A New Building Life-Cycle Embodied Performance Index

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Knowledge and research tying the environmental impact and embodied energy together is a largely unexplored area in the building industry. The aim of this study is to investigate the practicality of using the ratio between embodied energy and embodied carbon to measure the building's impact. This study is based on life-cycle assessment and proposes a new measure: life-cycle embodied performance (LCEP), in order to evaluate building performance. In this study, eight buildings located in the same climate zone with similar construction types are studied to test the proposed method. For each case, the embodied energy intensities and embodied carbon coefficients are calculated, and four environmental impact categories are quantified. The following observations can be drawn from the findings: (a) the ozone depletion potential could be used as an indicator to predict the value of LCEP; (b) the use of embodied energy and embodied carbon independently from each other could lead to incomplete assessments; and (c) the exterior wall system is a common significant factor influencing embodied energy and embodied carbon. The results lead to several conclusions: firstly, the proposed LCEP ratio, between embodied energy and embodied carbon, can serve as a genuine indicator of embodied performance. Secondly, environmental impact categories are not dependent on embodied energy, nor embodied carbon. Rather, they are proportional to LCEP. Lastly, among the different building materials studied, metal and concrete express the highest contribution towards embodied energy and embodied carbon.

INTRODUCTION

Numerous studies have demonstrated the increasingly important role that embodied energy plays in the building life cycle. For a conventional single-family house, the percentage of embodied energy could account for up to 40%–50% of the total life-cycle primary energy use [1]. For low-energy buildings (energy-efficient buildings) and net zero energy buildings, the percentage embodied energy accounts for could be as high as 74%–100% [2]. Regardless, the commonly accepted guidelines and methods of assessment and measurement for embodied energy have not been established. Previous studies demonstrate considerable variation in reported embodied energy values due to the high number of variables [3,4], including building materials [5] and building construction types [2]: there is inadequate published information on whole building life-cycle embodied energy reports [6]. Aside from a lack of consensus on measurement and procedures, embodied energy emissions and related carbon emissions are being largely ignored [7] as the focus is solely on operating energy.

Embodied energy is the energy consumed during a building's whole life cycle. This excludes the operating energy, but includes raw material extraction, product production, manufacturing, installation, on-site construction, maintenance, repair and replacement, and finally the demolition and disposal of a building [8]. Embodied carbon is used to measure the building's contribution to climate change, which is closely related to, but not equal to, embodied energy [8]. There are three principal differences between embodied energy and embodied carbon: (1) the same amount of embodied energy could be converted to a different amount of embodied carbon, depending on the energy mix of the regional energy resources [9] and other factors. For example, if coal comprises a higher percentage of the energy source than wind, there will be a higher conversion rate from embodied energy to embodied carbon. (2) Carbon can be emitted due to chemical processes and reactions that do not involve energy consumption; the carbon emitted during cement production is one example [9]. (3) Carbon can also be sequestered, as is the case with wood during its growth phase [8]. Hence, the material can consume energy and reduce emissions at the same time. For these reasons, the ratio between embodied energy and embodied carbon could be a more meaningful tool to assess the life-cycle embodied performance (LCEP) of a building.

The main purpose of this study is to investigate the utility of the ratio between embodied energy and embodied carbon. This ratio has the potential to measure the building's embodied and environmental impact. There are three essential investigative questions that will aid in this pursuit: (1) Is there correlation between life-cycle embodied energy (LCEE) and life-cycle embodied carbon (LCEC)? (2) Can a building's environmental impact

Figure 1. Case buildings

be predicted by the life-cycle embodied performance (LCEP)? (3) Which building components and materials contribute most to the overall embodied energy, embodied carbon and environmental impact?

METHOD AND MATERIALS

This study is based on life-cycle assessment; a variety of approaches were used, including a cost-optimality approach that originated in industry [10,11] and an energy-savings approach [12,13]. The study is organized into the following steps: (a) collecting data from case buildings; (b) defining systems and boundaries; (c) building 3D models and creating a bill of materials; (d) conducting embodied energy and embodied carbon analysis; (e) conducting environmental analysis; (f) comparing embodied energy, embodied carbon and their correlation to environmental impact.

EMBODIED CARBON

This project uses two variables to measure the LCEC: (a) life-cycle embodied carbon coefficient (LCECC), demonstrated in Equation (1) (2), and (b) life-cycle embodied carbon intensity (LCECI), demonstrated in Equation (3). These variables are investigated and compared for their reliability to evaluate building performance. In 1996, Alcorn proposed the term “Embodied Energy Coefficients” (EEC), which they used to measure the change of embodied energy for a variety of building materials used in New Zealand Housing between 1983 and 1996. The results showed 32% to 56% percentage for different materials reflecting the changes in construction and manufacturing methods and processes [13]. EEC was then later used by Dias and Polliyadda (2004) as “embodied carbon coefficients” [14] to measure the embodied performance of buildings. ”Life-cycle embodied energy intensity” is the new unit proposed in this project; it is most determined by building materials and assemblies, and is measured in kgCO2e /m2/yr.

$$\mathrm{LCEC} = \sum_{c=\mathrm{end}}^{c=1}(\mathrm{IEC}_c + \mathrm{REC}_c + \mathrm{DEC}_c) - \mathrm{REYC}_e \qquad (1)$$

$$\mathrm{LCECC}_{\,building} = \frac{\mathrm{LCEC}}{\mathrm{W} \times \mathrm{L}} \qquad (2)$$

where LCECC is life-cycle embodied carbon coefficient, measured by kgCO2eq/kg/yr. LCEC is the life-cycle embodied carbon of the building, measured by kgCO2e. W is the total weight of the building, calculated by kg. L is the total building

$$\mathrm{LCECI}_{\,building} = \frac{\mathrm{LCEC}}{\mathrm{A} \times \mathrm{L}} \qquad (3)$$

life span, in years.

where LCECI represents life-cycle embodied carbon intensity, measured in kgCO2eq/m2/yr., LCEC is the life-cycle embodied carbon of the building, measured in kgCO2eq. A represents the total floor area of the building (conditioned and unconditioned), measured in square meters (m2). L is the total building life span, in years.

Embodied Energy

Life-cycle embodied energy (LCEE) comprises all energy consumed during the entire building’s life span, except the operating energy. In this project, LCEE is measured by the life-cycle embodied energy intensity (LCEEI), measured in MJ/m2/yr from Equation (4). The life-cycle embodied energy coefficient (LCEEC), measured in MJ/kg/yr, refers to Equation

Table 1. Case project information.

Building #	Building Function	Floor Area (Sq.m)	Floor #	Yr of Construction	Yr of Renovations
A1 (A)	Academic	7,015	2	1972	-
A2 (C)	Academic	2,256	4	1957	2011
O1 (L)	Officea	4,218	4	1969	-
O2 (H)	Office	5,585	4	1964	2004
R1 (W)	Residential	982	4	1948	1984
R2 ()	Residential	2768	4	1955	2010

(5). These measurements allow buildings with different sizes, life spans and construction types to be compared, which will

$$\mathrm{LCEEC}_{building} = \frac{\mathrm{LCEE}}{\mathrm{W} \times \mathrm{L}} \quad (4)$$

provide a more accurate assessment of how energy intensive the buildings are:

where LCECC is the life-cycle embodied carbon coefficient,

$$\mathrm{LCEEI}_{building} = \frac{\mathrm{LCEE}}{\mathrm{A} \times \mathrm{L}} \quad (5)$$

measured in kgCO2eq/ m2/yr. LCEE is the total life-cycle embodied carbon of the building, measured in kgCO2eq. W is the total weight of building, calculated in kg. L is the total building life span, in years:

where LCECI represents life-cycle embodied carbon intensity, measured in kgCO2eq/m2/yr. LCEC is the total life-cycle embodied carbon of the building, measured in kgCO2eq. A represents the total floor area of the building (conditioned and unconditioned), measured in square meters(m2). L is the total building life span, in years.

Life-Cycle Embodied Performance (LCEP)

This project proposes a new measure: life-cycle embodied performance (LCEP). It is the ratio between embodied carbon intensity and embodied energy-use intensity. The ratio is measured in kgCO2eq/MJ. The smaller the LCEP value, the less

$$\mathrm{LCEP} = \frac{\mathrm{LCECI}}{\mathrm{LCEEI}} \quad (6)$$

carbon emitted is from the equal amount embodied energy used, whereas the higher LCEP value indicate higher embodied carbon emission with same amount of energy consumption. Therefore, the lower LCEP value, the better the life-cycle embodied performance of the building.

where LCECI represents life-cycle embodied carbon intensity, measured in kgCO2eq/m2/yr. LCEC is the total life-cycle embodied carbon of the building, measured in kgCO2eq. A represents the total floor area of the building (conditioned and unconditioned), measured in square meters(m2). L is the total building life span, in years.

CASE PROJECT SPECIFICATION

The building types include in this study are academic (educational) buildings (A1, A2), residential buildings (R1, R2) and office buildings (O1, O2). Building floor plans and 3D models are presented in Figure 1. Floor area, building height, year of construction, and year of renovation are listed in Table 1. The total floor area of buildings ranges between 982 m2 to 7015 m2. Floor heights range between 2 stories to 4 stories. The buildings are all over 45 years old, and three buildings have had major renovations since initial construction, while the other three have not.

STATISTICAL ANALYSES

Four single variable regression models are used to determine the dependency between the environment impact categories (AP, OD, SF, EP) and LCEP. A 95% confidence interval for each outcome measure and a Pearson's value of .05 were used determine statistical significance:

$$Y_i = \beta 0 + \beta 1 X_i + e \quad (7)$$

where Yi is the life-cycle embodied performance (LCEP), Xi is the environmental impact category, β0 is the intercept, and ϵI is standard deviation. Tables 4 and 5 represent the variables included in the four models.

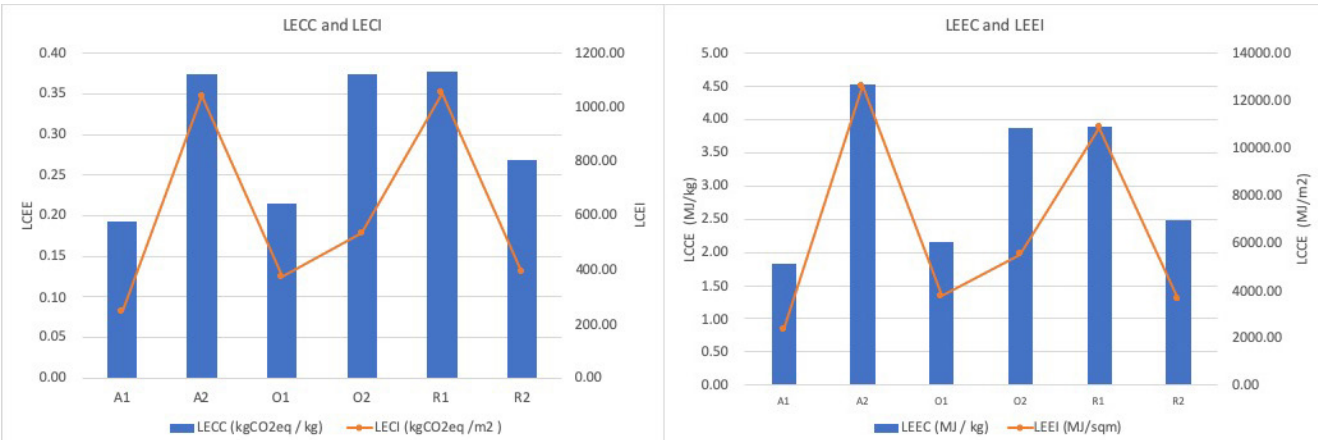

Figure 2. Embodied energy intensity and embodied carbon coefficient..

ANALYSIS FINDINGS

CORRELATION BETWEEN EMBODIED ENERGY AND EMBODIED CARBON

Two findings illustrated in Figure 2. First, the measured intensity has different results compared to the coefficient. For example, building O2 and R1 have similar coefficient (LCECC and LCEEC) value, although R1 has > 97% higher intensity (LCECI and LCEEI) value than those of O2. Also, O1 and O2 have comparable intensities, whereas, the coefficient of O2 is twice that of O1. Secondly, findings reveal that the buildings' function (type), size and height do not have a direct influence on life-cycle-embodied carbon and life cycle embodied energy. For instance, building O2 area is almost 6 times over the R1, however, those two buildings have similar embodied energy coefficient. A2 and R2 have similar building area, but very different embodied energy coefficients.

Figure 3 demonstrate that the ratio between energy and carbon is a better measurement for building performance compared to coefficient or intensity alone. When we look at the embodied energy and embodied carbon independently from each other, A2 has highest LCEEI, 12,614.20 kgCO2eq/kg (illustrated in blue), and the second highest LCECC, 0.37 MJ/m2 (illustrated in orange). Based on these scores, A2 can be rated with the lowest performance, which opposes the results when using the ratio between embodied energy and embodied carbon. As explained previously, a lower LCEP value implies a better embodied performance on the part of the building. Among the six buildings studied, A2 has the lowest LCEP score, 0.083, which means A2 emits the least amount of carbon while consuming the same amount of energy. Therefore, using the proposed model, building A2 has the best life-cycle embodied performance within the sample size.

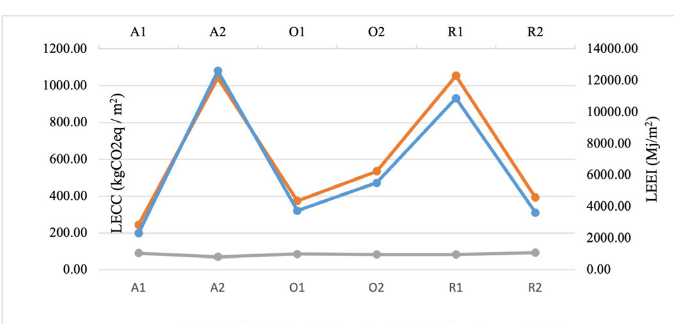

Figure 3. Life-cycle embodied energy intensity and life-cycle embodied carbon coefficient and life-cycle embodied performance.

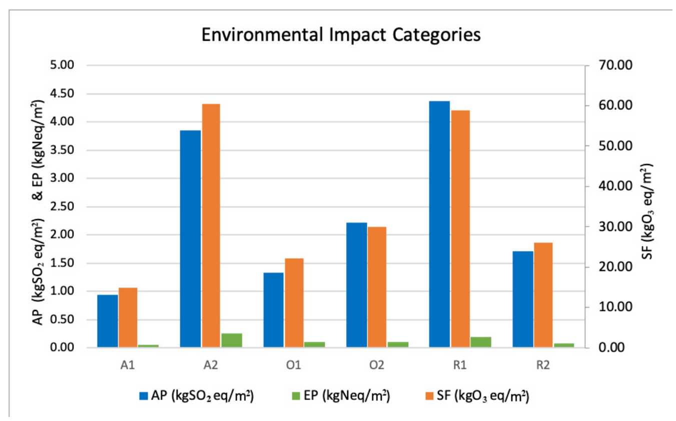

Figure 4. Environmental impact categories: AP, EP and SF.

CORRELATION BETWEEN ENVIRONMENTAL IMPACT AND LCEP

The results in this section are derived from the four single-regression models using input from Equation (2)–(6). There are large variations in all four environmental categories; Acidification Potential (AP) intensities range between 0.94 to 4.37 kgSO2eq/m2, Eutrophication Potential (EP) Intensities range between 0.05 to 0.26 kgNeq/m2, Smog Formation Potential (SP) intensities range between 14.85 to 58.87 kgO-3eq/ m2/yr, and Ozone Depletion Potential (OD) intensities range between 7.51E-07 to 3.27E-05CFC-11eq/ m2/yr.

Table 2. Linear regression model of correlation between environment impact and LCEP.

Category	R-Squared	Adjusted R-Squared	Significance F	*p*-Value	Significance
AP	0.161	−0.049	0.431	0.431	No
OD	0.877	0.846	0.006	0.006	Yes
SF	0.214	0.017	0.356	0.356	No
EP	0.387	0.234	0.187	0.187	No

It is difficult to compare buildings' embodied performance based on the total environmental impact through their entire life, so impact intensity (measured in floor area per year) was used. Figure 4 and Table 2 demonstrates the clear correlation between AP intensity and SF intensity: high AP couples with high SF, which indicates acidification potential as a causal factor for smog formation potential. Figure 4 also demonstrates that higher AP and SF do not always result in a higher EP. For example, office building 2 (O2) has higher AP and SF compared to office building 1 (O1), but lower EP than that of O1. This result indicates that causal factors differ between embodied EP, and AP and SF.

The general finding from this study is demonstrate in Table 2, which shows the results from four linear regression models. Among the four environment categories, it shows statistical significance in Ozone Depletion potential, with a p-value of 0.006 (less than .05). The R-squared value of OD is 0.877, which means 87.7% LCEP value in the data set could be predicted or interpreted by the value of OD value. This result means Ozone Depletion potential could be used as an indicator to predict the value of LCEP, or, the building life cycle embodied performance is correlated with OD.

BUILDING COMPONENTS AND MATERIALS' CONTRIBUTION

In order to gain a better understanding of what building components or materials contribute the most to embodied carbon, embodied energy, and environmental impact, detailed analyses are conducted for each building. For the embodied carbon, concrete accounts for 51%, and metal accounts for 31% in the O2 building. In the A2 building, the concrete contribution is 17%, and metal is 51%. In the A1 building, concrete is responsible for 51% of LCEC. The finding reveals the top 3 buildings with highest LCEE are O2, A2 and A1 again. Among all the material categories, concrete and metal are the primary contributors to embodied energy. In the A2 building, concrete contributes to 17% of LCEE and metal accounts for 52% of LCEE; and in the O2 building, concrete contributes 51% of LCEE and metal accounts for 31% of LCEE. Overall, the two residential buildings have lower LCEC and LCEE than the other buildings. This is not because of the smaller building's footprint, it is mostly determined by the building materials used.

As far as building assembly groups, the building floors contribute the most to embodied carbon in A1, A2 and O1. In O2 and R1, walls, including exterior walls and interior walls, are the largest contributor. In R2, windows contribute the most to embodied carbon. For embodied energy, walls are the largest contributor in A1, A2, O1, O2 and R1. R2 is the exception, where windows accounts for more than 50% of embodied energy. When examining the embodied energy and embodied carbon together, building walls, especially exterior walls, are a common significant factor. For future building renovations, replacing or upgrading existing exterior walls with low embodied energy and carbon components can effectively reduce the overall embodied energy and carbon.

For environmental impact, Figure 5 illustrates how residential buildings perform better in all four environmental categories, and commercial buildings and academic buildings' performance varies quite a lot depending on the impact categories.

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DISCUSSION AND CONCLUSIONS

From the results of this analysis, several conclusions can be drawn. First, the results illustrate a clear difference between embodied energy and embodied carbon. There are two different units of measurement, which do not always correlate to each other. In addition, building function, size, and construction year vary considerably. In order to get a better sense of the embodied performance of a building with a long life span, a more manageable and comparable measurement unit is needed. When embodied carbon and embodied energy are used separately, the results will not provide a comprehensive understanding of the building's embodied performance. Instead, the ratio between embodied energy and embodied carbon can serve as a genuine indicator of embodied performance. This ratio appears to be correlated to ozone depletion potential, and not any of the other environmental impact categories measured in this study.

Second, environmental impact categories are not dependent on embodied energy, nor embodied carbon. Rather, they are proportional to LCEP. A2 and R1 have the highest environmental impact intensities in all four categories (AP, OD, EP, SF), however, LCEP indicates that A2 and R1 perform better (with lowest LCEP score) in terms of reducing their embodied emissions. The LCEP is proportionally inverse to environment impact potentials. Potentially, with more data, a statistical model could be created to predict the potential environmental impact in all four categories, using LCEP as an indicator when designing new buildings. This could reduce the complexity of current environmental impact assessments and could, therefore, help designers overcome the challenges of including environmental impact potentials as design criteria. Also, the results reveal hotspots that contributing to ozone depletion: metal manufacturing and production processes, which provide a direction for mitigation strategies.

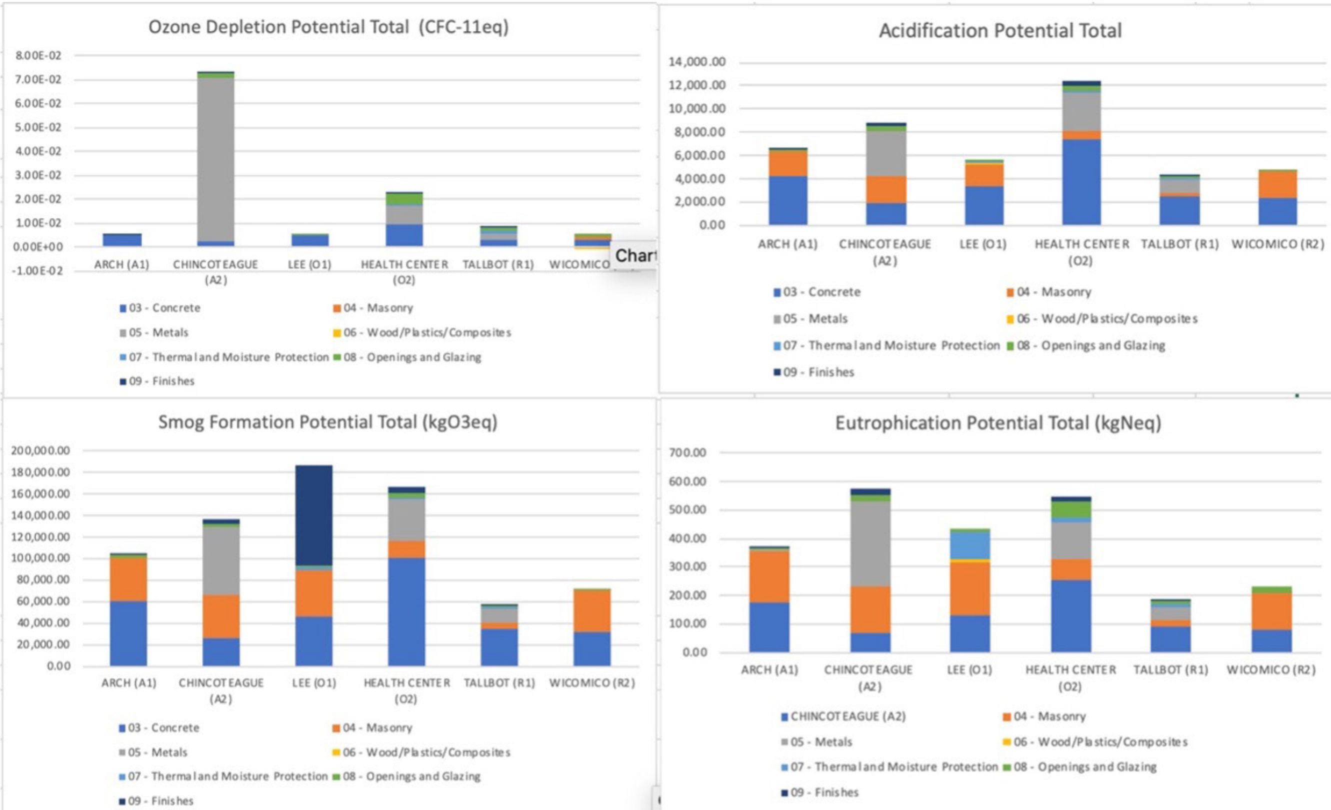

Figure 5. IContribution to total environmental impact per building.

Third, among the different building materials studies, metal and concrete express the highest contribution to embodied energy and embodied carbon. For building components, building exterior wall systems are the biggest embodied energy consumers and polluters, which indicates that building façade and wall systems could play significant roles in reducing embodied carbon and energy. This, in turn, would improve buildings' embodied performance.

Three primary observations can be extrapolated from this study:

1. Ozone depletion potential may be usable as an indicator to predict the value of LCEP

2. Using LCEE and LCEC independently from each other can lead to incomplete assessments

3. Regardless of the large variation in the performance of different building types, building exterior assemblies, particularly exterior walls, are a common significant factor influencing embodied energy and embodied carbon.

The significance of this study can be explained in three areas. Firstly, the actual building data is recorded and analyzed: original construction documents and historical records are collected and used to perform embodied energy, embodied carbon, and environment impact analysis. Secondly, this study investigates the case buildings at a detailed level to identify the contribution from each building assemblies' categories towards energy, carbon and environmental impact. Lastly, four environmental impact categories are assessed to gain a broad understanding of building's impact in addition to its contribution to global warming.

This study also has limitations that must be taken into account. First, the limited number of case buildings is an important limiting factor; more buildings need to be included in these studies. Second, the results of the analysis are dependent on the reliability and accuracy of the data provided by facility management offices and manufacturers. In order to make a more accurate assessment, detailed data is required from actual buildings. There are multiple barriers to acquiring this actual data, especially for existing buildings. Most older existing buildings do not have archives with complete, original construction documents. Often these buildings have also undergone multiple renovations, which can make collecting real data very challenging. There is potential that an algorithm could overcome such uncertainty, and a sensitivity analysis could be used to verify the robustness of the analysis results The third limitation is related to the scalability of the proposed method. It is possible to generalize construction types and methods for buildings built around the same time period, in a similar climate zone and in a geographic location. We can then use one or two buildings as a prototype to represent a portfolio of similar buildings, and then apply the proposed method on a much larger scale, such as an entire campus [14,15], neighborhood [16], city [17], or industry [18]. However, overgeneralizing could distort the findings and undermine the reliability of the analysis results as well. In order to prevent this overgeneralization, it is critical in the next steps to look into climate, geographic location and construction types as key influencing factors on the results.

ENDNOTES

1. Gustavsson, L.; Joelsson, A.; Sathre, R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy Build. 2010, 42, 230–242.

2. Chastas, P.; Theodosiou, T.; Bikas, D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Build. Environ. 2016, 105, 267–282.

3. Hu, M. The Embodied Impact of Existing Building Stock. In Toward Sustainability Through Digital Technologies and Practices in the Eurasian Region; IGI Global, Hershey, U.S.A: 2020; pp. 1–31.

4. Dixit, M.; Fernandez-Solis, J.L.; Lavy, S.; Culp, C.H. Need for an embodied energy measurement protocol for buildings: A review paper. Renew. Sustain. Energy Rev. 2012, 16, 3730–3743.

5. Cabeza, L.F.; Barreneche, C.; Miró, L.; Morera, J.M.; Bartolí, E.; Fernandez, A.I. Low carbon and low embodied energy materials in buildings: A review. Renew. Sustain. Energy Rev. 2013, 23, 536–542.

6. Optis, M.; Wild, P. Inadequate documentation in published life cycle energy reports on buildings. Int. J. Life Cycle Assess. 2010, 15, 644–651.

7. Kneifel, J.; O'Rear, E.; Webb, D.; O'Fallon, C. An Exploration of the Relationship between Improvements in Energy Efficiency and Life-Cycle Energy and Carbon Emissions using the BIRDS Low-Energy Residential Database. Energy Build. 2017, 160, 19–33.

8. De Wolf, C.; Pomponi, F.; Moncaster, A.M. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. Energy Build. 2017, 140, 68–80.

9. Hendriks, C.; Worrell, E.; Price, L.; Martin, N.; Meida, L.O.; De Jager, D.; Riemer, P. Emission reduction of greenhouse gases from the cement industry. In Greenhouse Gas Control Technologies 4; Elsevier, Amsterdam, Netherlands: 1999; pp. 939–944.

10. Lucchi, E.; Tabak, M.; Troi, A. The "Cost Optimality" Approach for the Internal Insulation of Historic Buildings. Energy Procedia 2017, 133, 412–423.

11. Bogdan, A.; Kouloumpi, I.; Thomsen, K.E.; Aggerholm, S.; Enseling, A.; Loga, T.; Witczak, K. Implementing the cost-optimal methodology in EU countries: Lessons learned from three case studies. Energy Procedia 2015, 78, 2022–2027.

12. Andra, B.; Kašs, K.; Edīte, K.; Gatis, Ž.; Agris, K.; Dagnija, B.; Armands, G.; Reinis, P.; Marika, R.; Lelde, T.; et al. Robust Internal Thermal Insulation of Historic Buildings-State of the art on historic building insulation materials and retrofit strategies. Lirias 2019 (V21), 1–87.

13. Akkurt, G.; Aste, N.; Borderon, J.; Buda, A.; Calzolari, M.; Chung, D.; Costanzo, V.; Del Pero, C.; Evola, G.; Huerto-Cardenas, H.; et al. Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions. Renew. Sustain. Energy Rev. 2020, 118, 109509.

14. Hu, M. Life-cycle environmental assessment of energy-retrofit strategies on a campus scale. Build. Res. Inf. 2019 (V4), 1–22.

15. Stephan, A.; Muñoz, S.; Healey, G.; Alcorn, J. Analysing material and embodied environmental flows of an Australian university—Towards a more circular economy. Resour. Conserv. Recycl. 2020, 155, 104632.

16. Stephan, A.; Crawford, R.H.; De Myttenaere, K. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. Build. Environ. 2013, 68, 35–49.

17. Ripa, M.; Fiorentino, G.; Vacca, V.; Ulgiati, S. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). J. Clean. Prod. 2017, 142, 445–460.

18. Crawford, R.H.; Stephan, A.; Prideaux, F. A comprehensive database of environmental flow coefficients for construction materials: Closing the loop in environmental design. In Proceedings of the 53rd International Conference of the Architectural Science Association 2019: Revisiting the Role of Architecture for 'Surviving' Development, Roorkee, Uttrakhand, India, 28–30 November 2019.