Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 196 (2017) 1003 – 1010

Procedia Engineering

www.elsevier.com/locate/procedia

Creative Construction Conference 2017, CCC 2017, 19-22 June 2017, Primošten, Croatia

Improving the life cycle energy performance of apartment units through façade design

André Stephan[a]*, Christopher A. Jensen[a], Robert H. Crawford[a]

[a]*Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, Victoria 3010, Australia*

Abstract

The construction and operation of buildings require huge amounts of resources and contribute to climate change and resource depletion. In Australia, apartment buildings are increasingly being erected and are typically characterized by fully-glazed façades with a limited understanding of the life cycle implications of such design. This study uses a typical apartment unit in three climates (Melbourne, Australia; Brisbane, Australia; and Dunedin, New Zealand) and tests 87 different façade variations involving a range of window-to-wall ratios, window types and wall types. For each variation, the life cycle energy demand is quantified over 50 years and compared to that of the base case. Results show that the window-to-wall ratio is the most significant parameter and that smaller glazed areas reduce both embodied and operational energy use. Climate and orientation are other significant parameters, modifying the ranking of variations in terms of life cycle energy performance. In addition, the embodied energy of the façade represented, on average, 45% of the apartments' life cycle energy demand, highlighting the importance of material selection. Reducing glazed area, considering a life cycle approach and carefully composing a façade with respect to climate and orientation are therefore critical factors in improving the life cycle energy performance of apartment units.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2017

Keywords: Life cycle energy analysis; embodied energy; heating and cooling; Australia.

1. Introduction

Greenhouse gas emissions (GHGE) from human activity are driving climate change and the disruption of the water cycle and ecosystems, globally [1]. A large share of these emissions can be attributed to the operation of buildings

* Corresponding author. Tel.: +61383445929
E-mail address: andre.stephan@unimelb.edu.au

1877-7058
Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2017
doi:10.1016/j.proeng.2017.08.042

alone, which represented an estimated 32% of global final energy use and 19% of GHGE in 2010. Should indirect energy use and emissions, such as those associated with manufacturing and replacing building materials, be accounted for, the significance of the building sector in mitigating climate change would be further reinforced [2-4]. Improving the life cycle environmental performance of buildings is therefore essential [5, 6].

While the operational energy efficiency of buildings is regulated in many countries (e.g. Energy Performance of Buildings Directive in the European Union [7], Star Rating Scheme in Australia [8]), their embodied energy is only starting to be considered (see for instance the Dutch regulation on embodied environmental requirements [9]). An increasing number of studies on quantifying the life cycle environmental performance of buildings has been published on the matter in recent years [6, 10-13]. However, while many studies have investigated the relationship between façade design and operational performance (e.g. [14]), few focus on optimizing the life cycle energy performance of apartment units. With the construction of ~100 million m² of apartments since 2004 in Australia (based on data from [15]) and the rapid increase in the ratio of apartment units to houses, it is critical to inform their design to ensure their life cycle energy performance. Otherwise, poor designs could result in significant energy use and associated greenhouse gas emissions, now and for decades to come.

Among existing studies on the life cycle environmental performance of apartment units and façade-related elements, Özkan and Onan [16] have studied the life cycle cost implications of various insulation thickness and glazing areas in apartment buildings in Turkey but their study does not consider embodied energy. Takano *et al.* [17] have quantified the life cycle energy demand of various dwelling types in Finland, including apartments. Their study considers a range of parameters, notably different structural materials and framing systems, but does not evaluate the effect of glazing area and glazing type. In an Australian context, Matthews and Treloar [18] have compared the life cycle energy performance of single and double glazing and demonstrated that the additional embodied energy in double-glazed windows is quickly paid back. However, their study considers only one orientation and glazing ratio and does not therefore evaluate a broad range of façade designs. More recently, Crawford *et al.* [19] have investigated the net life cycle energy benefits of houses with increasing energy efficiency levels. They reveal that past a certain insulation level that is close to current minimum requirements in Australia, increasing the energy efficiency of a house through additional insulation results in an increased life cycle energy use. While they consider different insulation levels for the house, they do not vary the design of the façade. In light of these studies and the increasing construction of apartment buildings in Australia, there is a need to better understand the relationship between façade design and life cycle energy performance to minimize energy use and reduce associated environmental effects.

1.1. Aim and Scope

The aim of this study is to evaluate the life cycle energy performance of an apartment unit for a range of façade designs, including glazing type, window to wall ratio, wall type, and orientation, in order to identify optimal designs and provide design guidelines.

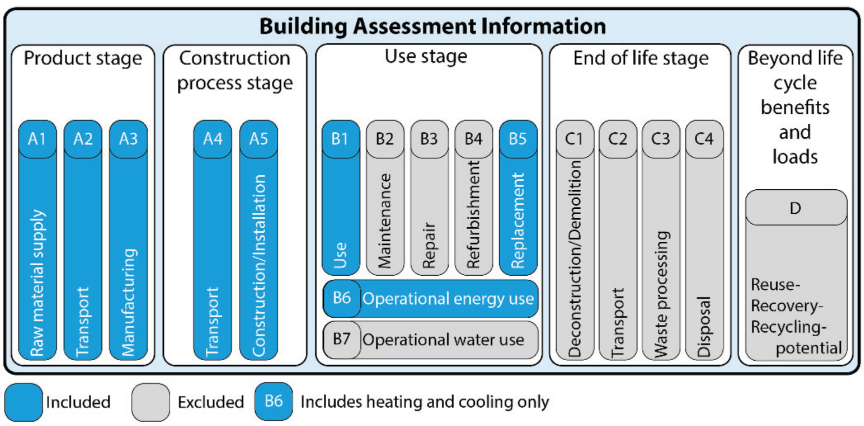

Figure 1: Scope of the study in terms of life cycle stages considered. Note: Adapted from European Standard 15978 [20].

The study focuses on primary energy use, which is representative of broader environmental effects, as established by studies from multiple countries [21-23]. The paper uses a representative apartment unit in the climate of Melbourne, Australia as a case study and adopts a life cycle approach. The scope of the life cycle energy analysis is depicted in Figure 1, according to the European Standard 15978 [20]. Note that the 'end of life' stage is not considered because of the large uncertainties regarding the fate of the building, decades into the future.

The method used to quantify the life cycle energy performance of apartment units is described in Section 2. Results are presented in Section 3 before discussing and concluding in Section 4.

2. Method

This section describes the overall research method, the case study apartment unit and how embodied, operational and life cycle energy use is quantified.

2.1. Overall research method

Figure 2 represents the research method. A base case apartment unit in the cities of Melbourne and Brisbane, Australia and Dunedin, New Zealand is first considered and its embodied, operational and life cycle energy demands are quantified over 50 years to establish a baseline scenario. The façade of the unit is then altered by modifying its window-to-wall ratio, glazing type and wall type. The life cycle energy demand of each variation is also quantified. The orientation of the worst-performing and best-performing units is changed to cover a broader set of solutions, resulting in a total of 87 variations. By comparing the life cycle energy performance of all variations to the base case, guidelines for façade design will be identified.

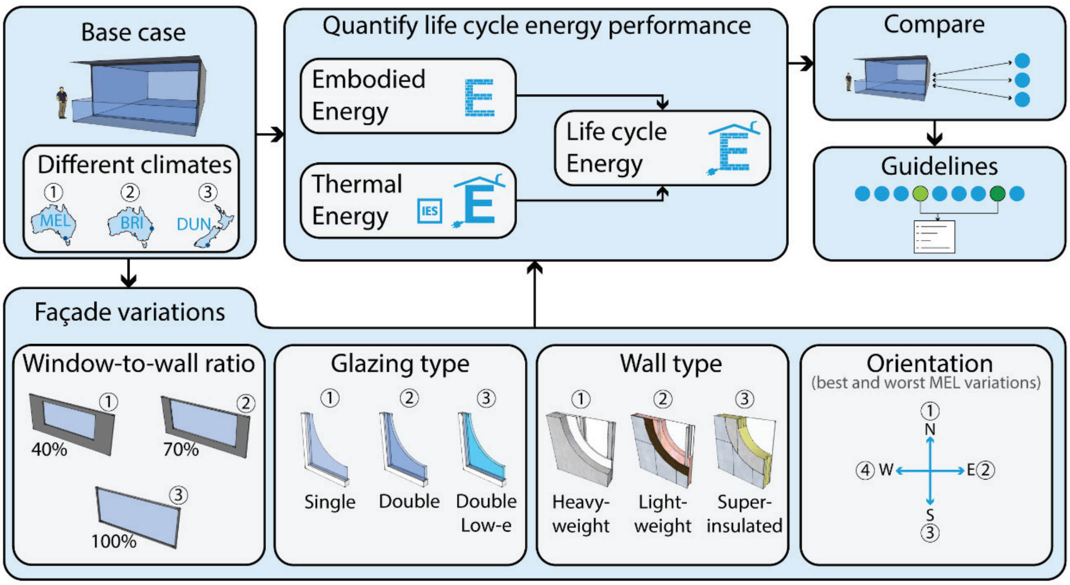

Figure 2: Overall research method. Note: MEL: Melbourne, Australia, BRI: Brisbane, Australia and DUN: Dunedin, New Zealand.

2.2. Case study apartment unit and variations

The base case apartment unit is simulated in: Melbourne's temperate oceanic climate (*Cfb* according to the Köppen-Geiger classification), Brisbane's humid subtropical climate (*Cfa*); and in the colder temperate oceanic climate of

Dunedin, New Zealand. Using three different climates will broaden the applicability of the results. The main characteristics of the case study apartment unit are provided in Table 1.

Table 1. Characteristics of the case study unit

Case study apartment unit characteristic	Base case	Investigated variations
Period of analysis	50 years	50 years
Climate	Melbourne, Australia (*Cfb*)	Brisbane, Australia (*Cfa*); Dunedin, New Zealand (*Cfb*)
Width, height between storeys, depth	6 m, 3 m, 10 m	N/A
Gross floor area	60 m^2	N/A
Number of façades	1	N/A
Structure	Concrete-frame	N/A
Internal walls	Timber-framed plasterboard	N/A
Floor finish	Living: parquet flooring	N/A
	Bedrooms: carpet	
Window-to-wall ratio	100%	70%; 40%
Window frames	Aluminium	N/A
Glazing type	Single glazing	Double glazing; Double-glazed low-emissivity coated
Window[a] U-value ($W/(m^2 \cdot K)$)	6.2	4.0; 2.7
Outer wall	Prefabricated heavyweight wall (150 mm concrete, 20 mm EPS; 28 mm Battens and air gap; 10 mm plasterboard; water-based paint)	Lightweight wall (3 mm Aluminum cladding, 18 mm plywood board; 90 mm steel frame and fiberglass insulation; 10 mm plasterboard; water-based paint); Superinsulated wall (3 mm Aluminum cladding, 200 mm PU panel with steel cover sheet; 10 mm plasterboard; water-based paint)
Orientation	North	East, South, West
Coefficient of performance for heating/cooling	3.0/2.5 (reverse cycle split system)	N/A
Primary energy conversion factor for electricity	3.4[b]	3.1[b] (Brisbane, Australia); 2.38[c] (New Zealand)

Note: [a]Including frames; [b]Based on Treloar [24]; [c]Barber [25]; EPS: expanded polystyrene, PU: polyurethane.

Variations to the window-to-wall ratios and glazing types are based on typical practice in Australia. The heavyweight and lightweight walls are also derived from standard assembly compositions from the Building Code of Australia [8]. The superinsulated wall variation represents the trend towards zero energy housing and/or buildings meeting the *passivhaus* certification.

2.3. Quantifying embodied energy

Embodied energy is quantified using the input-output-based hybrid analysis technique developed by Treloar [26], validated by Crawford [27] and subsequently applied in a range of studies [4, 19, 28, 29]. This approach combines economic input-output data at a sectorial level which are extracted using structural path analysis [30]. Certain data points are then substituted with more reliable industrial process data for the material being studied, using the path exchange method [31]. The resulting hybrid data provides a systemically complete account of energy use, ensured by input-output data, where the most reliable process data are integrated. At a whole building level, this approach can produce embodied energy figures up to four times higher [32-34] than those produced by process analysis [35].

The life cycle embodied energy of an apartment unit is calculated as per Equation (1), by:

1. Deriving the bill of material quantities of the unit;
2. Multiplying the quantity of each material by its relevant hybrid embodied energy coefficient, taken from Treloar and Crawford [36];
3. Replacing materials over 50 years, based on average material service lives from [37, 38]; and
4. Adding the 'input-output remainder' which covers all non-material-related energy inputs across the supply chain (see Crawford [34] for more details).

$$LCEE_u = \sum_{m=1}^{M}\left(Q_{m,u} \times w_m \times EC_m\right) + \left(TERRBS - \sum_{m=1}^{M} TER_m\right) \times C_u + \sum_{m=1}^{M}\left[\left\lceil \frac{POA}{SL_m} - 1 \right\rceil \times \left[\left(Q_{m,u} \times w_m \times EC_m\right) + \left(TERRBS - TER_m - NATER_m\right) \times C_{m,u}\right]\right] \quad (1)$$

Where: $LCEE_u$ is the life cycle embodied energy of the apartment unit u in GJ; M is the total number of materials in the apartment unit; $Q_{m,u}$ is the quantity of material m in the apartment unit u (e.g. m² of glass); w_m is the wastage factor of material m (e.g. 1.03 for glass); EC_m is the hybrid energy coefficient of material m in GJ per functional unit; *TERRBS* is the total energy requirement of the residential building sector, in GJ/AUD; TER_m is the total energy requirement of the input-output pathway representing material m, in GJ/AUD; and C_u is the cost of the apartment unit u in AUD; *POA* is the period of analysis, in years; SL_m is the service life of the material m, in years; $NATER_m$ is the total energy requirement of all input-output pathways not associated with the installation or production process of material m being replaced, in GJ/AUD, e.g. pathways representing concrete production when replacing plasterboard; and $C_{m,u}$ is the cost of the material m in AUD in the apartment unit u.

2.4. Quantifying thermal operational energy

The thermal operational energy of each variation in each climate is calculated using the Integrated Environmental Solutions (IES) software. IES is an advanced dynamic building energy simulation model that is widely used within the Australian construction industry. It meets the International Energy Agency's BESTEST validation [39] for building energy simulation models.

The apartment is modeled as a single thermal zone. Typical comfort range temperatures of 20ºC for heating and 26ºC for cooling are used. Heat transfer through party walls, the ceiling and the slab are considered null. Internal gains are scheduled as per the NATHERS requirements [40], for each zone and typical occupant schedules are used.

Final heating and cooling energy demands are converted to delivered energy by using the coefficient of performance of the heating/cooling system, respectively. The resulting delivered energy demand is then converted to primary energy terms by multiplying the primary energy conversion factor for electricity in Victoria, Australia. The primary energy demand is finally multiplied by the period of analysis to obtain the life cycle thermal operational energy demand. This is summarized in Equation (2).

$$LCTOPE_u = POA \times \left(PEF_u^{\mathrm{H}} \times \frac{FE_u^{\mathrm{H}}}{\eta_u^{\mathrm{H}}} + PEF_u^{\mathrm{C}} \times \frac{FE_u^{\mathrm{C}}}{\eta_u^{\mathrm{C}}} \right) \quad (2)$$

Where: $LCTOPE_u$ is the life cycle primary thermal operational energy of the apartment unit u in GJ; *POA* is the period of analysis, in years; $PEF^{\mathrm{H}}_{\mathrm{u}}$ and $PEF^{\mathrm{C}}_{\mathrm{u}}$ are the primary energy conversion factors for the heating and cooling energy sources in apartment unit u, respectively, in GJ/GJ; $FE^{\mathrm{H}}_{\mathrm{u}}$ and $FE^{\mathrm{C}}_{\mathrm{u}}$ are the final annual heating and cooling energy demands of apartment unit u (as calculated by IES in study), respectively, in GJ; and $\eta^{\mathrm{H}}_{\mathrm{u}}$ and $\eta^{\mathrm{C}}_{\mathrm{u}}$ are the heating and cooling systems efficiency of apartment unit u, respectively.

2.5. *Quantifying life cycle energy*

The life cycle energy demand of an apartment unit *u* is the addition of its life cycle embodied energy and its life cycle thermal operational energy.

3. Results

Figure 3 compares the life cycle energy demand of all variations to the base casein Melbourne's climate across the categories of initial embodied energy, recurrent embodied energy (associated with material replacement), heating primary energy and cooling primary energy. Results show that the life cycle energy demand is reduced in almost all variations. The most energy saving variation is the combination of a window-to-wall ratio of 40%, double-glazed (DG) low-emissivity windows and heavyweight walls. This variation not only reduces thermal operational energy through improved performance but also slightly reduces embodied energy. This is because even though DG windows require more energy to produce and replace, using less operational energy offsets their higher energy intensity.

It is interesting to note that fully glazed façades with double glazing or double-glazed low emissivity windows result in an increase in both embodied and cooling energy, even though the reduction in heating demand more than offsets these. Overheating should be carefully considered for these variations.

The results demonstrate the significance of the window-to-wall ratio (WWR) as variations are clearly stratified accordingly. They also highlight that DG windows payback their embodied energy quickly in Melbourne's climate: single glazed windows result in the highest life cycle energy demand for a fixed WWR, regardless of wall type. In addition, while the superinsulated wall would tend to imply a much higher embodied energy demand, notably using polyurethane, its structural design does not require additional reinforcements and therefore reduces the need for other energy-intensive materials, notably steel (compared to the lightweight variation).

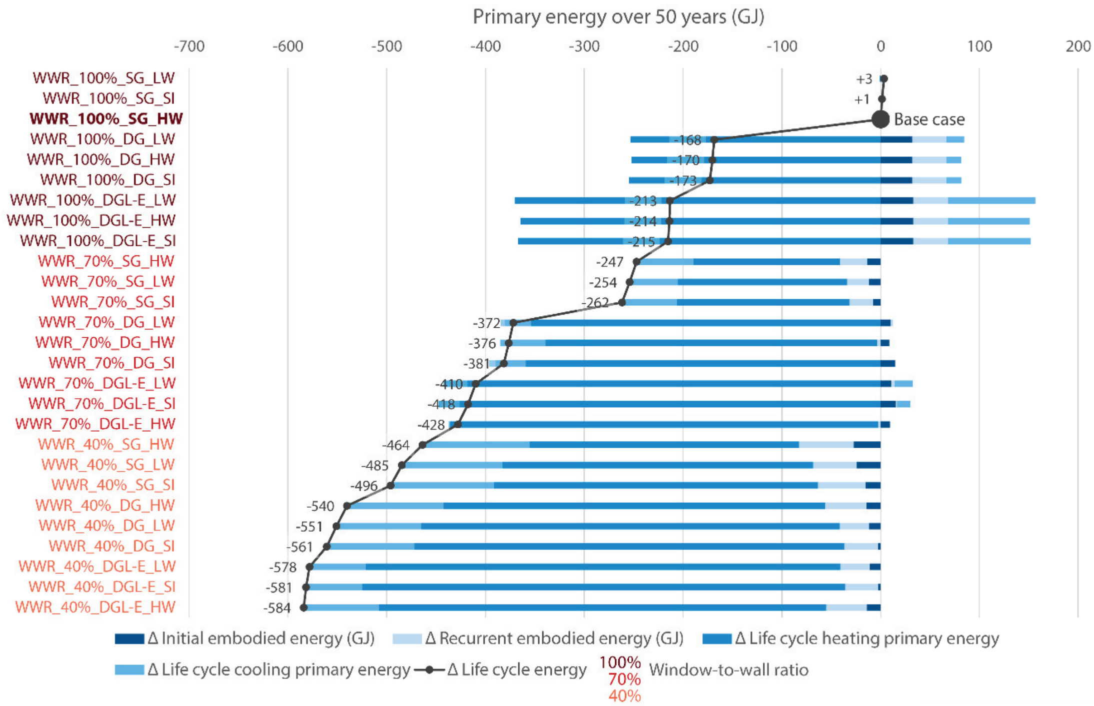

Figure 3: Comparison between the life cycle energy demand of each variation and that of the base case for Melbourne's climate, by use. Note: WWR: window-to-wall ratio, SG: single glazed windows; DG: double-glazed window: DGL-E: double-glazed low-emissivity window; LW: lightweight wall; HW: heavyweight wall; and SI: superinsulated wall.

In addition to the above variations, climate and orientation are critical. While results for Brisbane, Dunedin, and other orientations are not presented in detail due to lack of space, the main observations are presented below.

Climate has a notable impact on results both in absolute life cycle energy performance and in the ranking of the different variations. For Brisbane's cooling-dominated climate, the variation leading to the best performance is a 40% WWR façade with single glazing and heavyweight walls (444 GJ reduction compared to the base case in Brisbane). In addition, the effect of the WWR is as significant, leading to three clear clusters of performance, arranged by WWR. For Dunedin, the colder climate affects the stratification of performance by WWR as three of the top ten variations (7,8 and 10) have a WWR of 70% and benefit from double-glazed low-emissivity windows. Furthermore, the top performing variation has a WWR of 40%, double-glazed low-emissivity windows and superinsulated walls. It is also important to note that even though Dunedin's climate is colder than Melbourne's, lower primary energy requirements for electricity result in a reduced life cycle energy demand for its best case (1,580 GJ compared to 1,657 GJ).

The orientation of the best and worst performing variations in Melbourne's climate was varied to the east, south, and west (from north). While the changes in heating and cooling follow accepted trends (more heating for all three orientations, less cooling for the south and more cooling for east and west), the absolute variation in primary energy is within 63-190 GJ. This is significant as 190 GJ represents 32% of the energy reduction of the optimal measure. Façade composition should therefore be optimized for life cycle energy performance, for each orientation.

4. Discussion and conclusion

This paper has evaluated the life cycle energy performance of an apartment unit depending on a range of façade compositions, climates and orientations. Three main findings can be discussed.

Firstly, glass is a very energy intensive material with relatively poor thermal properties. As shown above, reducing the amount of glazing in apartment units, regardless of the climate and orientation, results in significant life cycle energy savings. The trend towards fully glazed apartment units not only requires more embodied energy, and more heating and cooling (as shown in Ochoa *et al.* [14]) but would also necessitate the installation of awnings and shading systems that in turn require embodied energy to produce. The life cycle energy performance of apartments could therefore be reduced by adopting a smaller window-to-wall ratio.

Secondly, this study highlights the significance of a life cycle approach as the life cycle embodied energy of the façade alone is equivalent to 29-62% of the life cycle thermal energy demand, with an average of 45%. Omitting embodied energy can therefore lead to suboptimal solutions, as demonstrated in a number of studies (e.g. [4, 19]).

Thirdly, climatic conditions significantly affect the life cycle energy balance of buildings, by affecting operational energy demand and therefore the energy payback time for assemblies. For example, the variations in Brisbane's climate clearly indicate that installing low-emissivity double glazing increases both embodied and operational energy. Orientation was also found to be a determining factor for the life cycle energy performance of façades. A façade composition should therefore be optimized for both embodied and operational energy depending on orientation.

As for any modelling exercise, this study suffers from a range of limitations. The end-of-life stage is not considered and it can result in significant amounts of waste and associated effects on the environment. The study only takes into account a limited set of variables associated with façade composition and therefore it does not explore the entire range of solutions. Similarly, it uses a single apartment unit typology, i.e. one-façade apartments. Additional parameters, such as orientation for all variations, frame type, shading and heating and cooling systems, as well as the number of façades, may identify solutions with lower life cycle energy use. Future research will explore these and help identify optimal combinations of façade compositions and systems for different climates and orientations. This will contribute to informing the construction practice in Australia and elsewhere, in order to reduce its environmental effects.

References

[1] IPCC. Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. In: Stocker TF, Qin D, Plattner G-K, Tignor MMB, Allen SK, Boschung J, et al., editors. Cambridge: Cambridge University Press; 2013.

[2] Anderson JE, Wulfhorst G, Lang W. Energy analysis of the built environment—A review and outlook. Renewable and Sustainable Energy Reviews. 2015;44:149-58.

[3] Dixit MK, Fernández-Solís JL, Lavy S, Culp CH. Need for an embodied energy measurement protocol for buildings: A review paper. Renewable

and Sustainable Energy Reviews. 2012;16:3730-43.
[4] Stephan A, Crawford RH. A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings. Archit Sci Rev. 2014;57:39-48.
[5] Säynäjoki A, Heinonen J, Junnila S, Horvath A. Can life-cycle assessment produce reliable policy guidelines in the building sector? Environ Res Lett. 2017;12:013001.
[6] Chau CK, Leung TM, Ng WY. A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. Appl Energ. 2015;143:395-413.
[7] EC. Directive 2010/31/EU of the European Parliament and the Council of the European Union of the 19 May 2010 on the Energy Performance of Buildings. Official Journal of the European Communities. Brussels: European Parliament and the Council of the European Union; 2010. p.23.
[8] ABCB. Building Code of Australia (BCA) 2016. Australia: Australian Building Codes Board; 2016.
[9] de Klijn-Chevalerias M, Javed S. The Dutch approach for assessing and reducing environmental impacts of building materials. Building and Environment. 2017;111:147-59.
[10] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: An overview. Energ Buildings. 2010;42:1592-600.
[11] Sharma A, Saxena A, Sethi M, Shree V, Varun. Life cycle assessment of buildings: A review. Renewable and Sustainable Energy Reviews. 2011;15:871-5.
[12] Karimpour M, Belusko M, Xing K, Bruno F. Minimising the life cycle energy of buildings: Review and analysis. Building and Environment. 2014;73:106-14.
[13] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment. 2016;105:267-82.
[14] Ochoa CE, Aries MBC, van Loenen EJ, Hensen JLM. Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Appl Energ. 2012;95:238-45.
[15] ABS. *8752.0 - Building Activity, Australia, Jun 2016*. Australian Bureau of Statistics, Available from http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8752.0Jun%202016?OpenDocument#Time, 2016 (Accessed January 4th 2017).
[16] Özkan DB, Onan C. Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey. Appl Energ. 2011;88:1331-42.
[17] Takano A, Pal SK, Kuittinen M, Alanne K. Life cycle energy balance of residential buildings: A case study on hypothetical building models in Finland. Energ Buildings. 2015;105:154-64.
[18] Matthews T, Treloar GJ. Net energy analysis of double glazing for residential buildings in temperate climates. Structural Survey. 2001;19:201-8.
[19] Crawford RH, Bartak EL, Stephan A, Jensen CA. Evaluating the life cycle energy benefits of energy efficiency regulations for buildings. Renewable and Sustainable Energy Reviews. 2016;63:435-51.
[20] European Standard 15978. Sustainability of construction works -Assessment of environmental performance of buildings - Calculation method. Brussels: European Committee for Standardization (CEN); 2011. p.66.
[21] Oregi X, Hernandez P, Gazulla C, Isasa M. Integrating Simplified and Full Life Cycle Approaches in Decision Making for Building Energy Refurbishment: Benefits and Barriers. Buildings. 2015;5:354-80.
[22] Allacker K. Sustainable building. The development of an evaluation method [Ph.D. thesis]. Leuven: Katholieke Universiteit Leuven; 2010.
[23] Junnila S. The environmental impact of an office building throughout its life cycle [PhD thesis]. Espoo: Helsinki University of Technology Construction Economics and Management; 2004.
[24] Treloar GJ. A comprehensive embodied energy analysis framework [Ph.D. Thesis]. Geelong: Deakin University; 1998.
[25] Barber A. New Zealand fuel and electricity total primary energy and life cycle greenhouse gas emission factors 2010. Kumeu, New Zealand: Agrilink; 2011. p.15.
[26] Treloar GJ. Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. Econ Systems Res. 1997;9:375-91.
[27] Crawford RH. Validation of a hybrid life-cycle inventory analysis method. J Environ Manage. 2008;88:496-506.
[28] Stephan A, Stephan L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. Appl Energ. 2016;161:445-64.
[29] Crawford RH, Czerniakowski I, Fuller RJ. A comprehensive framework for assessing the life-cycle energy of building construction assemblies. Archit Sci Rev. 2010;53:288-96.
[30] Miller RE, Blair PD. Input-output analysis: foundations and extensions. Cambridge: Cambridge University Press; 2009.
[31] Lenzen M, Crawford R. The Path Exchange Method for Hybrid LCA. Environ Sci Technol. 2009;43:8251-6.
[32] Stephan A, Stephan L. Reducing the total life cycle energy demand of recent residential buildings in Lebanon. Energy. 2014;74:618-37.
[33] Crawford RH, Stephan A. The significance of embodied energy in certified passive houses. ICCBM 2013: International Conference on Construction and Building Materials. Copenhagen: World Academy of Science, Engineering and Technology; 2013. p.473-9.
[34] Crawford RH. Life cycle assessment in the built environment. London: Spon Press; 2011.
[35] Majeau-Bettez G, Strømman AH, Hertwich EG. Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. Environ Sci Technol. 2011;45:10170-7.
[36] Treloar GJ, Crawford RH. Database of embodied energy and water values for materials. Melbourne: The University of Melbourne; 2010, https://doi.org/10.4225/49/588eeeeda28af.
[37] NAHB, Bank of America. Study of life expectancy of home materials. In: Jackson J, editor. Washington DC: National Association of Home Builders; 2007. p.19.
[38] Ding G. The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities [Ph.D. thesis]. Sydney: University of Technology; 2004.
[39] Judkoff R, Neymark J. International Energy Agency building energy simulation test (BESTEST) and diagnostic method. Golden, CO (US): National Renewable Energy Laboratory; 1995.
[40] NatHERS. *Heat loads*, Available from http://nathers.gov.au/accredited-software/how-nathers-software-works/heat-loads, 2015 (Accessed October 20th 2015).