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Impact of Design Choices on the Life Cycle Energy of Modern Buildings

Mahsa Karimpour, Martin Belusko, Ke Xing, Frank Bruno

***Abstract*—**Traditionally, the embodied energy of design choices which reduce operational energy were assumed to have a negligible impact on the life cycle energy of buildings. However with new buildings having considerably lower operational energy, the significance of embodied energy increases. A life cycle assessment of a population of house designs was conducted in a mild and mixed climate zone. It was determined not only that embodied energy dominates life cycle energy, but that the impact on embodied of design choices was of equal significance to the impact on operational energy.

***Keywords*—**Building life cycle energy, embodied energy, energy design measures, low energy buildings.

I. Introduction

IT is believed that 40% of total energy consumption in the world is by buildings and 32% of total CO_2 emissions produced by building constructions [1]. Therefore, considerable research has been conducted into evaluating and reducing the life cycle energy of buildings over the past few decades. Since operational energy has a larger proportion of life cycle energy, the traditional focus has been on reducing this energy through improved building design or equipment efficiency [2], [3]. However, it can be argued that recently embodied energy analysis become more important due to applying carbon emission policies around the world. On the other hand, design of low energy buildings, results in an increase in embodied energy due to use of energy intensive materials [4]. So to achieve low life cycle energy buildings, operational and embodied energy need to be considered at the same time. [5] Showed that for low energy buildings, 40-60% of total life cycle energy is used for the production and construction phase. [6] Also concluded that in milder regions embodied energy can represent up to 25% of the total life cycle energy. [7] Presented a case study in Australia analyzing the embodied energy of some common material in the region.

They concluded that embodied energy has more impact on life cycle energy than had been expected. Limited research has been conducted into the impact of design choices which reduce the operational energy associated with heating and cooling, of a building design, which also affect the embodied energy. This study investigates the life cycle energy across the range of design choices in a mild and mixed climate.

Mahsa Karimpour is with School of Engineering, University of South Australia, Mawson Lakes Boulevard, Mawson Lakes, SA 5095, Australia (Corresponding author to provide phone: +61 8 8302 3663; e-mail: mahsa.karimpour_aghbolagh@mymail.unisa.edu.au).

Martin Belusko and Frank Bruno are with Barbara Hardy Institute, University of South Australia, Mawson Lakes Boulevard, Mawson Lakes, SA 5095, Australia.

Ke Xing is with School of Engineering, University of South Australia, Mawson Lakes Boulevard, Mawson Lakes, SA 5095, Australia.

II. Methodology

Life cycle energy of a building includes embodied energy and operational energy. Operational energy is the energy used for space cooling and heating, ventilation, lighting, hot water, and running electrical equipment in the dwelling. Embodied energy is the energy used to extract raw materials, transport and refine them, then use them for manufacturing and assembling new products, transportation of the products and construction at the building site. The goal of this study was to find and analyze the life cycle energy of a brick veneer house in Adelaide, Australia considering different design variables such as insulation levels and materials, including reflective foils, different types of floor covering and window glazing, and roof color. The influence of these design variables on annual energy demand of the house was investigated.

A. House Model Description

A conventional residential brick veneer house in Adelaide, Australia was selected for the purpose of this study. Generally, equal amounts of energy are needed to heat and cool a typical Adelaide house. The house has one floor with living area of 204.5 m². It has a garage with area 35.5 m², 4 bedrooms, 2 bathrooms and 1 kitchen. Fig. 1 presents the plan of the house.

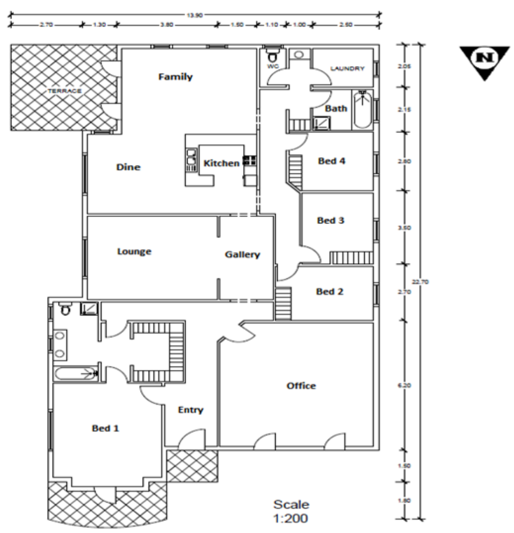

Fig. 1 House plan

The AccuRate software a simulation building model was used to conduct the building modelling. This software rates the thermal performance of buildings in terms of stars [8]. Ten stars represent a building requiring no heating and cooling, and the corresponding energy requirement is different for each location. Equation (1) expresses the relationship between stars and total heating and cooling demand for the house used in Adelaide, based on conditioned floor area. Where X is star and Y is MJ/m^2.

$$y = 2.3994x^2 - 58.366x + 362.95 \quad (1)$$

B. Selection of Design Variables for Operational Energy

The design variables selected reflect the dominant parameters applied in the building industry, which impact on the heating and cooling for a building design. Specifically the influence of using different amounts of insulation for ceiling and walls as well as the effect of using different types of glazing for windows are evaluated. The impact of using different radiation barriers such as roof color and adding foil in the roof is assessed as these factors affect cooling demand. Furthermore, the impact of typical floor coverings was considered, as this variable affects cooling and heating demand. Table I shows all different variables for each section. The range of wall insulation selected represents a poor, typical and high level. The options considered for internal wall insulation are no insulation (which is typical for nearly all existing homes), high level and very high level of insulation. The range of ceiling insulation represents poor, typical and high. The windows studied cover the full range in use. Until recently most new homes have single glazing with low emissivity single glazing becoming typical. Double glazing is dramatically increasing in use; however this is from a small base. The other design parameters represent the range of options typically used. Most homes in Adelaide apply dark colored roofing (a=0.9), followed by colors which achieve an absorptivity of 0.5 with only a small proportion applying light roofs (a=0.1). Although carpets were popular in the past, most homes today use tiles or timber as floor coverings in the living zone. These floor coverings are assumed throughout the house, even though carpets are often used in bedrooms.

All 1296 possible combinations of these variables were modelled with Accurate software. So the total population covers all configurations representing the range of likely star ratings.

Table II listed 10 best designs based on lowest operational energy. The operational energy is this table converted to primary energy and normalized for life time of 50 years. To find primary energy, annual heating energy was multiplying by heating conversion factor (1/1.75) and annual cooling energy also was multiplying by cooling conversion factor (1/1.4), then these two values were added to each other. These designs are dominated, by double glazed windows, foil insulation, high levels of bulk insulation, ceramic floor tiles and a range of roof colors. Although 3 out of the 10 designs apply a dark colored roof, the use of foil and ceramic floors confirm the importance of designing for reducing cooling demand.

TABLE I
VARIABLES CONSIDERED IN THE CURRENT STUDY

Type of glazing • Single glazed clear • Single glazed low_e • Double glazed clear • Double glazed low_e External wall insulation • R1.0 • R2.5 • R4.0 Solar absorptance of roof • 0.9 • 0.5 • 0.1 Roof space • No foil • Foil	Internal wall insulation • R0.16 • R1.0 • R2.0 Ceiling insulation • R1.0 • R4.0 • R6.0 Floor covering • Timber • Ceramic tiles

Low _e = low emissivity

C. Embodied Energy Database

For calculating embodied energy in this study, all main construction materials were identified and quantified. These values were multiplied by embodied energy values taken from the Inventory of Carbon and Energy (ICE) data base which was collected by the Sustainable Energy Research Team (SERT) at department of mechanical engineering of university of Bath, UK in 2008 [9].

Four different types of insulation materials were studied in embodied energy section to investigate the impact of this factor. These four materials were: fiberglass, mineral wool, polystyrene and polyurethane. Tables III and IV presents embodied energy of each material.

III. RESULTS AND CONCLUSIONS

Fig. 2 presents the life cycle energy (LCE) as a function of the operational energy of all designs considered. For an operational energy of 900,000 MJ, consistent with 4 star rated homes, the embodied energy on average represents 30% of the LCE, and the variation in LCE with different materials is around 7%. For low energy homes, consistent with 7 stars and above, the operational energy is around 395,000 MJ. In this case the embodied energy on average represents 52% of the LCE for 7 stars and LCE can vary from 18% to 19.5%. This result clearly demonstrates that not only is the embodied energy significant for low energy homes, but design choices which are used to reduce operational energy have a significant impact on the embodied energy. Table V shows 10 best designs based on minimum life cycle energy designs across the entire population of choices. Firstly the result clearly shows that they all have fiberglass as an insulation material, being the insulation with the lowest embodied energy. Comparing to Table II, there are some noticeable changes.

The difference in the embodied energy in floor coverings is small, and therefore for both lists the floor coverings are the same. Although cooling loads are reduced with foil, however this impact is outweighed by the higher embodied energy and none of the lowest LCE designs include foil. As a result there are only 2 designs with dark colored roofing, as without foil dark colored roofing can significantly increase cooling loads. The levels of bulk insulation remain unchanged. However of most importance, the design with the lowest Life cycle energy is not the design with the lowest operational energy.

TABLE II
TEN BEST DESIGNS BASED ON MINIMUM OPERATIONAL ENERGY

Window type	Internal wall	External wall	Ceiling	Solar absorptance of the roof	Floor covering	Roof space	Primary operational energy (MJ) over 50 years	Ratio of heating to total primary operational energy
Double glazed low-e	R2.0	R4.0	R6.0	0.5	Ceramic tiles	foil	256,457	0.40
Double glazed low-e	R2.0	R4.0	R6.0	0.1	Ceramic tiles	foil	258,035	0.47
Double glazed low-e	R2.0	R4.0	R6.0	0.9	Ceramic tiles	foil	259,371	0.34
Double glazed low-e	R1.0	R4.0	R6.0	0.5	Ceramic tiles	foil	262,164	0.42
Double glazed low-e	R1.0	R4.0	R6.0	0.9	Ceramic tiles	foil	264,107	0.36
Double glazed low-e	R1.0	R4.0	R6.0	0.1	Ceramic tiles	foil	265,200	0.49
Double glazed low-e	R2.0	R4.0	R6.0	0.1	Ceramic tiles	no foil	269,085	0.49
Double glazed low-e	R2.0	R2.5	R6.0	0.5	Ceramic tiles	foil	269,935	0.42
Double glazed low-e	R2.0	R2.5	R6.0	0.1	Ceramic tiles	foil	270,178	0.40
Double glazed low-e	R2.0	R2.5	R6.0	0.9	Ceramic tiles	foil	270,664	0.36

TABLE III
EMBODIED ENERGY (MJ) / M2

Material	Foil	Timber	Ceramic	Single glazed glass/single glazed low-e	Double glazed glass/ double glazed low-e
Embodied energy(MJ)/m^2	110.16	93.6	108	181.89	303.15

TABLE IV
EMBODIED ENERGY (MJ) OF FOUR INSULATION MATERIALS / M2

Insulation materials	Embodied energy/m^2
Insulation- fibreglass R1	9.856
Insulation- fiberglass R2	12.32
Insulation- fiberglass R2.5	24.64
Insulation- fiberglass R4	39.424
Insulation- fiberglass R6	85.652
Insulation- mineral wool R1	37.184
Insulation- mineral wool R2	40.3712
Insulation- mineral wool R2.5	53.12
Insulation- mineral wool R4	80.7424
Insulation- mineral wool R6	143.424
Insulation - expanded polystyrene R1	148.848
Insulation - expanded polystyrene R2	161.6064
Insulation - expanded polystyrene R2.5	191.376
Insulation - expanded polystyrene R4	297.696
Insulation - expanded polystyrene R6	499.704
Insulation - polyurethane R1	34.608
Insulation - polyurethane R2	51.912
Insulation - polyurethane R2.5	69.216
Insulation - polyurethane R4	129.78
Insulation- polyurethane R6	173.04

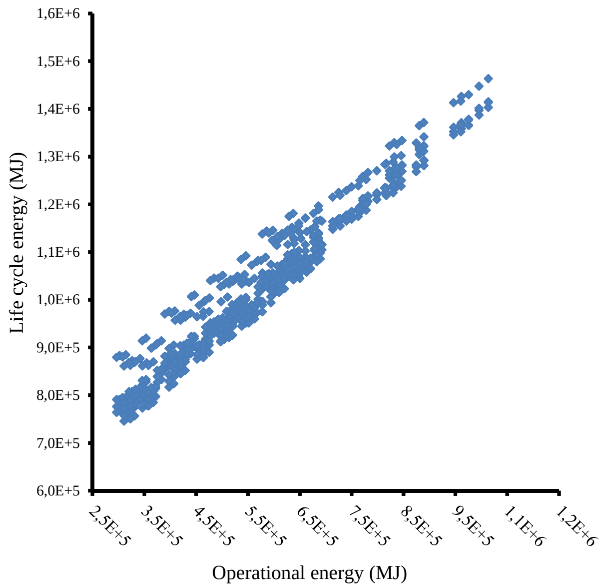

Fig. 2 Operational energy vs life cycle energy

TABLE V
TEN BEST DESIGNS BASED ON MINIMUM LIFE CYCLE ENERGY

Insulation materials	Window type	Internal wall	External wall	Ceiling	Solar absorptance of the roof	Floor covering	Roof space	Life cycle value	Embodied energy/ life cycle energy %	Stars
Fiberglass	Double glazed low-e	R2.0	R4.0	R6.0	0.1	Ceramic tiles	No foil	704,237.14	61.79	7.9
Fiberglass	Double glazed low-e	R2.0	R4.0	R6.0	0.5	Ceramic tiles	No foil	705,330.00	61.69	7.9
Fiberglass	Double glazed low-e	R1.0	R4.0	R6.0	0.1	Ceramic tiles	No foil	708,057.55	61.17	7.9
Fiberglass	Double glazed low-e	R1.0	R4.0	R6.0	0.5	Ceramic tiles	No foil	708,421.84	61.14	7.9
Fiberglass	Double glazed low-e	R2.0	R4.0	R6.0	0.9	Ceramic tiles	No foil	709,458.57	61.34	7.9
Fiberglass	Double glazed low-e	R2.0	R2.5	R6.0	0.5	Ceramic tiles	No foil	709,812.03	60.28	7.9
Fiberglass	Double glazed low-e	R2.0	R2.5	R6.0	0.1	Ceramic tiles	No foil	710,176.32	60.25	7.8
Fiberglass	Double glazed low-e	R1.0	R2.5	R6.0	0.5	Ceramic tiles	No foil	712,175.30	59.80	7.8
Fiberglass	Double glazed low-e	R1.0	R4.0	R6.0	0.9	Ceramic tiles	No foil	714,007.55	60.66	7.9
fiberglass	Double glazed low-e	R1.0	R2.5	R6.0	0.1	Ceramic tiles	No foil	715,696.73	59.50	7.8

IV. Conclusions

A life cycle assessment (LCA) study was completed on a large population of design choices which are generally used to reduce the operational energy associated with the heating and cooling needed for a building. The study focused on a single floor plan in a mixed climate requiring both heating and cooling. As expected, the importance of embodied energy increases with reduced operational energy. However, for typical low energy housing, embodied energy is the dominant factor in the LCA. Furthermore, the impact of design choices which impact on operational energy have equal of even more of an impact on embodied energy. Consequently, there is a need to incorporate LCA approaches to energy efficient building design to ensure that future buildings achieve the low energy objectives of current regulations.

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