂ emission as a result of high energy consumption. Here, even after construction, the maintenance of buildings require never-ending consumption of natural resources for years to come [5-7]. The construction industry is reported to contribute to one-third of total energy use and the emission of GHGs [8, 9]. Furthermore, commercial buildings are reported to contribute to one-fifth of the total domestic energy consumption [10]. Consequently, sustainability can be obtained through mitigating climate change through improving building construction process. Decisions made during the pre-construction and/or construction stages are among the most important decisions related to the sustainable design of the building. In contrast, after these stages, any decisions made to change and modify the design to fulfill a set of criteria could be inefficient and expensive [11].

There are several rating systems have been implemented to evaluate green or sustainable building status. One of these systems is the Environmental Management System (EMS) which is a popular rating tool with ISO guided series and it is widely used worldwide due to its advantages. This rating system has successfully helped construction firms in improving their environmental performance and policy, practice sustainability and safeguard their environmental reputations [12,16]. On the other hand, the environmental impact of materials as finished products have been largely ignored and the life cycle analysis (LCA) of ISO 14040 has not been implemented in the Malaysian construction industry [13]. This standard outlines a guideline for LCA principles and LCA based analysis which helps an organization to obtain information on ways to decrease



the general impact of its products and services to the environment. In this regard, it is imperative to have access to complete information to knowledge on the building's form, materials, context, and technical systems to assess the performance of a building life cycle realistically [14,15]. Thus, this study aims to identify and quantify the annual amount of lifecycle performance of the building in regard to the embodied carbon emission and energy consumption. Secondly, this study aims to ensure the optimum carbon emission in building lifecycle and to compare the result with the existing design.

METHODOLOGY

The ISO 14040 lifecycle assessment framework is used to assess the environmental impact of an office building. This framework is a lifecycle assessment which identifies, quantifies and evaluates a product's inputs, outputs and probable impact to the environment all through its life cycle, starting from the acquisition of raw material, its production, application, and disposal. LCA has been known as the most suitable tool for a comprehensive environmental assessment. In this light, this model is grounded in system thinking, in which the product or service can be defined as a system. A system's inventory presents a quantitative description of the materials and energy flowing through the boundary of the system. Similar to a majority of systems, here, the LCA is described through a linear model.

The boundary of the system could be quantified as the construction and operation stages, including the producing and transporting the building materials to the construction site, the equipment used for construction. Hence, the most relevant inventory data is the most important building materials were included to complete the model successfully. Meanwhile, during the second stage of LCA, inventory analysis was conducted to calculate the carbon emission from the quantified materials. This analysis includes calculating the total mass, emissions from transportation and materials emissions, for the embodied carbon emission from both basic and complex materials.

The calculation was achieved for embodied carbon emission by using the Inventory of Carbon & Energy (ICE V2.0). This inventory includes the latest carbon conversion rates database. The density value is projected in tonnes and can be related to each calculated volume and weight of each material. The inclusion of embodied carbon emission from transportation is highly recommended in LCA. Thus, this study has estimated the distances between building material's suppliers and the site location, which were within the 30km to 250km radius. Consequently, embodied carbon emission calculation from transportation of building materials will differ for different material. The case study building is a research and development office which has a reinforced concrete structure in two main blocks containing three upper floor and a single-story block for M&E purpose.

The MATLAB software was used to develop a carbon emission optimization model to assess environmental performance. Here, Genetic Algorithm parameters were set and the mutation rate was set to 25% while the percentage of fittest populations kept was 50%. The GA toolbox of MATLAB considered the population as 16 multiplied by the number of variables (20), hence there are 320 populations considered for each iteration.

The model development input stage was based on a range of material options from the case study's original material design. Here, modification of design and evaluation are the two stages which have been considered for the optimization model that is accordant with the ISO14040 guidelines. In the first stage, a database has been generated for building material sections which develop all potential project proposals in form of chromosomes. These chromosomes are made of a set of genes and every gene represents each work breakdown structure of the project. The second stage comprises of generating different project construction plans for the project and ascertain the optimal design solutions (Pareto set) of proposals (chromosomes). The process of generation (first stage) relies on the crossover and mutation processes. Meanwhile, the evaluation stage facilitates genetic-based approaches to evaluate and improve carbon emission. In this regard, there are 514 material options (variables) that can be evaluated by each chromosome.

RESULTS AND DISCUSSION

The calculation of carbon emission considered the substructure, superstructure, and finishes of the building. Staircase, slabs, beams, foundations, and columns are the building's structural components which are made of steel reinforcement and concrete. Meanwhile, the non-structural elements comprise of walls, plastering, painting, as well as their components including mortar and brick/block masonry, paint and mortar. Several types of flooring system have been used as finishing such as tiles, carpets, vinyl, and cement screed. The calculation also includes other building elements including doors, windows and metal and non-metal works made of aluminum, mild steel, glass, and wood included.

Figure 1 presents the breakdown of building components. In this regard, embodied carbon emission was categorised into five major construction elements which are, frame, work below lowest floor finishes (WBLFF), upper floor, roof structure and stairs structure. According to the outcome, concrete contributes to the highest level of carbon emission in the upper floor (27.38%), while WBLFF and building frame have the similar percentage (25.05%) followed by roof structure (19.60%) and

stair structure that has the lowest carbon emission contribution with 1.30%. In total, the concrete carbon emission is 2,665,465.03 kgCO₂.

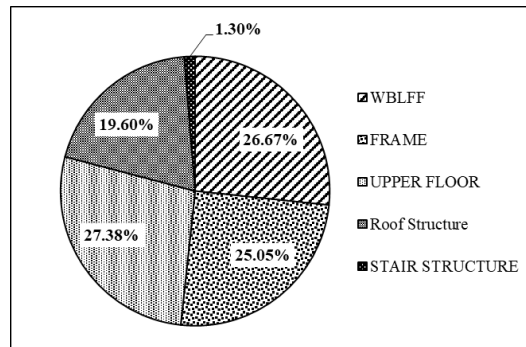


Figure 1. Five Primary Building Components

As shown in Figure 2, reinforcement steel is of the highest contributors to the building's carbon emission. It was found that the steel used as the structural beams for the building emitted the highest amount of carbon with 1,157,509.00 kgCO₂. In this regard, most of the carbon was emitted by the floor beams (434,190.40 kgCO₂) and the beams and girders (383,213.60 kgCO₂). They are followed by roof beams and ground and tie beams with 184,454.20 kgCO₂ and 155,652.00 kgCO₂, respectively. Isolated column stumps are the second highest contributor of carbon emission with 294,513.80 kgCO₂, followed by slabs (suspended floor, ground, roof, landing and lift slabs) with 216,627.60 kgCO₂. Pile caps recorded 64,043.00 kgCO₂ emission and Lift walls contributed to about 16,623.60 kgCO₂ emissions.

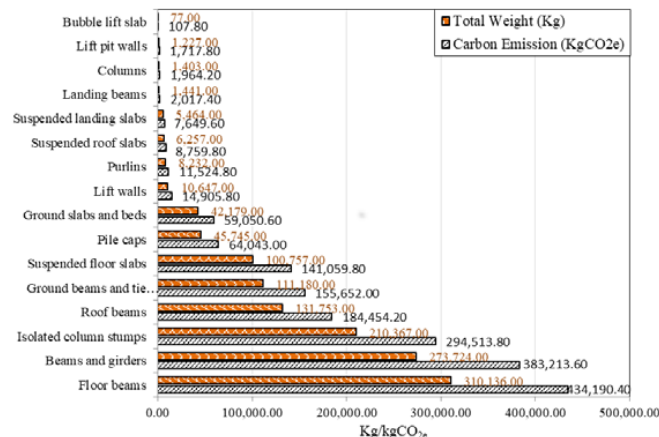


Figure 2. Total weight and carbon emission of steel bars

Figure 3 illustrates the carbon emission of the formwork. The highest level of carbon emission was from the building frame with 95,343.48 kgCO₂, while the upper floor has the second highest level of carbon emission with 53,585.84 kgCO₂, followed by roof structure (42,867.14 kgCO₂), WBLFF (22,841.64 kgCO₂) and the stair structure has the lowest carbon emission with 5,229.46 kgCO₂.

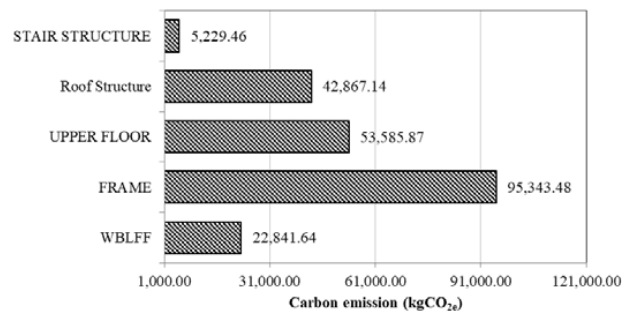


Figure 3. Carbon emission of formwork from major building elements

According to the findings, the third highest carbon emission component was mortar with 1,523,343.47 kgCO₂ emission. Table 1 shows the carbon emission from the mortar. Mortar has been widely used in finishes of the building (Wall finishes, Floor finishes, brickwork). The calculation highly depends on the thickness of mortar used for the particular area eg. internal and external floor finishes with 20mm thickness, and 10mm thick brickworks with mortar ratio of 1:6.

Table 1: Quantification and carbon emission from mortar and plaster

ID	Material Specifications	Weight of material (Kg/m ³)	Carbon Emission (KgCO ₂ e)
C1	1:3 Thickness (20mm)	1,969,460.85	436,886.10
C2	1:3 Thickness (42mm)	10,000.54	2,218.42
C3	1:3 Thickness (50mm)	979,146.00	217,204.25
C4	1:3 Thickness (60mm)	1,567,055.40	347,620.37
C5	1:3 Thickness (75mm)	734,445.00	162,922.16
C6	1:3 Thickness (20mm)-Finishes	845,950.70	187,025.81
C7	1:6 Thickness (10mm)-Brickworks	1,238,514.81	169,466.36
Total carbon emission			1,523,343.47

Various materials have been used as a part of internal and external finishes for every individual component such as wall finishes, floor finishes, and ceiling finishes. Figure 4 illustrates that the highest carbon emission level belongs to homogenous and ceramic tiles with the embodied emission of 531331.51 kgCO₂ (35%), aluminum works such as in cladding, ceilings contribute to 21% followed by granite and marble slabs contribute to 16% of the total carbon emission. Porcelain tiles contribute to 12% of the total carbon emission with 184,542.45 kgCO₂. %, while paint works contributed to about 2% and timber has the lowest carbon emission with 1%.

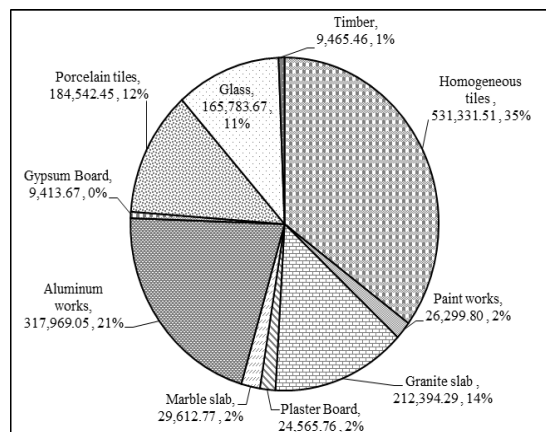


Figure 4. Building Finishes Carbon Emission

Figure 5 illustrates the results of comparison between the different building materials. The building's structural system contributes to the highest level of carbon emissions at 51%, which is the highest out of other building materials. It can be observed that concrete is the largest single component which contributed to 30%, steel contributes to the second highest level of carbon emission with 22%, followed by mortar with 20%, brick/block works (10%), finishes (9%). The lowest carbon emission belongs to timber and glass with 3% and 1.5 %.

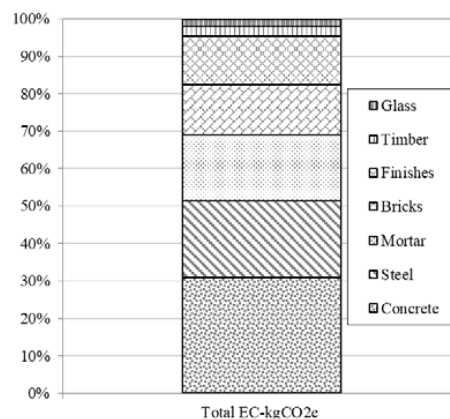
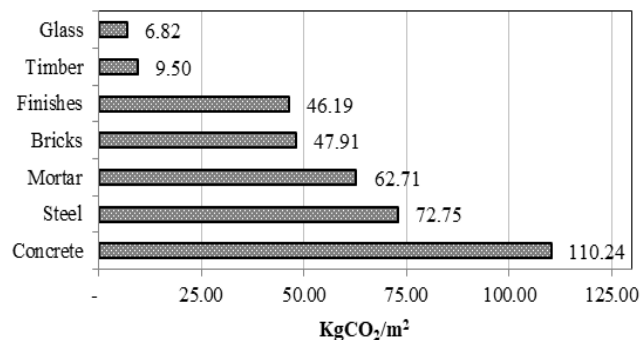


Figure 5. Building Elements Embodied Carbon Emission

In order to understand the nature of carbon emission and the GFA of the building, the building elements were further analysed. Figure 6 shows the contribution of every individual material's carbon emission per GFA. Expectedly concrete has the highest carbon emission per square meter with 110.24 kgCO₂/m², this is followed by steel with 72.75kgCO₂/m² carbon emission per square meter, mortar with 62.71kgCO₂/m², brick and block works (47.91kgCO₂/m²), finishes (46.19kgCO₂/m²), timber (9.50kgCO₂/m²) and glass (6.82kgCO₂/m²).

Figure 6. Carbon Emission Per GFA (m²)

Carbon Emission Optimization model

The reinforced concrete superstructure of the building recorded an estimated GFA of 15,126 m². Based on the model development stages, the project's floor plan was divided into six subsections which are the internal floor, ceiling, columns, internal and external walls, and façade. Each building material's carbon emission was calculated by using the Input-Out LCA method while the LCA method is used to calculate the carbon emitted by the production and transportation of the materials during the construction processes.

Optimization process was obtained based on 50, 100, 150, 200, and finally, 250 was the maximum number of iterations used for carbon emission evaluation since no further improvement was observed by increasing the iteration. As shown in Figure 7, carbon emission trend has been successfully reduced as compared to baseline design. The baseline building's carbon emission for each floor is 90,154.00. Figure 8 shows the comparison of the developed models and alternative design solutions. kgCO₂. The alternative design solutions were designed based on the deliberated combination of building materials and the results show the reduction of carbon emission. The decision makers in construction project will choose the final design solution that is considered to have optimum environmental protection, minimum carbon emissions, their own preferences, designer's recommendation and client's requirements.

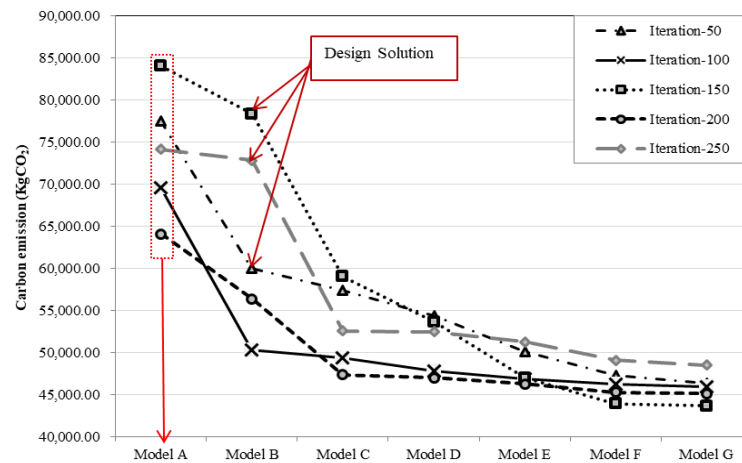


Figure 7. Design Solutions

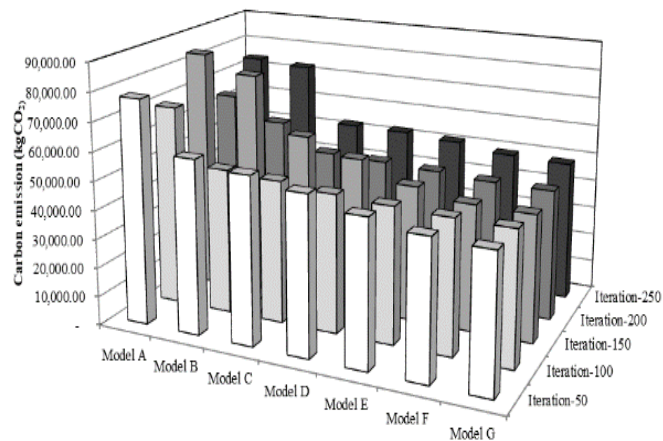


Figure 8. Carbon Emission Model Development

Figure 9 illustrates the proposed design models for the case study. 150 iterations with the lowest amount of carbon emission were selected. The results were further examined to compare the amount of carbon emission reduction with the original design. Table 2 illustrates the Pareto set for carbon emission evaluation which was used to ascertain the trade-off between carbon emission from the original design and the number of emissions generated by the alternative models based on 150 iterations.

Table 2. Carbon Emission Reduction from Alternative Designs

Alternative Designs	Reduction (100%)
Model A	6.72
Model B	13.05
Model C	34.48
Model D	40.42
Model E	47.79
Model F	51.23
Model G	51.50

Model A recorded a 6.72% carbon emission reduction, while Model B recorded the carbon reduction of 13.05%. Model C and Model D have 34.48% and 40.42% carbon emission reduction, respectively. Model E and Model F have 47.79% and 51.23% for carbon emission reduction respectively. In this regard, Model F and Model G are deemed to have optimum

carbon emission with the reduction of 51.23% and 51.50%. Figure 9 shows the comparison of carbon emission from the original which show that the carbon reduction optimization occurs with a with a more than 50% reduction compared to the original design.

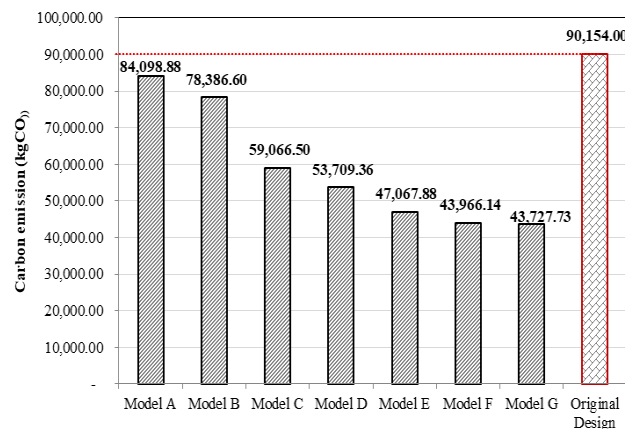


Figure 9. Carbon Emission comparison

CONCLUSION

The Malaysian government has set a voluntary target in order to reduce its carbon emission to 40% carbon emission by 2020. This target might be unachievable when there is no serious attempt to reduce carbon emission as well as in introducing sustainable solutions. Thus, this study is aimed to determine total energy consumption and the carbon emission of an office building. Based on the calculations and simulations conducted, the total amount of carbon emission from the case study building was 90,154 kgCO₂.

The optimization model designed works to manage environmental performances of construction projects. Such optimization model offers alternative optimal design solutions for construction projects which can be adopted from the early design stage of construction. This study has generated several alternative design solutions that could significantly reduce the level of carbon emission as compared with the original design. It indicates that the model is valid and can be used for practice. The capability of the model in generating better results is considered good since the obtained result satisfies the required objective functions at minimizing carbon emission. From the generated design solutions, the construction professionals would refer to the materials options list and identify what is acceptable to be selected and used for the construction project based on the client's requirements.

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