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The impact of different insulation options on the life cycle energy demands of a hypothetical residential building.

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Abstract

Selecting materials that are energy efficient over their life cycle at the early stage of a design is dependent upon numerous parameters that make determination of all their impacts on the environment difficult. Choice of thermal insulation options for a building's external walls significantly affects its life cycle energy demands. However, the accurate impact analysis of different insulation options from a life cycle energy assessment (LCEA) viewpoint is influenced by numerous interrelated parameters and is generally too complex for designers to determine in the early material selection stage of design. The aim of this paper is to highlight this complexity by using the example of an evaluation of the LCEA of 18 different forms of thermal insulations that vary in type and thickness for a multi-storey residential building in Sydney, Australia. The sensitivity of the results to the Window to Wall Ratio (WWR), as an another effective variable on the building's operational energy demands, is then analysed.

The study indicates that different thermal insulation options of external walls have a marginal impact on the building cooling energy demands in Sydney's climatic zone, whereas they significantly affect the heating energy demands. In addition, changing of insulation options produce significant increases in the embodied energy. The impact of various WWRs on the building's operational energy changes the result of the optimum and the least efficient choices among the 18 insulation options.

Overall, the example highlights that it is not possible to quantify all the effective parameters in selecting materials in terms of designing an energy efficient building through its life cycle. This paper is part of a larger research project attempting to simplify the LCEA and enable designers to identify the most effective variables on a building's life cycle energy demand when selecting materials at the early design stage.

Keywords: Type your keywords here, separated by semicolons ;

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1. Introduction

Together the construction and operation of buildings are responsible for significant energy consumption and consequential generation of greenhouse gas (GHG) emissions. Existing buildings consume more than 40% of the world's total primary energy and account for 24% of global carbon dioxide (CO_2) emissions [1].The residential sector is the most energy-intensive, consuming about 60% of the overall energy used by the buildings [2]. Moreover, building envelopes are known to be responsible for more than 50% of the embodied energy contribution in residential buildings [3]. Envelope related energy demand is determined based on the assumption that heat transfers by thermal transmission through the building envelope and solar gains. Most of the envelope-related parameters have an influence on the thermal balance in residential buildings. Results show that there is a strong correlation between envelope related energy demand and the operational energy demands of buildings [4]. Hence, the operational energy reduction requires the use of materials or layers of materials in the construction of the building envelope that have low thermal conductivity and significant heat capacity, [5] and thermal insulation and window systems are the most effective parameters impacting operational energy. Because these materials may negatively affect the total life cycle energy demand of a building by increasing the embodied energy, if designers are to minimise the life cycle energy demands they need to understand the individual impact of each variable on energy performance as well as the dependencies between them in order to select appropriate materials/systems at the early design stages. However, because of the complexities of determining environmental impact and uncertainty about the later stages of a buildings lifespan, introducing an energy efficient design approach that takes into consideration every stage of building's life cycle in order to reduce energy consumption is rarely focussed upon by designers at the building's material selection stage.

This paper highlights the complexity of life cycle assessment in terms of selecting materials for the life cycle energy efficient buildings by analysing the effective variables on the building thermal performance. This study investigates the role of different thermal insulation options for external walls and quantifies them in terms of the operational energy (heating and cooling), and the embodied energy (EE) in a hypothetical multi-story residential building in Sydney, Australia. The sensitivity of the building's life cycle energy demands is analysed by applying 18 different insulation options varying in type and thickness. Window to Wall Ratio (WWR) is also considered as another effective variable on the building thermal performance with the aim of highlighting that how the effective parameters on the building's energy performance. are interrelated and need to be analysed from different points of view at the early design stages.

2. Background

There is a growing body of literature comparing the energy and consequential carbon embodied in buildings employing different construction systems and alternative materials. Reducing the energy demand and CO_2 emissions attributed to buildings is an important goal for government climate policy [6], as building construction and occupation is a significant contributor of global CO_2 emissions, being responsible for almost a quarter of total global CO_2 emissions attributable to the energy use in buildings [7].

Consideration of building life cycle energy analysis helps develop strategies for reducing buildings' primary energy use and controlling emissions [8]. Reducing the operational energy by increasing use of materials, especially energy intensive materials, has been challenged by studies demonstrating that it may inadvertently increase embodied energy [9].

The significant impact of facade design on a building's energy performance has been shown by several studies considering various influential parameters, e.g.[4; 5; 10-13] . These studies highlighted that building envelope design is considered one of the typical energy-saving areas of focus. Moreover, building designers can play an influential role in minimizing buildings' environmental impact by making the appropriate design decisions in regard to selection and integration of buildings' envelope components at the early stage of the design. Thermal insulation materials and window systems have a significant role in providing indoor environmental quality and achieving energy efficiency from a life cycle point of view, as the building envelope represents approximately 50-60% of the total heat gain in buildings and building envelope materials contribute significantly to the life cycle energy consumption by influencing the cooling load in larger buildings [14; 15].

The increase in near-zero energy buildings has encouraged designers to use passive solutions for the envelope and use increasing insulation thickness in buildings all over the world. Consequently, the contribution of these materials to the life cycle environmental impact of buildings is of growing significance [16].

The level of complexity and certainty/uncertainty is different in each phase of life cycle assessment. A study on the life cycle environmental impact of a limited number of façade materials on a multi-storey residential building illustrated the changing degree of certainty and the need to rely on both quantitative and qualitative analysis methods during different phases [17].

3. Research design

This study applies qualitative and quantitative analysis to highlight the complexity of the life cycle energy assessment of a residential building façade, concentrating on the building's thermal performance. It examines the effect of changing the insulation layer's options and WWRs. A range of six common insulation materials — Glass Fibre, Expanded Polystyrene (EPS) foam slab (40% and 100% recycled), Cellulose Fibre, Rock Wool and, Extruded Polystyrene (XPS) — is analysed to determine the impact of material selection on a multi-storey residential building's life cycle energy demands.

3.1. Definition of a hypothetical building as a case study in Sydney

This study takes a four storey residential building in Sydney (33°52.071′ S, 151°12.4392′ E) with an assumed 50-year life span as a hypothetical case study building. The building shape is rectangular (long axis east-west) with a total floor area of 3135 m2. At the ground floor, one unit is substituted by an office. Overall the building includes 31 residential units, 1 office, corridors and vertical distribution zones. For the purpose of this paper a hypothetical façade system consisting of the following materials remained unchanged in the analyses: Cement-bonded particle board, timber stud, Gypsum plasterboard, paint. The insulation between the cement bonded particleboard and the gypsum plasterboard was varied both in terms of type (6 types described above) and thickness (30, 60, 90mm), giving 18 permutations in total. Timber framed/double glazed units (clear glass-3mm/6mm air) are employed for the case study windows as they are considered an energy efficient window system for a residential building in Sydney [18]. WWR of 40% has been applied for the base case.

3.2. Life Cycle Energy Assessment (LCEA)

Building life cycle energy demands are affected by various direct and indirect parameters. Direct contributors include construction, operation, renovation and demolition, while indirect contributors include the production of materials used in construction and technical installations [9]. The life cycle energy impact of various thermal insulation types and thicknesses was analysed in this study by quantifying their embodied energy and, the building's operational energy used for operating heating and cooling systems in order to maintain indoor comfort conditions.

3.3. Operational Energy (OPE)

A building's facade design affects heating and cooling energy demands as it is the main area where thermal losses and gains occur [10]. The thermal properties of the reference building were modelled in DesignBuilder. The initial model was selected from a Department of Energy (DOE) reference building of mid-rise residential apartments in the USA. Configurations of the model were changed for Sydney's climatic location. All settings for construction, lighting and HVAC configurations were inherited from the DOE. Configurations were set to be compliant with the building code of Australia [19], in particular deemed-to-satisfy provisions. Heating and cooling are based on gas and electricity respectively. All internal load schedules were changed accordingly based on Nationwide House Energy

Rating Scheme [20]. The optimized window system was a double glazed unit with timber frame. The final model is fully described in the previous research by this author [18].

3.4. Embodied Energy (EE)

Embodied energy includes: the initial embodied energy which is the total energy used to transform raw materials into ready to use building products; the recurrent embodied energy, which is the energy required for the substitution and maintenance of components and materials; and the disposal energy, which is the energy used for demolition and disposal of materials or possible reuse or recycling after the building's useful life. Crowther showed that the amount of energy required for the disposal phase is extremely low in comparison with the energy demand of a building during its whole life cycle, and it is less than 1% of total embodied energy [21]. SimaPro 8.2.0 (Australian database- AusLCI unit processes) is used in this study to quantify the initial embodied energy. The software databases include a variety of parameters such as construction materials, transportation, installation and waste treatment. The cumulative energy demand (version 2.02) method used to quantify the embodied energy is analysed by ACLAs best practice LCIA Recommendation (version 2.0). The constant parameters were defined for each material and all input from the techno sphere (materials and fuels) are described based on AusLCI unit process records. The impact of employing various insulation types and thicknesses on the building's EE are comparatively analysed based on the following assumptions: there is no replacement required the for insulation layer as they are a weather protected layer and the service life of insulation materials are mostly more than 50 years (which is the assumed building service life); the disposal energy is considered 1% of initial EE; all other transportation and installation processes are considered constants in this analysis, not affecting comparative results for the purposes of this study.

4. Results and Discussion

The impact of testing six common insulation materials with three different thicknesses (30, 60 and 90 mm) for the operational energy and the embodied energy of a residential building has been evaluated. Table 1 shows the result of EE of each insulation option. The effect of employing various insulation options on the building heating and cooling energy demands is compared in Fig 1. It is evident that choice of insulation layers does not have any significant effect on the cooling energy demands in Sydney climatic zone; differences are less than 2%. However, the choice of insulation has a significant effect on heating energy demand of about 43%. In terms of EE, the various insulation types and thicknesses have a significant affect (Fig 2). Comparing Fig 1 and Fig 2 shows that the pattern of change in heating energy is similar in all insulation types and it decreases significantly by increasing the insulation thickness from 30mm to 90mm. However, choice of insulation types is responsible for significant changes in the amount of EE. For instance, EE of different insulation options for the building's external walls increases from 9.40 GJ for EPS(100%recycled)/30mm to 281.03 GJ for XPS/90mm.

WWR is an another variable that may significantly affect the energy efficiency of the building's façade. As window materials (e.g. energy efficient glass) are very energy intensive to manufacture, increasing the ratio of transparent parts of the façade dramatically increases the façade EE. The choice of window to wall ratio has also a significant influence on the buildings' heating and cooling energy demands. However, the influence would vary in different climates.

Table 2 illustrates how heating and cooling energy demands in the case study building change under the influence of different WWR for the various insulation options. Examination of the data shows that the cooling energy dramatically increases when WWR is changed from 20% to 80% and the increase always follows the same pattern for all insulation options. While choice of WWR has insignificant impact on the heating energy, the change does not follow any specific pattern for cooling energy. Table 3. The best and worst choice of external walls' insulation options shows the best and worst choices of external wall insulation options (among the 18 options for this study) for a residential building in Sydney/Australia in terms of their impact on heating and cooling energy demand, EE and, the total energy demands for EE and OPE of the building's external walls.

Table 1. Embodied energy of thermal insulation layers.

Insulation materials	Density (Kg/m^3)	U-Value (W/m-k)	EE (MJ/m^2)
Glass fibre	14	0.04	
30mm			19.09
60mm			38.08
90mm			57.17
EPS (100% recycled)	28	0.036	
30mm			9.97
60mm			19.90
90mm			26.87
Cellulose	28	0.036	
30mm			12.83
60mm			25.55
90mm			38.38
Rock wool	28	0.036	
30mm			49.09
60mm			98.07
90mm			147.46
EXP	35	0.03	
30mm			99.38
60mm			198.97
90mm			297.95
EPS (45% recycled)	28	0.036	
30mm			50.70
60mm			101
90mm			152.51

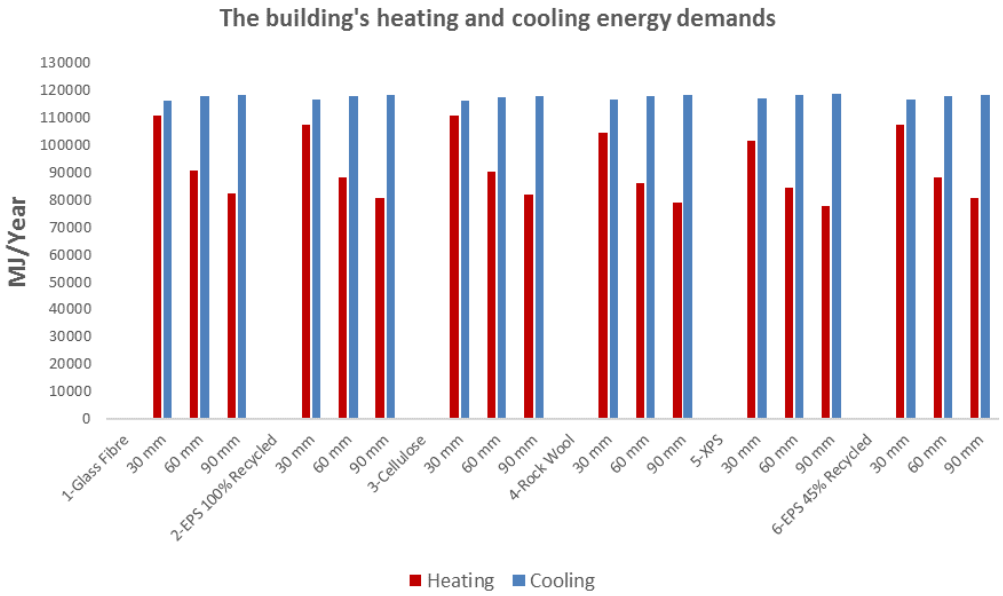

Fig 1. Impact of applying different insulation options on the building's heating and cooling energy demands.

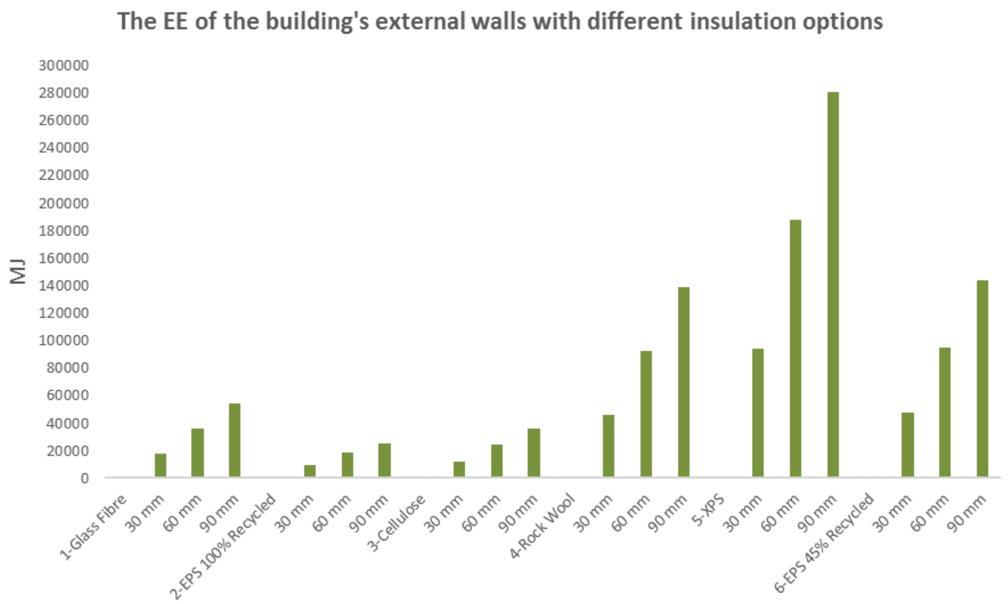

Fig 2. Embodied Energy of the building's external walls with different insulation options.

Table 2. Comparison of the building's heating/cooling energy demands with different insulation options and WWR.

	Heating (MJ/m²)				Cooling(MJ/m²)			
WWR	20%	40%	60%	80%	20%	40%	60%	80%
1-Glass Fibre								
30 mm	40.96	35.33	33.95	30.72	18.51	37.08	58.23	79.74
60 mm	31.67	28.90	29.79	31.69	18.43	37.49	58.75	79.69
90 mm	27.87	26.25	28.03	30.72	18.45	37.69	58.94	79.74
2-EPS 100% Recycled								
30 mm	39.30	34.18	33.20	33.50	18.48	37.13	58.32	79.46
60 mm	30.56	28.12	29.27	31.42	18.43	37.54	58.82	79.74
90 mm	27.01	25.64	27.89	30.53	18.44	37.70	58.94	79.76
3-Cellulose								
30 mm	40.89	35.28	33.90	33.85	18.49	37.05	58.21	79.38
60 mm	31.54	28.79	29.67	31.64	18.39	37.44	58.70	79.66
90 mm	27.66	26.07	27.89	30.00	18.37	37.59	59.17	79.69
4-Rock Wool								
30 mm	37.97	33.26	32.61	33.20	18.45	37.18	58.39	79.52
60 mm	29.67	27.49	28.86	31.20	18.42	37.56	58.85	79.76
90 mm	26.30	25.11	27.27	30.32	18.41	37.69	58.97	79.76
5-XPS								
30 mm	36.67	32.36	32.04	32.90	18.45	37.26	58.49	79.59
60 mm	30.49	26.96	28.52	31.03	18.45	37.65	58.94	79.82
90 mm	25.78	24.78	27.06	30.20	18.47	37.79	59.06	79.82
6-EPS 45% Recycled								
30 mm	39.30	34.18	33.20	33.50	18.48	37.13	58.32	79.46
60 mm	30.56	28.12	29.27	31.42	18.43	37.54	58.82	79.74
90 mm	27.01	25.64	27.89	30.53	18.44	37.70	58.94	79.76

Table 3. The best and worst choice of external walls' insulation options

WWR	Heating		Cooling		IEE		OPE + IEE	
	Best	Worst	Best	Worst	Best	Worst	Best	Worst
20%	XPS 90mm	Glass fibre 30mm	Cellulose 90mm	Glass fibre 30mm	EPS 30mm	XPS 90mm	EPS 90mm	XPS 90mm
40%	XPS 90mm	Glass fibre 30mm	Cellulose 30mm	XPS 90mm	EPS 30mm	XPS 90mm	EPS 90mm	Glass fibre 30mm
60%	XPS 90mm	Glass fibre 30mm	Cellulose 30mm	EPS 30mm	EPS 30mm	XPS 90mm	Rockwool 90mm	Glass fibre 30mm
80%	Cellulose 90mm	Cellulose 30mm	Cellulose 30mm	XPS 90mm	EPS 30mm	XPS 90mm	EPS 30mm	XPS 90mm

(EPS is the 100% recycled one)

5. Conclusions

The aim of this study was to draw attention to the fact that the consideration of all effective variables on the building's life cycle energy demands is very complicated for designers to comprehend at the early design stages. The analyses demonstrated that a relatively small change such as varying the quantum and type of wall build-up had a significant effect on the life cycle energy demands associated with a multi-storey residential building in Sydney, Australia. A parametric analysis was carried out to define the sensitivity of these indicators to six common insulation types with three different thicknesses (30mm,60mm and 90mm) for each. In total, 18 different options were calculated. All the analyses involved the use of DesignBuilder and SimaPro software for the calculation of the operational and the embodied energy respectively. The impact of different window to wall ratios was also shown to significantly affect the building's heating and cooling energy.

Studying the heating and cooling energy of the hypothetical case study employing different insulation options on their external walls indicated that the impact of changing insulation options is different for heating and cooling energy demand. For this temperate climate study, the choice of different insulation options applied to a residential building's external walls significantly affected heating energy demands while it had insignificant influence on the cooling energy.

Changing insulation options had significant impact on the EE related to the residential building's external walls. The results identified a difference of 138% between employing EPS/30mm (the least efficient) and XPS/90mm (the optimum among the 18 analysed options).

Applying different window to wall ratio of 20%, 30%, 40% and 80% for the case study building shows cooling energy is more sensitive to this variable compared to heating energy. Increasing WWR from 20% to 80% caused significant increase in cooling energy while, in total, it had an insignificant effect on the heating energy. The study indicates that the impact of the material selection and material distribution in terms of WWR for a building façade is different for the heating, cooling and the embodied energy demands of a building.

Overall, the material selection at the early design stages is dependent upon several parameters whose impact on the building's life cycle energy demands could not be easily quantified by designers. Minimising the impact of some types of materials such as thermal insulation on the building's energy demands needs more attention due to considering the effect of several interrelated parameters. It should be noted that changing in location/climate and service life of the building significantly affect the building's LCEA.

To achieve environmentally conscious solutions, it is important for designers to shift from focusing on operational impacts to a fuller consideration of life cycle environmental impacts at the early design stages. Designers should be made aware of the level of complexity in each LCEA phase. This small study has illustrated that designers need to rely on both quantitative and qualitative analysis methods to comprehensively assess all effective parameters for selecting the building's materials with the aim of minimising the building's life cycle energy demands.

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