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A integrated environmental and cost optimization approach for low carbon buildings

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ABSTRACT

Minimizing the lifecycle environmental impact of buildings is urgently needed to achieve carbon neutrality in the coming decades. Low carbon buildings can only be achieved by optimizing the performance of buildings throughout all lifecycle phases. Currently, conventional methods are mostly used to reduce the operational impacts of buildings whereas they may limit the likelihood of enhancing the embodied performance. To improve whole lifecycle performance, enhanced methods such as the life cycle assessment (LCA) and life cycle costing (LCC) need to be coupled to allow for building performance analyses across different stages. Considering the complexities of these assessments, they are often not sufficiently integrated into whole building modelling processes. To account for both embodied and operational impacts of buildings, this study proposes a robust parametric BIM-based lifecycle optimization method to achieve building designs with least environmental and economic costs. LCA and LCC are optimized with a non-dominated sorting genetic algorithm II (NSGA-II) and applied to a case study building. The results show that the optimal design of the case building can reduce the CED, GWP and cost by 35%, 42% and 26% respectively. This integrated approach provides a robust and effective solution to optimize the whole lifecycle performance of buildings towards carbon neutrality.

Keywords: life cycle assessment, life cycle costing, building information modelling, whole lifecycle optimization, low carbon buildings.

NONMENCLATURE

Abbreviations	
LCA	Life cycle assessment
LCC	Life cycle costing
BIM	Building information modelling
NSGA-II	non-dominated sorting genetic algorithm II
CED	Cumulative energy demand
GWP	Global warming potential
BIPV	Building integrated photovoltaic

1. INTRODUCTION

Increasing efforts are being made to reduce atmospheric carbon emissions in order to limit global temperatures within 1.5 degrees Celsius of pre-industrial levels [1]. As a key part of the built environment, buildings consume large amounts of energy with consequential carbon emissions. Hence, buildings play a crucial role in the race to curb carbon emission through sustainable construction and the use of renewable energy systems. To reduce the environmental impacts of buildings, significant efforts have been made to drastically reduce energy use during the operational phase of buildings while supplying energy demands with renewable energy sources [2–4]. Conceivably, this improves the environmental impacts of buildings during the operational phase, however it may yield negative embodied impacts [5]. In passive/low energy buildings, the generated negative embodied impacts to implement measures that improve operational performances are sometimes too high to make the building environmentally friendly from a whole lifecycle perspective [6]. To ensure a comprehensive improvement in the whole lifecycle performance of buildings, enhancing performance assessment methods such as life cycle assessment (LCA) and life cycle costing is required [7]. However, the complexities of their implementation have limited the ease of applications during the building design process [8]. These methods are often applied in hindsight to satisfy building assessment criteria rather than being implemented in an iterative design approach to improve the performance of buildings. Contrary to the above, building information modelling (BIM) provides endless opportunities for integrated sustainability assessments including LCA and LCC [8]. Thus, the integration of LCA and LCC within BIM can enhance LCA and LCC assessments during the design of buildings from an early design stage [9–11]. Besides, BIM-based LCA and LCC can be enhanced with mathematical optimizations to search design space for feasible solutions in an iterative approach. However, limited research studies have focused on integrated BIM-based LCA and LCC optimization for the whole lifecycle of buildings [12]. To fill this research gap, this study proposes a parametric BIM-based LCA and LCC optimization method to reduce the life cycle energy, carbon emission and cost of buildings. In this approach LCA, LCC and an optimization algorithm are integrated within a BIM platform to optimize the performance of buildings based passive parameters and integrated renewable energy systems. The proposed method is outlined followed by an illustration through a case study building. This practical implementation of BIM-based LCA and LCC with mainstream BIM tools can enhance the application of sustainability assessments among architects and designers to reduce the environmental impacts of buildings in a cost-effective way.

2. RESEARCH METHODOLOGY

This parametric BIM-based LCA and LCC optimization approach is implemented by parametric building modelling as well as parallel LCA and LCC assessments followed by an optimization. The whole process is built in Rhino/Grasshopper tools and its native plugins. Fig. 1 illustrates the framework of the methodology.

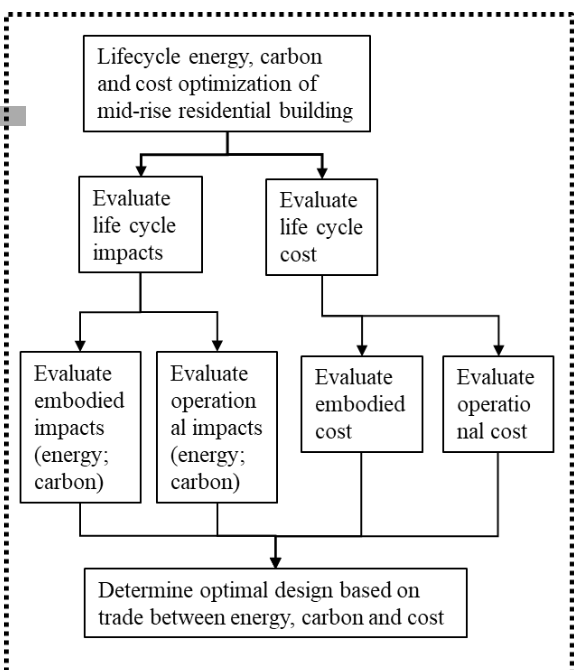

Fig. 1. Framework of the study

The parametric building modelling entails developing a BIM model based on several parameters such as building width to length ratio, window to wall ratio (WWR) for north, east, south, and west orientations, building orientation, window, walls, roof and floor constructions, and renewable energy systems (roof photovoltaics and building integrated photovoltaics (BIPV)). The parameters can easily be modified to include several strategies. For each parameter, a range of values based on acceptable design limits can be set using a slider as shown in Fig. 2.

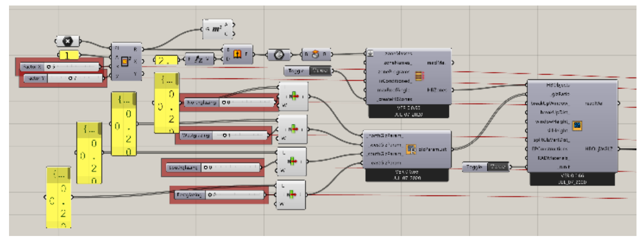

Fig. 2. Parametric modelling of building model

Based on this, several configurations of building models can be generated. Since the approach is modular, more complex geometries or community scale models can be integrated into this parametric assessment. The parallel LCA and LCC assessment is segmented into embodied and operational impact assessments. For the embodied impact assessment, native grasshopper nodes are first used to setup a detailed database of embodied impacts for commonly used materials / components / assemblies within the assessment framework. The database is structured in a systematic approach so that new materials / components / assemblies can be easily included.

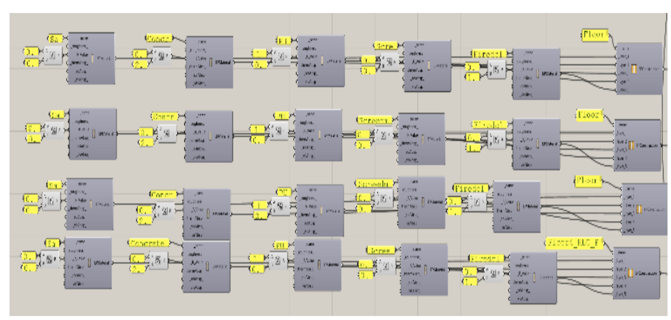

Fig. 3. Structure of database

Fig. 3 illustrates structure of the database for different walls, roofs, floors, and window constructions. The impact coefficient in terms of numerous environmental indicators such as cumulative energy demand (CED), global warming potential (GWP) and economic indicator cost is included in the database so that the impacts of various constructions can be estimated by multiplying the quantity of constructions by an impact coefficient. For the operation impacts, ladybug/honeybee tools are used to simulate the energy performance of the parametric building model. The thermophysical properties of the same constructions found in the database such as the U-value and visible transmittance are also structured in a systematic manner to enable parallel assessments with variations of building constructions.

Besides the thermophysical properties, other elements of the operational impact assessment such as schedules, occupancy loads, ventilation systems, renewable energy systems and shading are modelled using native grasshopper component and ladybug / honeybee plugins. Based on this setup, the operational energy use (which includes building energy use and renewable energy generation) and embodied impact are estimated whenever the building model is varied using the slider. While the embodied carbon emission is generated from the database, the operational carbon is estimated based on the energy mix of onsite renewable and grid electricity. The cost of constructions / assemblies is also integrated into the database so that the initial cost and recurrent cost of building construction can be estimated. Also, energy rates are integrated into the assessment framework to assess the cost of energy use. Cost related estimates are discounted to their net present values to account for time value of money.

Table 1. Variables for design optimization

Design variable		**Range**
Building orientation		0° - 360°
Shape coefficient		0.5 - 1
Window to wall ratio East façade (North, South, East, West)		0.2 - 0.8
Window construction		
Wall construction		
Roof construction		
Floor construction		
PV installation (15% efficiency mono-crystalline PV modules	Roof top PV	10% - 80% roof area
	North façade	10% - 90% façade area
	South façade	10% - 90% façade area
	West façade	10% - 90% façade area
	East façade	10% - 90% façade area
Rooftop PV orientation		North, South, East, West
Rooftop PV tilt		5° - 15°

Following the parallel LCA and LCC assessment, an optimization method is integrated using Wallacei plug-in in Grasshopper/Rhino. The optimization applies a non-dominated sorting genetic algorithm II (NSGA-II) to search design space for sustainable design solutions. The parametric parameters used to design the initial building model are connected to the Wallacei optimization node as genomes whereas the total LCC and LCA (GWP and CED) are connected as objectives. A multi-objective optimization is thus setup to find the design option that reduces the building energy use, carbon emissions and cost simultaneously based on the defined building parameters.

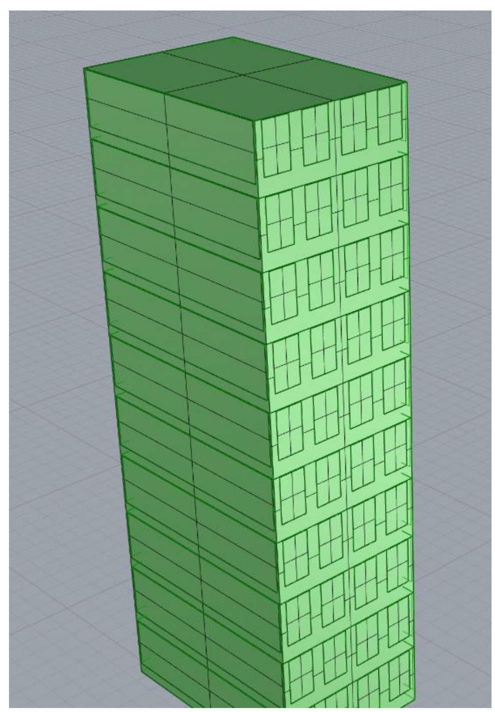

Fig. 4. 3D Model of case study building

Once the optimization parameters such as the population size, generation size and termination criteria are set, the optimization is started and results are stored for visualization and processing using the Wallacei nodes. After the optimization is completed, the results can be re-written into Grasshopper to visualize the resultant building model in 3D forms in Rhino.

A case study is implemented on a building located in Ghana, a subtropical climatic region. The building has a total area of 6400 m^2 and 10 floors. Table 1 Illustrates the range of design parameters while the building model is illustrated in Fig. 4. Based on these range of parameters, a whole lifecycle optimization of the building is performed and results are illustrated below.

3. RESULTS

A BIM-based LCA and LCC optimization is performed to generate design solutions with varied building geometries, thermophysical properties and renewable energy systems that can produce the optimal energy use carbon emissions and cost.

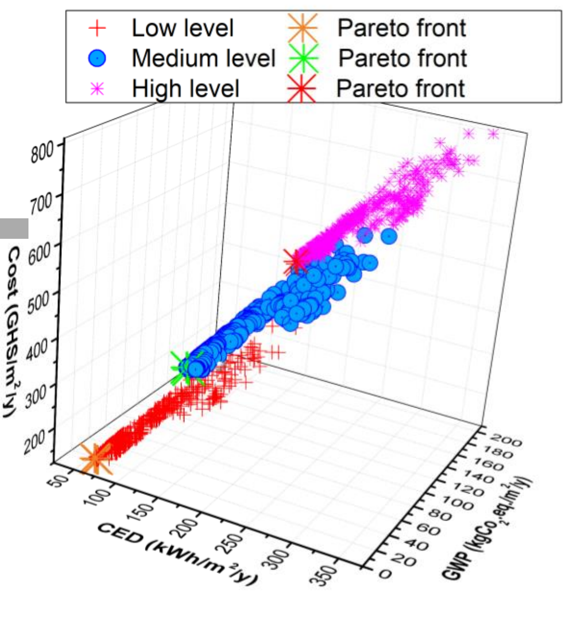

Fig. 3D Scatterplot of optimization results

As shown in Fig. 5, the range of design solutions is illustrated in a 3D scatter plot of CED, GWP and cost. Also, two levels of occupancy loads which reflect a low level and high level in comparison to the original levels are illustrated to show the impacts of confounding factors. The pareto front which shows the solutions for which one indicator cannot be improved without affecting the other are selected and ranked to show the best performing solutions. From the initial design, the baseline model was simulated with a CED, GWP and Cost of 207 kWh/m^2/y, 141 kgCO2.eq./m^2/y and USD 79.73/m^2/y. The embodied and operational impacts contributed to 79% and 21% of CED, 77% and 23% of GWP, respectively. The optimization results indicated a reduction in CED, GWP and Cost by 35%, 42% and 26% respectively. Furthermore, the low-level confounding factor caused an unproportionate reduction in CED, GWP and cost. Specifically, CED and Cost are reduced by 52% and 57% while GWP is reduced by 74%. In the case of the high-level confounding factor, CED and cost are increased by 64% and 73% while GWP is increased by 89%. A breakdown of the optimized results show that embodied and operational impacts contribute to 37% and 63% of CED and 39% and 61% of GWP respectively. The results illustrate how the share of embodied impacts is increased in passive/low energy buildings. Also, the large variations in energy use and carbon emission illustrate the critical impact of occupancy behavior towards the reduction of building related carbon emissions. The method illustrated in this study provides an exemplary guidance for architects, designers, and engineers to implement LCA and LCC for the whole lifecycle of buildings for reducing building related environmental impacts.

4. CONCLUSION

This study has developed a parametric BIM-based LCA and LCC optimization framework to reduce the whole lifecycle environmental impacts of building in a cost-effective approach. The method is proved to enhance building LCA and LCC in such a way that either the embodied or operational impacts is not improved at the expense of the other. This parametric approach can be integrated into the workflow of architects, designers and engineers to design cost effective low carbon buildings.

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