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Evaluating the Significance of Recurrent Embodied Energy in Life Cycle Embodied Energy of Residential Buildings

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Abstract

This study discusses the obvious gap in the Life Cycle Energy Assessment literature. Much of it only focuses on initial embodied energy and pays little or no attention to recurring embodied energy. This paper presents a study on embodied energy analysis considering both the initial and recurring embodied energy in typical linked double-storey terraced houses over a 50 years' building service life. The findings from the study provide insights into embodied energy and the significance of recurring embodied energy in contributing towards the building energy demand. The embodied energy of the houses ranged from 8.05 to 9.85GJ/m^2, with an average of 8.95 GJ/m^2 while, the recurrent embodied energy ranged from 2.37 to 3.49 GJ/m^2 with an average of 2.93 GJ/m^2. The average recurrent embodied energy equates to 33% of total embodied energy, and this component can significantly influence the life cycle of embodied energy. The study also identifies building materials that can significantly reduce the embodied energy demand.

Disciplinary: Architecture, Energy & Sustainability.

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1 Introduction

Present-day buildings account for almost 40% of the world's total primary energy consumption and 24% of the CO_2 emissions (WEO, 2019). In 2016, the Malaysian construction sector recorded moderate growth at 7.4% (CIDB Malaysia, 2017). The rapid rate of urbanisation has increased the demand for housing and energy and is a major factor in global warming. Urbanisation and the associated infrastructure will impact the environment by consuming building materials and energy (Rauf & Crawford, 2014). The building materials for the construction and operation of these buildings are derived from primary energy (oil, natural gas or coal) and secondary energy (electricity), and the embodied energy alone could account for a substantial amount of a building's carbon footprint throughout its lifecycle (Vukotic et al., 2015). Thus, the EE is significant from a lifecycle perspective, and there are a substantial amount of studies conducted to evaluate the EE in residential buildings; however, most of these studies concentrates on the assessment of the initial embodied energy (EE_i) (Crawford, 2013; Rauf & Crawford, 2013; Treloar et al., 2000) whilst, assuming the recurring embodied energy (EE_r) as insignificant.

Though EE contributes merely 10–20% to life cycle energy, the opportunity for its reduction should not be disregarded (Ramesh et al., 2012). Similarly, most studies in Malaysia focus on the impact assessment of various building materials and the advantages of integrating industrialised building systems (IBS) to conventional construction systems (Treloar et al., 2000). Relatively, fewer studies have been conducted to analyse the EE_r that occurs due to maintenance and refurbishment activities throughout the service life (Rauf & Crawford, 2013). Mari (2007) conducted a study on the initial EE (EE_{mi}) of five types of terraced houses; however, the study had limitations; it only considered the initial EE (EE_{mi}) of materials. A limited number of studies have reported on EE_r (Treloar et al., 2000); nevertheless, the significance of EE_r is still less understood and analysed. Therefore, the significance of EE_r in EE during a building's life span should be further investigated. This study aims to

- estimate the EE for the main building materials, including the EE_r and the construction energy (E_c) that used in the construction of terraced link houses
- identify and rank building materials studied from the EE perspective
- to evaluate building materials with significant potential for reduction in EE demand

2 Literature Review

Treloar et al. (2000) has stated that EE_r related to building material or component replacement and periodic maintenance can represent up to 32% of its EE_i. Whilst Crawford (2013) stated that the amount of EE_r is affected by the service life of individual building materials and the frequency of maintenance. Crawford (2013) analysed a house in Melbourne, reported a figure of 2319GJ (8GJ/m^2) as the EE_r associated with maintenance and refurbishment over the 50-year life of the house. This figure equates to 60% of EE_i; it is comparatively higher than the 32% figure suggested in Treoloar et al. (2000), and the total life cycle EE of the house was 6210GJ (or 21.3GJ/m^2). Thormark (2006) reported the total of EE_{mi} and EE_r for 50 years for 20 apartments of 3 different designs ranging between 6.1-7.6GJ/m^2; however, this figure did not include the E_c. A Brazilian study, Paulsen and Sposto (2013) stated an EE of 7.2GJ/m^2 with the EE_r component at 50% of the EE_i. Contrasting to before mentioned studies, a study on residential buildings in India by Ramesh et al. (2012) stated that the EE_r component accounted for only 9% of the EE_i. Ezema (2015) reported an EE_r of 46.5% of the 7.38GJ/m^2 of EE for a Nigerian multistory residential building.

Buchanan and Honey (1994) suggested a figure of 2.32-5.53GJ/m^2 for a 94m^2 house, whilst Debnath et al. (1995) studied load-bearing houses with 1 and 2 storeys and a four-story RC frame structure conveyed an EE$_i$ of 3-5GJ/m^2. Monahan and Powell (2011) compared the embodied carbon of a low energy residential building in the UK, reported the EE$_i$ figure of 5.7-8.2GJ/m^2. Reddy and Jagadish (2003) examined EE of typical conventional urban houses with RC frame structure, and masonry infill walls reported the EE$_i$ within the range of 3.8-4.2 GJ/m^2 (excluding E$_c$). Hammond and Jones (2008) stated the average EE of the 14 real-world case studies houses in the UK to be 5340 MJ/m^2. The literature clearly describes the significance of EE, EE$_i$ and EE$_r$ to the energy profile of a building; thus, the study explores the significance of EE$_i$ and EE$_r$ in typical local houses.

3 Method

The chosen houses are of double-storey link terraced intermediate units located at Klang Valley. These houses are typical urban examples with four bedrooms and three bathrooms, with a gross floor area (GFA) of 130-150m^2. Built-up areas of the chosen houses (H1 and H2) are 137m^2 and 145m^{2,} respectively. These houses were constructed meeting specifications, standards and quality approved by the local authorities in 2010.

3.1 Method of Analysis

The EE$_i$ and EE$_r$ demand of the two houses was quantified for a service life of 50 years. The common materials included in the scope of the embodied energy analysis are listed in Table I. The EE analysis included all building materials and components essential for constructing the houses, excluding fences, landscapes, driveway and paths, furniture and other loose household objects. The analysis did not include any white goods and furniture that may be fitted to the houses (e.g., stove, dishwasher, air-conditioner, microwaves, toasters, etc.). The number of building materials was extracted from the bill of quantities provided by the quantity surveyor. A model by Ramesh et al. (2010) was used in determining the EE for the case study houses. The calculation of the EE were done using Excel spreadsheet. The total EE calculated in the study is divided into two main parts. They are the EE$_i$ inclusive of the energy required for construction and installation of building components during the construction phase (E$_c$) and the EE$_r$ that occurs due to replacement and maintenance of building materials or components during the use phase of the houses.

Table 1: Common building materials, which characterise the houses.

Building Component	Construction Materials	
	House H1	House H2
Structure	RC Concrete 25	RC Concrete 25
Formwork	Plywood	Plywood
Door panels	Timber with paint	Plywood with paint
Wall Int. and Ext.	Clay and Cement sand	Clay and Cement sand
Wall finishes	Plaster, Paint and Ceramics	Plaster, Paint and Ceramics
Floor finishes	Marble and Ceramic	Ceramic tiles
Glazing	4mm clear float glass.	4mm clear float
Roof Truss	Timber	Timber
Roof Covering	Concrete Roof tiles	Concrete Roof tiles
Doors frames	Timber	Timber
Windows frames	Extruded aluminium	Extruded aluminium

3.1.1 Initial Embodied Energy (EEi)

The EE_i of a building is the sum of the EE of all building materials used in its construction. The EE_i that occurs during the material manufacturing and production and on-site construction life cycle stages is influenced by material embodied energy coefficient (ECmi), material mass (Qmi), transportation distance, construction methods, and application context. Process-based analysis was employed to calculate the EE associated with the construction of the houses. Delivered quantities of building materials (Q_{mi}) used for the construction of the houses were multiplied with the EC_{mi} of the respective materials, obtained from the construction materials database from India Construction Materials Database (EDGE Buildings, 2019) and CE (2019), where the EC_{mi} were determined based on the cradle to gate production processes as the local EC_{mi} of materials is yet to be established. However, the study is limited to major building materials that have the most effect on the construction. An existing model by Ramesh et al. (2010) was employed to calculate the EE_i is expressed as

$$EEi = \sum Qmi\ ECmi + Ec \qquad (1).$$

3.1.2 Construction Energy (E_c)

The E_c is the energy needed for the erection of the building and its components involving a range of processes and activities, for instance, drying, lighting of sheds and of the building itself, electricity for machinery, etc. Past investigations have documented a figure of 7-10% of the EE_i of a building for the energy used during the construction process (Cole, 1999). Bardhan (2011) reported an average figure of $0.2GJ/m^2$ as construction associated energy based on a study conducted on a construction site using the "top-down and bottom-up method". According to the author, started using a top-down approach, the computed energy for building construction was about $0.22GJ/m^2$, while the bottom-up approach was $0.18GJ/m^2$, suggesting an average figure of $0.2GJ/m^2$ as the energy consumed during the construction phase. The energy data about the various construction processes and activities were collated from Adalberth (1997). Manual energy (labour) involved in the repair or maintenance work is not considered in the study. Therefore, calculated E_c using the energy data for the construction activities and processes is $0.18GJ/m^2$ and $0.20GJ/m^2$ for the house for H1 and H2, respectively. Therefore, the average value of E_c for the study is $0.19GJ/m^2$, which is comparable to the average energy reported by Bardhan (2011). However, the average E_c for the case study houses is only 3.3% of the EE_i, which is lesser than the 7-10% (Cole, 1998). The reason for this is that local Ec calculation does not include heating required for sheds and construction objects due to the difference in the climatic zones.

3.1.3 Recurrent Embodied Energy (EE_r)

EE_r is the sum of the embodied energy of building materials used to maintain and replace worn-out building materials and components and rehabilitate a building over its service life. The EE_r depends on a building's service life (Chen, Burnett, & Chau, 2001). Additionally, individual building materials and components hold different service life, affecting the amount of EE_r of a building (Chau et al., 2007). The building's operational or use phase includes building operation, repair, replacement, and maintenance activities, which consume energy and resources (Dixit et al., 2014a, 2014b). These activities use building materials and include energy-demanding construction processes (Utama & Gheewala, 2009). These activities or processes contribute to the EE_r (Chen et al., 2001; Ding, 2007). The EE_r of a material is highly influenced by several factors: its service life, replacement factor, and nature and frequency of maintenance. The EE_r was estimated considering the number of times each material would possibly be replaced throughout the useful life of the building (Rauf & Crawford, 2013). The EE_r was computed using replacement factors (Rf) for materials or components. The sum of the EE_r can be expressed as:

$$EE_r = Q_{mi}\ EC_{mi}\ [(Sl_h / Sl_{mi}) - 1] \qquad (2),$$

where EE_r is the recurrent embodied energy of the house, in GJ; Sl_h is the service life of the house (50 years); Sl_{mi} is the service life of the building material, m; Q_{mi} is the number of materials delivered, m; EC_{mi} is the embodied energy coefficient of the material, m; Sl_h / Sl_{mi} is the replacement factor of building materials and components over a buildings life span. One is subtracted from the equation representing the first time the materials was used in the construction.

3.1.4 Service Life of Building Materials (Sl_{mi}) and Building Service Life (Sl_h)

Service life refers to the period after completion of construction during which a building or its components meet or exceed performance requirements (Kotaji et al., 2003).

Table 2: Common building materials, which characterise the houses.

Building Components/Materials	The service life of building materials and components			
	min	max	average	assumed
Concrete roof tiles	30	life time	40	30
Bricks		life time, 100+		50
Water-based paint	5	15	10	5
Solvent-based paint				5
Aluminum frame	15	40, 20	25	25
Timber	15	25	20	20
Plaster	30	50	20	30
Timber roof truss		life time		50
Marble			100+	50
Ceramic tile	75	100		50
Concrete Systems	lifetime			50
Window Glazing			10+	10
Door (plywood)			15	15

Building Components/Materials	The service life of building materials and components			
	min	max	average	assumed
Concrete roof tiles	30	life time	40	30
Bricks		life time, 100+		50
Water-based paint	5	15	10	5
Solvent-based paint				5
Aluminum frame	15	40, 20	25	25
Timber	15	25	20	20
Plaster	30	50	20	30
Timber roof truss		life time		50
Marble			100+	50
Ceramic tile	75	100		50
Concrete Systems	lifetime			50
Window Glazing			10+	10
Door (plywood)			15	15

Service life is often predicted from recorded performance over time or can be obtained from manufacturers. The Sl_{mi} influences the number of times a material will be replaced over the life of a building. Therefore, the lower the Sl_{mi}, the larger the number of building materials required for replacements and maintenances, the greater the EEr throughout the building's life.

The analysis period chosen for this study is 50 years, and it does not suggest that the houses would be unfit for further use after 50 years. Therefore, the average life span of the case study houses is assumed as 50 years based on earlier studies on energy consumption in buildings (Crawford, 2012; Reddy & Jagadish, 2003). This figure was then used to determine the replacement factors (Rf) of the materials. The average Sl_{mi} was derived from Rauf and Crawford (2013), Ding (2004), and Roofkey (2019), see Table 2.

3.1.5 Replacement Factor (Rf)

A replacement factor is the ratio of service life of a building or facility to the average service life of a building material or component", which is essential in assessing the amount of EE_r (Chen et al., 2001: Chau et al., 20017). The Rf provides a means to compare the durability of the building materials. In addition, it is an indication of the "number of times (including the first installation) that resource input is needed for installation of the material or component within $Sl_{h"}$ (Chau, 2007). The collated SL_{mi} was used to estimate the Rf, which is then used to calculate the EE_r associated with replacing materials over its life (see Table 3). The Rf of each of the materials or components was determined by

$$Rf = Sl_h / Sl_{mi} \quad (3).$$

Table 3: Common building materials characterising the houses.

Building Components/Materials	Calculated Rf	Building Components/Materials	Calculated Rf
Concrete roof tiles	1	Timber roof truss	0
Bricks	0	Marble	0
Water based paint	9	Ceramic tile	0
Solvent based paint	9	Poured-Concrete	0
Extruded Aluminium	1	Window Glazing	4
Timber door panels	2	Door (plywood)	2
Plaster	1		

3.1.6 Embodied Energy (EE)

EE of a building is the locked up energy of all the building materials utilised in the building and initial installations (EE_i), energy consumed for the erection and installation of building materials and components, (E_c) and energy incurred for the materials and components that are used for repairs, replacements, and maintenances of the building (EE_r). The model to analyse EE in this case study is adapted from Ramesh (2010) expressed as

$$EE = \sum EE_{mi} + E_c + \sum EE_r \quad (4).$$

4 Result and Discussion

4.1 Initial Embodied Energy (EE_i)

The total calculated EE_i associated with the initial construction of the houses was 778.11GJ and 922.15GJ for houses H1 and H2, respectively. On a per square meter basis, the EE_i figures are 5.68GJ/m^2 and 6.36GJ/m^2. These figures compare closely with a previous Malaysian study by Mari (2007), which reported EE_i that ranged between 4.12GJ/m^2 and 5.38GJ/m^2, which is a little lesser as the E_c was not included in the calculation. The study findings are also closely comparable with findings by Monahan and Powell (2011). An Indian study by Reddy and Jagadish (2003) reported the EE_i within the range of 3.8–4.25GJ/m^2, comparable yet lesser than the figure in this study as it did not include the E_c. The EE_i figures from this study conform to findings by Hammond and Jones (2008), which reported the average EE of 5340MJ/m^2.

On a material or component basis, the extruded aluminium used for window frames represents the greatest share of the EE_{mi} of the houses (28.26%). Despite this material being limited for the window frames, the EE_{mi} is large due to its high EC_{mi}. The current trend to use aluminium for doors and windows frames can significantly affect the energy input into a building (Reddy & Jagadish, 2003). The findings also correspond with findings by Mari (2007), which suggests timber as an energy-efficient substitute for aluminium. The subsequent significant EE_{mi} demand ranges from 9.67% to 11.11% for building materials, including cement sand bricks, reinforcement, timber truss, and concrete. These materials make up most of the structure of the houses and are large in quantity, though the EC_{mi} for these materials is much lower than EC_{mi} for extruded aluminium. The total EE_{mi} of the materials used for the structural components of the houses is 54.8%.

4.2 Recurring Embodied Energy (EE_r)

The structural materials of H1 and H2 represent the largest components of the EE_{mi}, 63% and 48%, respectively, but do not contribute to EE_r. Meanwhile, the finishing materials of HI and H2 demand lesser EE_{mi} of 37% and 52%, respectively; however, these materials or components are the core contributor to the EE_r. The EE_r of materials used for the structure of the houses is zero as the structural components are assumed to last as long as the houses. The EE_r over the 50-year life of both the houses was found to be 324.95GJ (2.37GJ/m^2) and 505.74GJ (3.49GJ/m^2), the average EEr of both H1 and H2 is 415.35GJ (2.93GJ/m^2), respectively. This figure equates to 33% of the total EE figure, which compares closely to the 32% figure reported by Treloar et al. (2000); however, it is much lesser than the 60% figure suggested by Crawford (2013). The use of input causes this significant difference–output-based hybrid embodied energy assessment approach Crawford's study. The EE_r figure of 33% in the study is also lower than the reported EE_r figure in Paulsen and Sposto (2013) and Ezema (2015). Conversely, it is higher than the reported EE_r in the Indian study (Ramesh et al., 2012).

On the material basis, the extruded aluminium represent the highest proportion of EE_r of the houses (56.45%), followed by the concrete roof tiles (18.7%). Despite being replaced only once within the 50 years lifetime, the EE_r of both these materials is high due to the high EC_{mi} of aluminium and many concrete roof tiles. This shows that poor selection materials with lower quality and high-energy intensity influence the recurring energy tremendously. Next, paint contributes 11.47% to the total EE_r figure. This is mostly due to the frequent replacement of wall paint (every five years). This proportion of EE_r can be reduced significantly if the frequency of repainting the walls is reduced. For instance, the other materials, wall plaster, door panels (plywood and timber), and glass for door and window represent 13.3% of EE_r. Findings from the study show that the EE_r component is significant to the total EE profile of the houses. The study reveals that EE_r of common building materials utilised in typical terraced houses is significant, 33% of total EE. The EE_r component is higher in this study than in previous studies (Ramesh et al., 2012) due to the frequent replacement and maintenance rate of lower quality and durability of building materials. Another factor contributing to this is the specification of materials with EC_{mi} by designers due to cost factors. This suggests that the EE_r component is significant in the life cycle embodied energy demand, and designers must give attention to reducing the EE_r of buildings by exploring alternatives, particularly in selecting the building materials during the design stages

4.3 Total Embodied Energy (EE)

The total EE demand associated with the case study houses is 1,103.06GJ (8.05GJ/m^2) and 1,427.89MJ (9.85GJ/m^2). The calculated average EE for the study is 1,265.47MJ (8.95GJ/m^2).

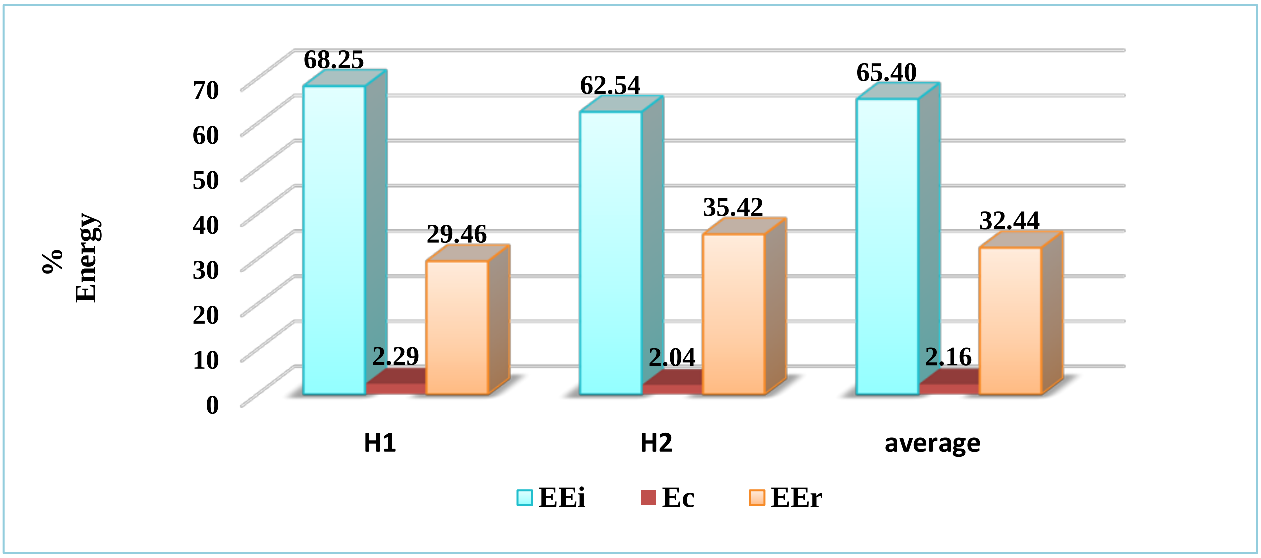

Figure 1: The proportion of building materials initial embodied recurrent embodied and construction energy for the case study houses

Figure 1 shows the EE_{mi} of building materials representing the largest proportion (65.40%) of the total average EE. This is followed by the average EE_r of the houses (32.44%), while the E_c represents only 2.16% of the total EE. These findings, though, is considerably higher but is comparable with previously reported values by Paulsen and Sposto (2013), Debnath et al. (1995), and Ezema (2015), yet it is lesser compared to EE reported by Treloar et al. (2000). Based on building materials, extruded aluminium contributes the highest to the EE (37.87%) due to the high EC_{mi} and inferior quality of the material. The concrete roofing tiles follows next with a figure of

12.59%. The finishing materials, for instance, paint, contributes significantly to EE. The EE_r of these materials are high (97MJ/kg) due to the frequent replacement, larger quantity and higher EC_{mi}, whilst materials like plaster with low EC_{mi} (1.3MJ/kg) also demands a significant amount of energy (6.08%) due to large quantity of material and replacement rate. Contrasting to the previous finding by Mari (2007), this study finding shows that the combined EE component is much more significant than the reported EE_r (32.94%), which significantly influences the total EE of the case study houses.

5 Conclusion

The study determines the significance of EE_r in contributing towards the total EE demand and identify materials that contribute significantly towards the total EE. The calculated total EE of the houses (H1 and H2) are 8.05 and 9.85GJ/m^2; thus, 8.95GJ/m^2 was the averaged EE. The EE_r for the houses are 2.37-3.49 GJ/m^2, and the averaged EE_r was 2.93GJ/m^2. The findings show that average EE_r equates to 33% of total EE, and this component (EE_r) of EE can significantly influence the life cycle EE. Findings have shown that EE_r can be as significant as the EE_{mi} of materials or even more for building over 50 years, for instance, materials such as aluminium, plaster, concrete roof tiles and water-based paint. The findings suggest there is potential in reducing the EE demand of the houses, thus reducing the impact of these materials on the environment. Therefore, any attempt to reduce EE demand should consider building materials with longer service life, lower EE_c and durability. The service life of building materials (durability) is the most significant criterion for selecting materials such as paint.

On the contrary, most designers do not emphasise Sl_{mi} and its impact on EE_r due to the cost factor. Consideration of alternative materials with recycled content could also reduce the initial and $EE_{r,}$ for instance, aluminium, cement sand plaster, concrete and concrete roof tiles. In addition, designers can consider alternative materials such as timber to substitute plywood for doors because plywood has a high EE_c despite its poor durability. The findings from the study though explicit to a building type and limited of process energy data, and Sl_{mi} from various published literature, provide a better understanding of life cycle EE and the significance of EE_r building materials used commonly in local construction of housing.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

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