DESIGN FACTOR-ORIENTED LIFE-CYCLE ENERGY OPTIMISATION FOR EARLY-STAGE BUILDING DESIGN

YANG YANG[1], LIKAI WANG[2] and MARCO CIMILLO[3]
[1,2,3]Xi'an Jiaotong-Liverpool University.
[1]yang.yang2104@student.xjtlu.edu.cn, 0009-0007-8659-1831
[2]wang.likai@outlook.com, 0000-0003-4054-649X
[3]marco.cimillo@xjtlu.edu.cn, 0000-0002-6260-4470

Abstract. The need for life-cycle energy (LCE) optimisation is imperative in the building sector. Computational optimisation has been adopted to evolve design populations search for desirable solutions with competitive LCE performance. However, prior studies typically focused on a predefined building form or typologies, which is less effective in assisting designers in space design exploration and informed decision-making. To remedy this gap, this study introduces a design factor-oriented LCE optimisation workflow integrating EvoMass and ClimateStudio within the Rhino-Grasshopper environment, with further steps of taking Window-to-Wall Ratios (WWRs) and multiple thermal zones into consideration. Through a case study, the results of the optimisation demonstrate the efficacy of the approach, revealing a considerable reduction of total energy needs. This study underscores the potential for energy savings through careful consideration of building massing, WWR, and multi-thermal zones in the LCE optimisation process when using a computational process, which also provides useful information for designers' decision-making at the early design stage.

Keywords. Building Massing, Multi-Thermal Zones, Window-to-Wall Ratio, Design Exploration, Life-Cycle Energy, Design Optimisation, Life-Cycle Analysis

1. Introduction

The construction and operation of buildings are significant contributors to global carbon emissions, accounting for approximately 37% of the total (United Nations Environment Programme, 2021). To address this pressing environmental concern, life-cycle energy (LCE) has been widely accepted as an effective approach to formulating strategies to reduce primary energy needs in buildings (Ramesh et al., 2010). LCE accounts for all energy inputs to a building in its life cycle, including operational energy (OE) and embodied energy (EE).

Energy efficiency measures (EEMs) are intended to improve the building's performance by changing critical building design factors (building forms, orientation

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 1, 465-474.

and window-to-wall ratios/WWRs), material types, material quantities and so on (Shadram & Mukkavaara, 2019). As substantial design modifications are more viable and impactful for LCE at early design stages (Yu et al., 2022), researchers are focusing more and more on optimising the impact of EEMs in LCE at early design stages. For instance, Vollmer et al. (2023) conducted a lifecycle-based parametric optimisation, considering building materials, energy systems and renewable energy systems as EEMs. Additionally, Shadram & Mukkavaara (2018) studied an integrated BIM-based framework for the optimisation of the trade-off between EE and OE for early design, considering material types and quantities.

Design factors should not be neglected as the first set of EEMs that can be implemented or changed early in the design phase (Shadram & Mukkavaara, 2019), but they were typically not considered in aforementioned studies. Thus, Shadram & Mukkavaara further studied building forms based on six different extrusions, revealing significant variations influenced by building forms in LCE pre-optimisation but modest differences in post-optimisation (Shadram & Mukkavaara, 2019). Other studies also focused on the life-cycle analysis (LCA) concerning the design factors of buildings. For instance, Jusselme et al. (2018) conducted a sensitivity analysis of LCA-based optimisation, which includes one archetypal geometry. Harter et al. (2020) investigated uncertainty analysis of LCE in early design, incorporating design factors (seven fixed extrusions and their orientation). In Yu et al.'s study (2022), the geometric variability is considered a critical point for LCE optimisation. The study tested an extrusion with partial variability on one side of the building using Design Explorer, conducting a case study on buildings with a single thermal zone. The aforementioned studies indicated that the design factor is one of the unignorable EEMs for LCE or LCA optimisation.

However, prior studies on design optimisation focusing on LCE typically adopted simple geometrical operations, such as extrusion, instead of more articulated variations of the spatial configuration of the building massing (Figure 1). At the same time, WWRs with single thermal zone were often widely used to simplify the optimisation task, which leads to inaccurate predictions of thermal loads. These limitations hinder architecture designers from fully exploring building typologies, implementing more accurate WWRs design optimisation based on multiple thermal zones.

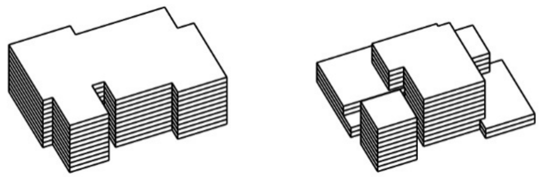

Figure 1: a) Building extrusion b) The spatial configuration of the building massing

To address these limitations, this paper proposes an LCE optimisation workflow focusing on early-stage design exploration by combining two tools (EvoMass and ClimateStudio) and taking WWRs for multi-thermal zones into consideration. The workflow includes the design factors of building massing, WWRs, and multi-thermal zones into the optimisation in order to enlarge the design space of the optimisation search so as to avoid the bias caused by the predetermined building forms and WWRs.

Thus, the study investigates the feasibility of design factors-oriented parametric optimisation and assesses its potential in terms of embodied, operational and total life-cycle energy through a case study. The case study highlights how the proposed design optimisation workflow enables architects to identify promising design directions and obtain information about the trade-offs and correlation between building massing forms, WWR and LCE needs.

2. Method

The study proposes a design optimisation workflow that combines EvoMass and ClimateStudio to achieve an automatic design generation, evaluation, and optimisation process. There are four steps as depicted in Figure 2: 1) Setting up the massing generation in EvoMass; 2) Defining thermal zones and corresponding WWRs based on the building massing generated by EvoMass; 3) LCE calculation and design evaluation using ClimateStudio; 4) Evolutionary optimisation based on Steady-stage Island Evolutionary Algorithm (SSIEA) in EvoMass.

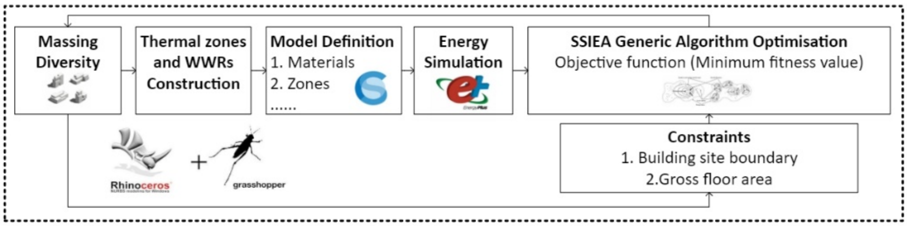

Figure 2 Workflow of the design optimisation.

In the first step, the massing generation is configured in EvoMass, an integrated evolutionary building massing design tool facilitating the automatic generation of optimised design iterations for architecture designers (Wang, 2022).

Subsequently, the generated massing is automatically segmented into multiple thermal zones using the Boolean function within a cutter massing approach. At the same time, the orientations of windows are specified and categorised within individual thermal zones. This step is aimed at avoiding the issue caused by single-zoning approaches, such as unbalanced WWRs on different building façade surfaces and inaccurate predictions of thermal loads since a surplus of solar gains in one zone may be credited to the heating or cooling required in another.

In the third step, the energy model is built using ClimateStudio (ClimateStudio, 2023), a Grasshopper plug-in for building EE and OE models. ClimateStudio is built upon validated simulation engines, EnergyPlus (Testing and Validation, 2014) and Radiance (Gregory, 2019). The thermal zones, construction elements, orientation, WWR values and other design parameters subject to LCE optimisation are defined in ClimateStudio for the initial designs of the buildings. The output of EnergyPlus on the annual energy use is used to obtain the OE.

In the final step, SSIEA is used to evolve the design population. SSIEA adopts a multi-island approach, subdividing the design population into several subpopulations. This approach guides each subpopulation to focus on different regions in the design space, preventing optimisation from being confined to a single region (Wang et al., 2020). Thus, SSIEA is particularly adept at providing diverse solutions for designers at the initial design stage.

3. Case study and results

3.1. DESIGN SETTING AND CONDITION

The selected case for this study is a five-story educational building within Xi'an Jiaotong-Liverpool University in Suzhou, China, which contains offices, lecture halls, studios, and fab labs. The gross floor area of this building is 15000m². Figure 3 provides detailed information about the building. Suzhou is characterised as a hot-summer-cold-winter (HSCW) climate whose data are obtained from standard EnergyPlus Weather files (.EPW) via the Ladybug website (EPW Map, 2023).

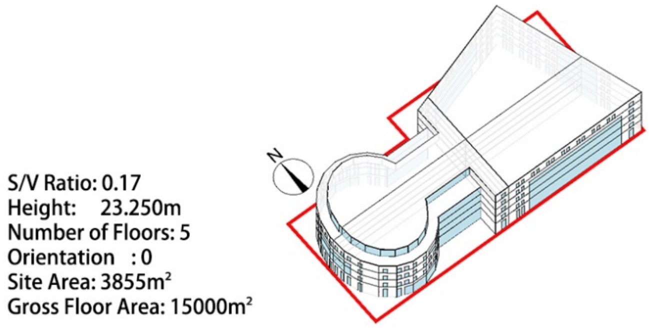

Figure 3 ClimateStudio energy model of the actual building

3.2. SCENARIO SETTING AND BENCHMARKS

To demonstrate the effectiveness of the proposed workflow, the automatic generative design is compared with following scenario-based benchmarks: the actual building (AB) and best international practice (BI).

The AB was defined according to the specifications outlined in the section of the HSCW zone in GB50189-2015 (MOHURD & AQSIQ, 2015), except WWRs. WWRs are defined as the real situation. The standard stipulates the baseline requirements for all commercial buildings in China (Table 1).

The high-performance benchmark was created to represent the Best International Practice (BI) based on the BREEAM In-Use International Technical Manual: Commercial SD243-V6.0.0 (BRE group, 2020). The Building Research Establishment's Environmental Assessment Method, or BREEAM, is one of the most comprehensive and widely used environmental assessment tools worldwide.

The scenarios of benchmarks AB and BI are summarised in Table 2. The values that meet benchmarks in the ClimateStudio database are written in parenthesis and applied in the simulation. Window distribution in AB and BI has been modified according to relevant standards, expressed as WWRs by GB50189-2015 and as window-to-floor ratio (WFR) by BREAAM. Glazing components have been selected to meet both U-value and SHGC requirements.

The building’s other construction elements were chosen by considering designs suitable for the HSCW zone, following "NECB-2020 Non-residential School/university" (Table 3). While the same materials are applied across all scenarios, different insulation thicknesses are defined to alter the U-value.

Table 1 Parameters applied in ClimateStudio

Parameters	Values	Parameters	Values
Buildings' lifespan	50 years	WWRs	0.4-0.7
Heating set point	20 °C	Mechanical ventilation	10 L/s/p
Cooling set point	26 °C	People	6 m² per person
Opening time	7:00~18:00	Infiltration	0.15 ACH

Table 2 Scenarios of benchmarks

Parameter	AB	BI
U-value of external wall	1 W/(m²·k)	0.625 (0.616) W/(m²·k)
EE of external wall	390.5 MJ/ m²	506 MJ/ m²
U-value of roof	0.7 W/(m²·k)	0.5 (0.492) W/(m²·k)
EE of roof	481 MJ/ m²	506 MJ/ m²
U-value of glazing	3.0 (2.69) W/(m²·k)	2.32 (1.8) W/(m²·k)
SHGC	0.44 (0.358)	0.5 (0.296)
Total WWRs	0.49	0.63
EE of glazing	431 MJ/ m²	427 MJ/ m²
Total WFRs	0.2	0.257

Table 3 Information of other construction sets

Construction	U-Value	Thermal Capacitance	EE
Partition	2.422 W/(m²·k)	118.6 kJ/k/m²	26.6 MJ/m²
Slab	2.273 W/(m²·k)	456 kJ/k/m²	360 MJ/m²
External floor	0.386 W/(m²·k)	293.566 kJ/k/m²	183.6 MJ/m²
Ground slab	0.703 W/(m²·k)	472.001 kJ/k/m²	441.095 MJ/m²
Ground wall	0.955 W/(m²·k)	464.131 kJ/k/m²	446.025 MJ/m²

3.3. OPTIMISATION SETTING

The following values are defined in EvoMass based on the site characteristics: 1) Five floors; 2) Column spacing of X=5.265, Y=5.15; 3) Unit mass of vertical size from 1 to 5; 4) Unit mass of horizontal size from1 to 18; 5) 15000 m² of target gross floor area (TGFA). The 'additive form generation' in EvoMass is tested for geometric exploration. Figure 4 illustrates four samples of the EvoMass generated massing and WWRs with four thermal zones aligned with the settings in this paper.

The generated massing design is segmented into four thermal zones—north-east, north-west, south-east, and west-east—via a cutting volume created by connecting centre points of the site boundary perpendicularly. Individual WWRs are defined for each façade surface based on its orientation, i.e. the north, south, west, and east.

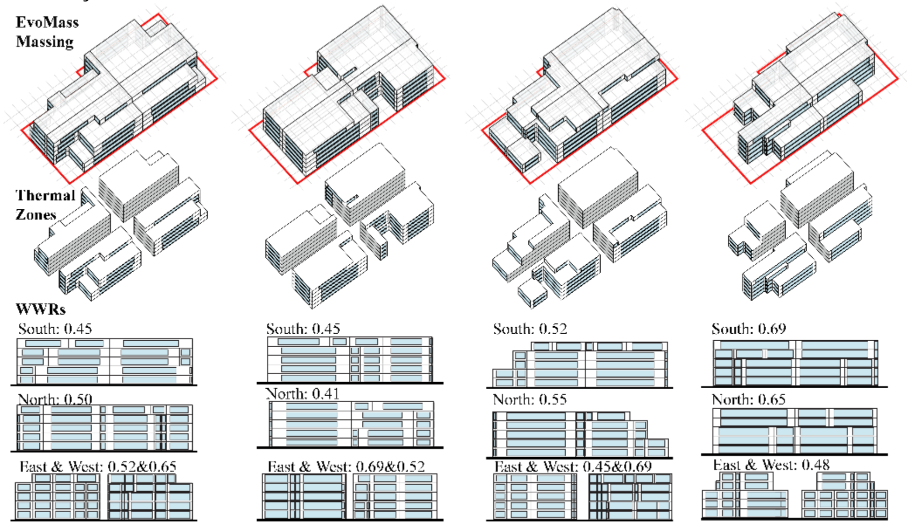

Figure 4: EvoMass generated massing and WWRs with thermal zones aligned with the setting

In order to mitigate the unbalance between lower EE and higher OE in total energy (TE) and to equally weigh the EE and OE, the fitness is calculated based on the multiplication of EE/m² and OE/m². The optimisation objective is to minimise the fitness value, with a TGFA serving as a penalty function for excluding designs failing to satisfy the GFA requirements. The fitness function is defined as follows:

$$fitness = \left(1 + \left|\frac{GFA-TGFA}{TGFA}\right|\right) \times \frac{\mathrm{EE/m^2 \times OE/m^2}}{1000} \tag{1}$$

In Equation 1:

EE/m² (MJ) is the embodied energy per square meter.

OE/m² (MJ) is the operational energy per square meter.

GFA (m²) is the gross floor area.

TGFA (m²) is the target gross floor area.

OE and EE are equalised to reduce the bias toward OE in this particular case study, which does not necessarily provide a representative ratio between the two values. A number of simplifications in the model are, in fact, likely to produce an overestimation of the OE and an underestimation of the EE. These include the removal of the internal components and the adoption of uniform occupancy and ventilation rates for the whole building.

3.4. RESULTS AND COMPARISON STUDY

Simulations and optimisations are conducted on a computer with a 2.7 GHz Intel Core CPU and 8GB RAM, running Microsoft Windows 10 Enterprise LTSC as the operating system. Each simulation run takes 1 minute on average. In order to eradicate the influence of GFA on energy needs, the results with GFA (15000±750 m²) are selected in the following sections. There are 797 satisfying designs out of 1200 generated designs during the whole optimisation process (Figure 5).

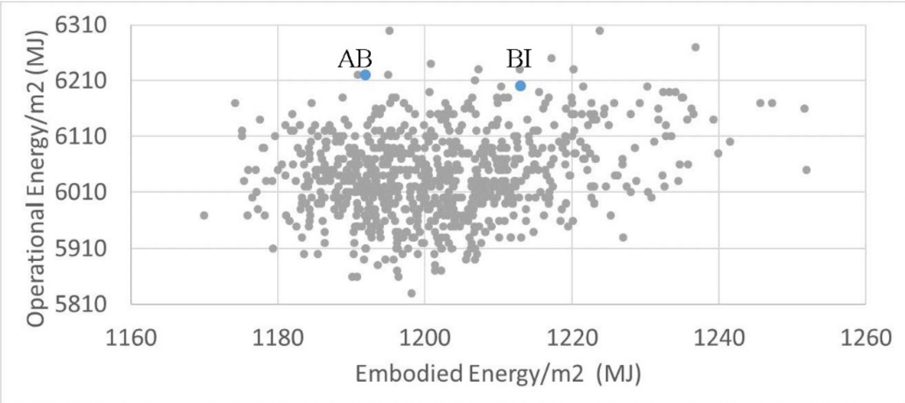

Figure 5 The results of optimised solutions and scenarios

3.4.1. General energy saving

The primary energy of EE/m² and OE/m² for AB and BI is simulated, which reveals that BI and AB consume similar TE/m². The optimisation is conducted based on the BI scenario setting in Section 3.2. The comparison in Figure 6 shows a potential for LCE saving by design factor-oriented optimisation, particularly for OE. The optimal solution accounts for 7.4% in OE/m² and 6.6% in TE/m², when it is compared to the highest energy-need solution. Compared to BI, the energy use decreases by up to around 5.5% for TE/m² and 6% for OE/m².

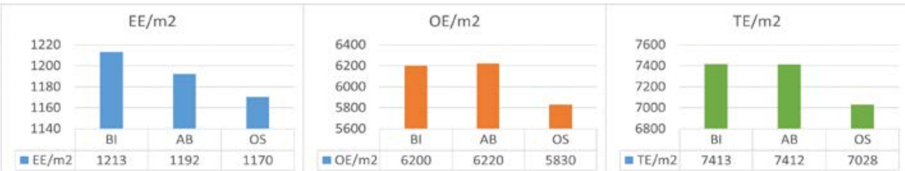

Figure 6 Comparison of best-optimised solutions and benchmarks

3.4.2. Building massing characteristics

The fifteen highest-ranking elites are selected from optimal solutions and grouped into three categories (C1-Maximum Fitness Percentage, C2-Minimum OE, C3-Minimum Surface/Volume Ratio). Figure 7 summarises their performance indicators, while Figure 8 provides the average of each indicator of the elites from C1, C2, and C3.

C1 elites achieve the best average fitness among these three optimisation processes. In terms of massing, the C1 elites showcase a tendency toward a rectangular-extrusion volume elongating along the east-west direction, favouring the reduction of OE/m². In addition, as OE/m² accounts for major energy needs in LCE, reduction of OE can achieve fewer energy needs, even taking the risk of the trade-off with EE/m².

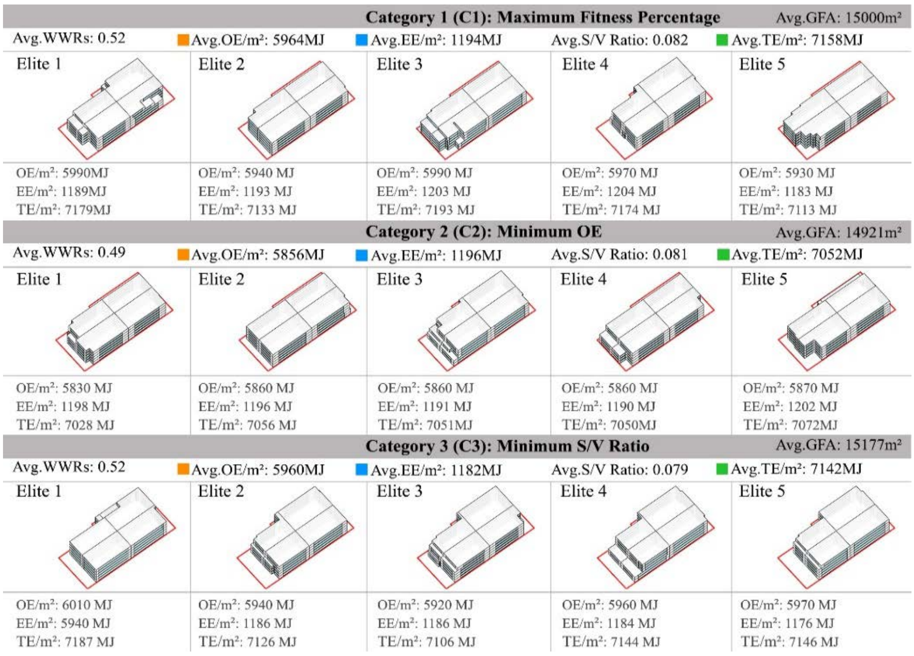

Figure 7: Fifteen highest-ranking design elites from the results of the case study in three categories

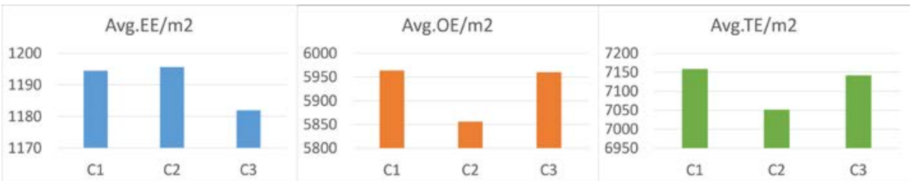

Figure 8: Average EE, OE, WWRs, TE/m2 of elite results of the case study in three categories

C2 elites share a similar north-south-side longer rectangular profile as C1 but with fewer step-backs or setbacks, achieving the lowest OE/m², highest EE/m², and least TE/m². As mentioned in C1 elites, the results of C2 elites reveal that the longer rectangular extrusion is beneficial for reducing OE/m². Moreover, it allows C2 elites to achieve a greater reduction of OE/m² by taking advantage of less S/V ratio and GFA.

On the other hand, the elites in C3, with the lowest S/V ratio, consume more energy than C1 and C2. Despite common recommendations for lower S/V ratios to reduce energy needs, C3 elites highlight the importance of considering the integral impact of various design factors (like WWRs), as solely focusing on minimising the S/V ratio may not lead to reduced energy needs. Thus, the C3 elites demonstrate the importance of considering multiple design factors for effective LCE optimisation.

3.4.3. Correlation Analysis

The impact of variables is illustrated by the correlation coefficients listed in Table 5.

The correlation has been calculated for EE/m², OE/m², and TE/m², assigning numerical values to all variables. The correlation analysis shows that the S/V ratio significantly influences TE/m², with a notable impact from north, south and west WWRs.

Table 5 Correlation analysis

	North WWR	South WWR	East WWR	West WWR	S/V Ratio
EE/m2	-0.09282	0.01233	-0.10603	0.019703	0.789915
OE/m2	0.479456	0.33908	0.329014	0.345862	0.525172
TE/m2	0.438372	0.323147	0.293695	0.33081	0.630219

4. Discussion and Conclusions

The outcomes of the case study underscore the considerable impact of different combinations of design factors (specifically, in this study, building massing and WWRs across multiple thermal zones) on LCE performance. In addition, the comparison study also highlights the necessity of the proposed automatic generative design optimisation workflow. The proposed design workflow should be considerably more accurate than conventional scenario workflows with a limited number of combinations modelled and iterated manually. Moreover, the workflow is able to help designers understand the design trade-offs between OE and EE, and the extracted design implications related to these two aspects can also allow designers to synthesise this information in the subsequent design ideation and development process.

While the preliminary results of optimisation in this study are promising, further research is needed, particularly in devising segmentation solutions for more intricate thermal zones. For instance, subdividing a large thermal zone into several logically generated parts based on the building's configuration could enhance the precision of the optimisation process. Moreover, the integration of additional factors into the optimisation workflow is imperative. Consideration of material properties, for instance, could offer a more holistic approach to optimisation. Additionally, the incorporation of constraints on objective functions, such as comfort hours and solar irradiation, is essential for a comprehensive evaluation. Although the single-objective optimisation in this study has yielded valuable results, delving into multi-objective optimisation (MOO) could be the subsequent step. This would enable a more thorough exploration of the impact of EEMs implemented during the design phase on the EE and OE trade-off, ultimately striving to minimise the building's LCE. Finally, due to the development of the study on net-zero buildings, the OE tends to account for less in LCE at some point when buildings are renovated into net-zero ones. Thus, the scope of OE before renovation and how EE makes up for it should be studied in future.

To conclude, this study proposes a design factor-oriented LCE optimisation workflow by integrating EvoMass and ClimateStudio to take into consideration building massing variations and WWRs for multi-thermal zones. The paper provides a better understanding of design factors' optimisation that may contribute to the reduction of energy needs and provide valuable information to support sustainable building design. Further research should consider more design factors, constraints, MOO and net-zero renovation to minimise a building's LCE holistically.

Acknowledgements

This study is supported by Xi'an Jiaotong - Liverpool University Research Development Fund (RDF-23-01-107).

References

BRE group. (2020). SD6063 BREEAM In-Use International Commercial Technical Manual.

ClimateStudio. (2023). Solemma. Retrieved November 13, 2023, from https://www.solemma.com/climatestudio/accuracy

EPW Map. (2023). Retrieved November 18, 2023, from https://www.ladybug.tools/epwmap/

Gregory, W. (2019, November 9). *The RADIANCE Lighting Simulation and Rendering System.* Radsite. https://www.radiance-online.org/archived/radsite/radiance/papers/sg94.1/accurate.html

Harter, H., Singh, M. M., Schneider-Marin, P., Lang, W., & Geyer, P. (2020). Uncertainty Analysis of Life Cycle Energy Assessment in Early Stages of Design. *Energy and Buildings,* 208, 109635. https://doi.org/10.1016/j.enbuild.2019.109635

Jusselme, T., Rey, E., & Andersen, M. (2018). An integrative approach for embodied energy: Towards an LCA -based data-driven design method. *Renewable and Sustainable Energy Reviews,* 88, 123–132. https://doi.org/10.1016/j.rser.2018.02.036

MOHURD, & AQSIQ. (2015). Design standard for energy efficiency of public buildings GB50189-2015.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* 42(10), 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Shadram, F., & Mukkavaara, J. (2018). An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy. *Energy and Buildings,* 158, 1189–1205. https://doi.org/10.1016/j.enbuild.2017.11.017

Shadram, F., & Mukkavaara, J. (2019). Exploring the effects of several energy efficiency measures on the embodied/operational energy trade-off: A case study of swedish residential buildings. *Energy and Buildings,* 183, 283–296. https://doi.org/10.1016/j.enbuild.2018.11.026

Testing and Validation. (2014). EnergyPlus. Retrieved February 17, 2024, from https://energyplus.net/testing

United Nations Environment Programme. (2021). 2*021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector.* Nairobi

Vollmer, M., Theilig, K., Takser, I., Reitberger, R., & Lang, W. (2023). Life cycle-based parametric optimization of buildings towards climate neutrality and its implications for environmental protection. *IOP Conference Series: Earth and Environmental Science,* 1196, 012050. https://doi.org/10.1088/1755-1315/1196/1/012050

Wang, L. (2022). Workflow for applying optimization-based design exploration to early-stage architectural design – Case study based on EvoMass. *International Journal of Architectural Computing,* 20(1), 41–60. https://doi.org/10.1177/14780771221082254

Wang, L., Janssen, P., & Ji, G. (2020). SSIEA: A hybrid evolutionary algorithm for supporting conceptual architectural design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing,* 34(4), 458–476. https://doi.org/10.1017/S0890060420000281

Yu, H., Yang, W., Li, Q., & Li, J. (2022). Optimizing Buildings' Life Cycle Performance While Allowing Diversity in the Early Design Stage. *Sustainability,* 14(14), Article 14. https://doi.org/10.3390/su14148316