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Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia

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Abstract

The Australian Green Infrastructure Council (AGIC) is currently leading a new approach to the delivering and operating of infrastructure through a more careful examination of the carbon footprint of construction activities. Using a life cycle assessment (LCA) methodology, this paper presents life cycle greenhouse gas (GHG) emissions and energy analysis of the Engineering Pavilion (hereinafter referred to as Building 216), at Curtin University Western Australia. The University utilises a Building Management System (BMS) to reduce its overall operational energy consumption.

This LCA analysis employed a 'mining to use' approach, in other words, the analysis takes into account all of the stages up to the utilisation stage. The life cycle GHG emissions and embodied energy of Building 216 were calculated to be 14,229 tonne CO_2-e and 172 TJ, respectively. This paper identified the 'hotspots', or the stages in production and operation of Building 216 that were the cause of the majority of the GHG emissions. From this, proposals for further improvements in environmental management may be made. The usage stage of the building produces 63% less GHG emissions than the University average, due to the implementation of the BMS. This system has played a significant role in reducing the total embodied energy consumption of the building (i.e., 20% less than the University average).

Keywords: LCA; Building; BMS; GHG emissions; Embodied energy

1. Introduction

In general, buildings contribute approximately 30% to total global GHG emissions (UNEP, 2009). In efforts to reduce global warming, GHG reductions in this area would make a significant contribution (UNEP, 2009). According to the Intergovernmental Panel on Climate Change (IPCC), there are three areas to focus on in reducing emissions from buildings: reducing energy consumption and building embodied energy, switching to renewable energy, and controlling non CO_2 emissions (Levine and Urge-Vorsatz, 2007). In Australia, regulation is already reshaping the built environment, with mandatory disclosure of the National Australian Built Environment Rating System driving higher levels of energy efficiency in commercial buildings. The carbon price also encouraged more informed decision-making across the economy (GBCA, 2013), although this is no longer the case due to change in government in 2013.

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Australia's per capita greenhouse gas emissions are the highest of any OECD country and are among the highest in the world (Garnaut, 2008). The nation's built environment is experiencing enormous pressure due to its population increase, economic growth, and the government's existing energy and environmental policies (Department of Environment, 2011). Almost a quarter (23%) of Australia's total GHG emissions are the result of the energy demand from the building sector (Department of Environment, 2009). The building sector, comprising residential and commercial buildings, drives a large proportion of Australia's economic activity (Electrical Solutions, 2008). The building sector's contribution to GHG emissions is mainly driven by its end use of, or demand for, electricity (operational energy). For example, there are approximately 21 million square metres of commercial office space in Australia, spread across 3980 buildings (The Parliament of the Commonwealth of Australia, 2010). However, in the main, these offices have not been designed to consider energy efficiency or solar passive design or their long-term environmental and social impact (Department of Climate Change and Energy Efficiency, 2012; Property Council of Australia, 2008).

Along with GHG emissions, energy consumption is often used to measure the environmental performance of buildings. Recent studies have highlighted the importance of both embodied energy and operational energy use attributable to buildings over their lifetime (Biswas et al., 2008). Embodied energy is the energy consumed by processes associated with the total production of a building, from the acquisition of natural resources from processes including mining and manufacturing, through transport and other functions, and finally, the operational energy, involving the energy utilised by the building's operations and use (air conditioning, heating and lighting, office and kitchen equipment).

The building industry has now acknowledged its environmental shortcomings, and through the Australian Green Infrastructure Council (AGIC) will lead a new approach to the delivering and operating of infrastructure by undertaking a more detailed examination of the carbon footprint (the total sets of greenhouse gas emissions caused by product life cycle stages) associated with construction activities.

Life cycle assessment (LCA) for green building design has recently been developed around the understanding that there is a shortage of holistic environmental assessment tools in the building industry (Horne et al., 2009). The life cycle assessment brings benefits to the decision-making process in that it can be used to review sustainability initiatives throughout the entire life cycle of the building, including the design, detailing, delivery and deconstruction phases. A number of studies in North America, Europe and Japan have used LCA as a useful tool for determining the carbon footprint and embodied energy consumption in assessing the environmental performance of buildings (Lemay, 2011; Bribián et al., 2009; Junnila and Horvath, 2003; Junnila et al., 2006; Suzuki and Oka, 1998). In 2000, Fay et al., applied the LCA in evaluating alternative design strategies for an energy efficient Australian residential building. Since then, no LCA study has yet been published which assesses the environmental impact from modern buildings in the public sector in Australia.

Energy consumption in Western Australia grew at an annualised rate of 6 per cent between 2008 and 2012, faster than the average increase across Australia of 1.1 per cent, linked to economic growth (CCA, 2013). This paper, thus, assessed the embodied energy and associated carbon GHG saving benefits of the use of an energy efficient building in Western Australia.

The new Building 216 "Engineering Pavilion Complex" at Curtin University in Western Australia comprises two building wings located around an exhibition plaza. Using an LCA methodology, this paper presents a life cycle GHG emissions and energy analysis of Stage 2 of Building 216 (Fig. 1). This paper identified the 'hotspots', or the stages which are the cause of most of the GHG emissions from the building construction and operational phases, so that further environmental management improvements can be made.

2. Methodology

Following Biswas (2014), this LCA is best termed as "streamlined" LCA (SLCA), as it does not take into account the recycling of building materials or their disposal into landfill. This SLCA that was employed followed the ISO14040–44 guidelines (ISO, 2006) in calculating the life cycle GHG emissions and embodied energy of Stage 2 of Building 216. The LCA is divided into four steps: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation (as presented in the 'Results' section of this report). This LCA has limited its focus to two impact categories only (Finkbeiner et al., 2011); global warming impact, or carbon footprint, and embodied energy. Finally, this LCA is process-based, where the input data, in the form of energy and chemicals for each of the processes of the building's life cycle, has been utilised in assessing global warming and embodied energy consumption impact.

2.1. Goal and scope definitions

The goal of this research is to assess the environmental performance of Building 216 in terms of carbon footprint and embodied energy consumption. Carbon footprint is the total sets of greenhouse gas emissions caused by building life cycle stages, including mining, manufacturing, transport and the use. In the current analysis, the embodied energy includes the energy consumed by processes associated with the production of the building, from the acquisition of natural resources to final consumption including mining, manufacturing, transport and the use of building. In this current research, energy consumption associated with the demolition and transportation to landfill have not been considered. This LCA is limited to three stages:

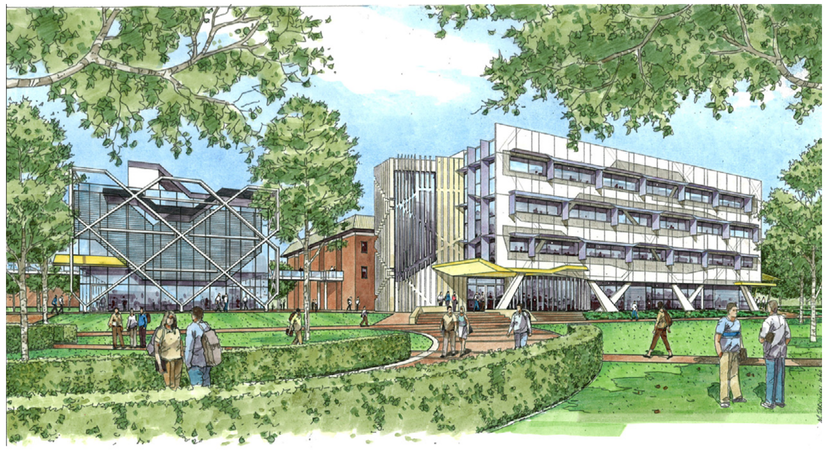

Fig. 1. Building 216.

the supply of construction materials, the construction stage and finally the usage stage.

The *'supply of construction materials'* stage includes the amount of greenhouse gas emissions associated with the mining, processing, and production of construction materials (e.g., concrete, steel, glass) along with transportation to the construction site (i.e., Curtin University). The locations for the gathering of the construction materials were advised by the Curtin University Project Management Department.

The *'construction stage'* includes the GHG emissions associated with the construction process, including fencing, site-clearing, excavation and filling, installation of a tower crane, concrete pouring, pre-casting, shuttering and mortar preparation.

The *'usage stage'* includes the GHG emissions associated with the energy consumption of end use appliances within the building, including lighting, computing, office and kitchen equipment, air conditioning, lifts, fans and heating.

The duration of the '*usage stage*' of the building was assumed at 50 years, and the end use energy consumption pattern has been considered to remain the same during this period. An increase in cooling load due to climatic change was also taken into account in order to determine the future energy consumption of the air conditioning system (Guan, 2009).

This LCA analysis identified the stages causing the most significant greenhouse emissions, the inputs (energy or materials) creating the largest carbon footprints (measured as weight of CO_2-e) and the production activities with the most embodied energy.

2.2. Inventory analysis

A life cycle inventory considers the amount of each input and output for processes which occur during the life cycle of a product. Undertaking a life cycle inventory is a necessary initial step in carrying out an LCA analysis. The inputs in terms of energy and material for Building 216 were obtained from the Curtin University Project Management Department.

The total amount of construction materials was estimated for the construction of the building. The building materials inventory was conducted in accordance with given schematic design drawings. Every item was calculated discretely and classified according to its base material, such as concrete or steel or glass. In the case of insufficient data, standard material specifications were assumed after consulting with the project architect. Since the estimation was based on schematic designs, the type and amount of materials which were finally selected showed some variation.

Tables 1–3 show the amount and sources of construction materials, energy consumption in construction, and end use applications, respectively. Electrical energy is mainly used for construction purposes and end use applications. Diesel engines were used for transportation, crane and mortar operations during the construction stage. Along with greenhouse gas emissions from electricity generation, and the combustion of diesel during the transportation, construction and usage stages, greenhouse gas emissions from other processes associated with the production of these inputs or construction materials (e.g., concrete, steel, glass, aluminium) were also included. Table 3 provides the data for calculating energy consumption over 50 year usage period.

All these inputs, including the energy and construction materials highlighted above were used to calculate the total GHG emissions associated with the life cycle of the production and use of Building 216.

2.3. Impact assessment

The greenhouse gas emissions assessment of the production and use of this building involves two steps. The first step calculates the total gases produced in each process, and the second step converts these gases to a CO_2-equivalent (CO_2-e).

Table 1
Amount and sources of different construction materials.

Materials	Location	Distance (km)	Amount	Unit	(tkm)
Bricks (midland bricks)	Midland	25	27.3	m^3	1251.3
Concrete – Precast	Maddington	15	362.5	m^3	13050.0
Concrete – Readymix	Welshpool	8	1844.3	m^3	35409.8
Cement (for mortar)		10	2.0	m^3	35.8
Sand (for mortar)		10	5.98	m^3	107.64
Steel – Structural (one steel)	Bibra lake	22	84.7	tonne	1863.3
Steel – Reinforcing (one steel)	Forrestfield	15	58.9	m^3	6982.0
Window frame + glass	Wangara	37	1932.8	m^2	185.9
Door frame + glass	Wangara	37	75.0	m^2	7.2
Other glass	Wangara	37	18.9	m^2	1.8
Metal roof cover	Maddington	14	399.6	m^3	13426.6
Drainage gutter	Maddington	14	23.3	m^3	782.208
Trafficable grating		15	2580	m^2	38.7
Ceiling suspension system	Welshpool	10	32,440	m^2	m^2
Paints + accessories	Osborne park	17	m^2	m^2	53.6
Carpet + relevant accessories	Osborne park	17	3593	m^2	73.3
Vinyl floor	Osborne park	17	330	m^2	28.0
Tiles	Osborne park	17	383	m^2	84.6
Plasterboard (Boral)	Canning vale	12	182	m^2	21.8
Insulation (Boral)	Canning vale	12	m^2	m^2	792.2
Timber-cladding	Osborne park	17	1.0	m^2	12.6
Timber-doors	Osborne park	17	4.5	m^2	57.9
PVC pipe	Osborne park	17	320.0	m	1.3

Notes: Distances assumed as the nearest available supplier/retailer from Curtin University.
Actual location of manufacturing factory may vary. 'tkm' means that a km travelled to carry a tonne of construction material.

Table 2
Energy consumption during the construction stage.

Main activities	Sub-activities	Total power	Unit
Builders moving to site	Diesel for transportation	12	Litre
	Crane operation	206,000	kWh
	Computers (200 watt)	1500	kWh
	Printer (350 watt)	175	kWh
	Air conditioner (1000 watt)	5000	kWh
	Telephone (10 watt)	25	kWh
	Lighting (100 watt)	2,500	kWh
Fencing around the site	Fences	24	Litre
	Tree chipper	240	Litre
Site clearing	Transfer/removal of green waste	250	Litre
	Levelling	500	Litre
Excavation and filling	Diesel for transportation	12	Litre
	Operation of excavator	1000	Litre
Installing tower crane	Installation by crane	1030	kWh
	Operation	38,250	kWh
Concrete pouring	Diesel for Ready mix truck	1456	Litres
	Concrete pump	59	Litres
	Operation	7175	kWh
Precast concrete	Diesel for transporting materials	102	Litre
		6180	kWh
Mortar preparation	Diesel for transport	12	Litres
	Operation	8250	kWh
Waste removal		48	Litre

Table 3
End-use energy consumption by different end-use appliances.

Appliances	Number of appliances/area	Avg. operating hour/day	Capacity
Lighting	500	7.75	12 W
Computer – desktop	188	12	190 W
Computer – laptop	120	4	17 W
Projector	16	6.5	325 W
Photocopier	5	3	3500 W
Printer	20	1	387.5 W
Fax machine	2	0.5	20 W
Telephone	60	0.5	10 W
Microwave oven	6	1	1500 W
Refrigerator	3	24	400 W
Coffee maker	2	1	1000 W
Lift	1	8	45 kW
Air conditioning	3495 m^2	10	41.2 kW
Heating/cooling	–	–	1.4 kW
Fan	–	–	7 kW

Note: In the case of air conditioner, the variable air volume (VAV) system, is connected to Curtin's central air conditioning system.

Step 1: The input (i.e., construction materials and energy) data in the life cycle inventory were put into the Simapro 7.2 (PRé Consultants, 2011) software to ascertain the greenhouse emissions associated with the production and use of the new building. The recorded units of input and output data from the life cycle inventory depend on the prescribed units of the relevant materials in Simapro or its libraries (PRé Consultants, 2011).

In order to make the LCA results more representative of Australian conditions, local databases and libraries were used. In the absence of Australian databases, European databases were included to carry out the analysis.

The Australian LCA database (RMIT, 2007) was the library used for construction materials information in order to calculate greenhouse gas emissions from the production of construction materials, such as aluminium, steel, concrete, and glass. The emissions factors for plaster board, paint and floor covers were obtained from the European database (Frischknecht et al., 1996), as Australian databases or libraries were unavailable (RMIT, 2007).

The library for the supply chain of construction materials to the point of use, was incorporated in order to assess the greenhouse gas emissions arising from the transportation of materials to the site. The unit for the transport library is tonne-kilometre (tkm). For example, 1863 tkm is required to carry 84.7 tonne kg of structural steel from Bibra Lake, which is 22 km away from the construction site (84.7 tonne × 22 km).

The library for Western Australian electricity generation was used to calculate the greenhouse gas emissions associated with the electric power used in the construction process (RMIT, 2007). In addition, the Australian database for diesel combustion was used to calculate the GHG emissions from crane and mortar operations (RMIT, 2007).

Step 2: Simapro 7.2 software calculated the greenhouse gas emissions, following the linking of the inputs and outputs to the relevant libraries. The programme sorted greenhouse gas emissions from the selected libraries, and then converted each selected greenhouse gas to CO_2-e. The Australian Greenhouse Gas method, developed by RMIT (RMIT, 2007), was used to assess the GHG emissions. The Cumulative Energy Demand Method was used to determine the embodied energy within the engineering building. Simapro software developed the process networks for determining the breakdown of GHG emissions and embodied energy from the production and use of Building 216.

3. Limitations

Foreign databases for some construction materials were used, due to the absence of local library information on these materials. Emission factors for plaster board, floor coverings and paint were obtained from the Eco-invent database, which is based on European production and energy sources. This may affect the accuracy of the LCA estimates provided.

4. Results and discussion

4.1. Carbon footprint analysis

The Life cycle GHG emissions and the embodied energy assessment of Building 216 considered a total building weight of 5633 tonnes and a gross area of 4020 m^2. The carbon footprint, including GHG emissions from the *mining, construction* and *usage stages* of the new building was 14,229 tonnes CO_2-e (Table 4). The '*usage stage*' produced a carbon footprint of 12,145 tonne CO_2-e, representing about 85% of the total life cycle GHG emissions. This is approximately seven times more carbon intensive than the '*supply of construction materials stage*' (1778 tonne CO_2-e and 13% of total emissions), and 40 times more carbon intensive than the '*construction stage*' (2% of total emissions) of the new building.

Table 4
Carbon footprint and embodied energy consumption of a new Engineering Pavilion (Building 216).

Stages	Carbon footprint tonnes of CO_2-e	Embodied energy TJ
Supply of construction materials	1778	18
Construction stage'	306	4
Usage stage	12,145	150
Total	14,229	172

Whilst the '*usage stage*' could contribute 0.06 tonne CO_2-e per m^2 per year during the 50 year life of the building, it is 63% lower than the University building '*usage stage*' average (i.e., 0.16 tonne CO_2-e) (Australian Government, 2009) due to the utilisation of an energy efficient Building Management System (BMS). The BMS has a computer based control system to monitor and control the automatic cooling of the air throughout the building to achieve the desired ambient temperature (i.e., 25 °C). The BMS operates the air conditioning system only when the inside temperature exceeds 25 °C.

Ngo et al. (2009) estimated that the GHG emissions associated with the production and supply of materials, construction and use stages of a typical Australian commercial building using no BMS was around 9.1 tonnes of CO_2-e/m^2. The percentage saving of GHG emissions has been estimated to be about 60% associated with the replacement of a traditional commercial building with a building like Curtin Engineering Pavilion.

Fig. 2 shows the GHG contributions of all end-use appliances during the '*usage stage*'. The cooling load (68.8%), lifts (15.0%) and fans (9.6%) are the major electricity consuming appliances and contribute more than 93% of the total emissions during the '*usage stage*'. Since the cooling load accounts for a significant proportion of the total energy consumption during the '*usage stage*' (Fig. 2), a reduction in the cooling load could decrease the life cycle GHG emissions significantly. Amenity utilities (i.e., office and kitchen appliances) like coffee machines, printers, projectors, telephones and microwave-ovens contribute a small portion 3%) of the total GHG emissions. Although refrigerators are a base load appliance, they account for only 1.3% of the total GHG emissions.

When supply of construction materials and construction stages were combined, it appeared that concrete accounted for a significant proportion (42%) of total emissions, from the mining to material production sub-stage (Fig. 3). However, the emissions from concrete on a per unit weight

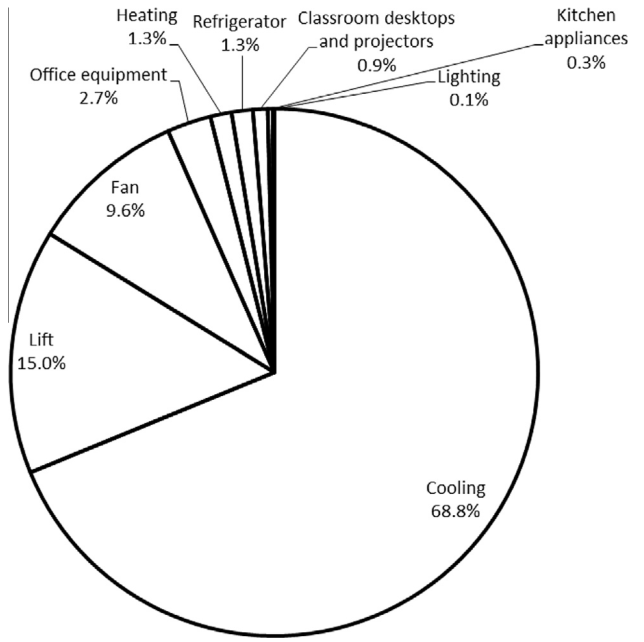

Fig. 2. Percentage contribution of inputs to GHG emissions during the *'Usage stage'*.

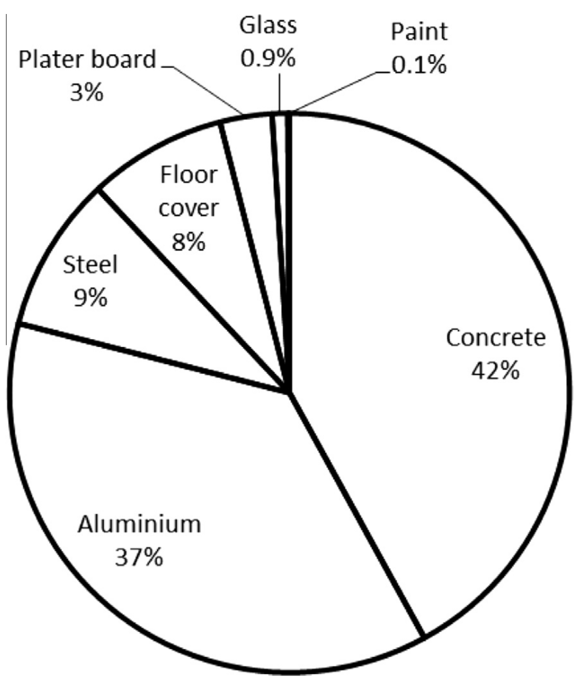

Fig. 3. GHG emissions from mining to production of construction materials.

basis (0.14 tonne of CO_2-e per tonne of concrete) were significantly lower than for aluminium (19 tonne of CO_2-e per tonne of aluminium). This is due to the higher energy requirements in converting alumina to aluminium.

Transport constitutes only 0.53% of the total GHG emissions in the *'mining to building construction stage'* (i.e., 2083 tonnes of CO_2-e). The construction sub-stage, using diesel fuel for crane and mortar operation purposes (i.e., 305 tonne of CO_2-e), produces around 6 times less GHG emissions than the mining to material production sub-stage (i.e., 1767 tonne of CO_2-e).

4.2. Embodied energy analysis

The total life cycle embodied energy of Building 216, with a projected 50-year life cycle is 172 TJ (terajoules) (Table 4), which is 20% less than the University's annual building energy consumption (215.4 TJ) (Australian Government, 2009), indicating the significant thermal comfort performance improvement of Building 216 (NDY Consulting Ltd., 2010). The '*usage stage*' accounts for 87% of the embodied energy in Building 216, with the '*supply of construction materials*' generating 11%, and the '*construction stage*' 2%. The energy consumption of the usage stage is 6.8 times higher than the energy consumption associated with actually constructing Building 216 (including the mining, processing, transportation and application of construction materials). The specific energy consumption of the usage stage is 0.75 GJ per m^2 per year, as opposed to 0.92 GJ per m^2 per year for the University building average.

Fig. 4 shows the contribution of embodied energy for different end use appliances as a percentage of the total embodied energy for the use stage. Electricity for thermal applications alone, including heating and cooling alone, account for 80% of the total embodied energy, followed by lifts (16%). Central lighting accounted for only 1 per cent of the total energy, as the building has been designed to receive more sunlight in order to avoid the need for lighting during the day, and all lamps used in this building are equipped with energy saving globes. The embodied

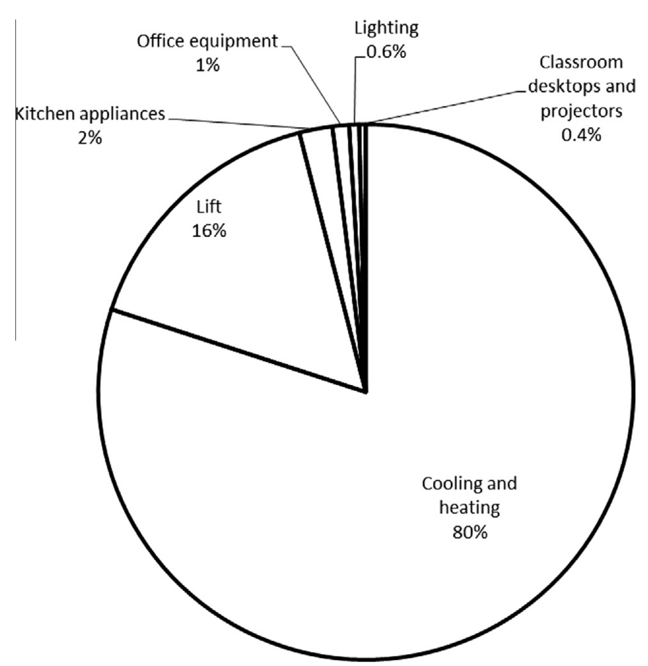

Fig. 4. Embodied energy consumption for different end use appliances.

energy associated with class rooms (i.e., computers, overhead projectors), offices (telephones, photocopiers, fax machines and printers), and kitchen appliances (i.e., micro-wave ovens, coffee machine) accounted for around 3% of the total energy consumption during the usage stage.

The embodied energy consumption of the mining to material production, transportation and construction sub-stages contributes 18 TJ, 0.08 TJ and 3.75 TJ, respectively. Although Fig. 5 shows that concrete has the highest share of the total GHG emissions, followed by aluminium; in the case of embodied energy it is reversed, with aluminium having the highest share (i.e., 39%) followed by concrete (i.e., 31%). This is because the production of aluminium requires about 200 times more energy than the production of concrete, and as a result GHG emissions from aluminium production are 19 times higher than those from concrete production (RMIT, 2007).

4.3. GHG emissions mitigation using cleaner production strategies

Whilst the *usage* stage contributes the largest portion of both GHG emissions and embodied energy consumption, there are no opportunities, other than using renewable energy, for improving the energy performance of the building. This is because this new building has implemented the Building Management System along with modern electrical equipment. It was therefore, seen as worthwhile to examine opportunities to reduce the environmental impact of material production on a life cycle basis. In addition, given the high energy intensities involved in the manufacture of concrete and aluminium, a number of areas could be further investigated in order to enhance the environmental performance of building construction materials.

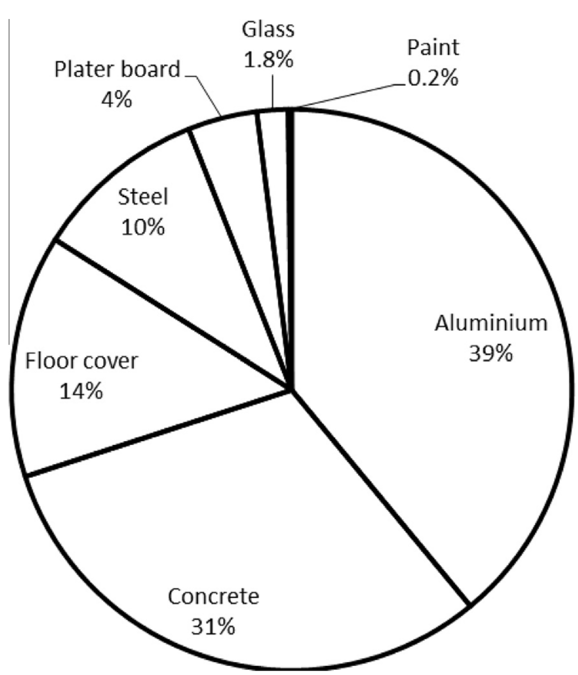

Fig. 5. Percentage of the total embodied energy of construction materials.

Research has highlighted the benefits of the following mitigation strategies in reducing the carbon footprint of a new building like Building 216 including:

1. The replacement of 30% by weight of cement with fly ash in concrete formulations (Nath, 2010).
2. The substitution of new aluminium with recycled aluminium, reducing GHG emissions by around 70% (Damgaard et al., 2009).
3. The substitution of new steel with recycled steel, reducing GHG emissions by around 60% (Damgaard et al., 2009).

Assuming the above substitutions can be made with functional equivalence between the alternative materials, it was estimated that 47% of the total GHG emissions in the mining to material production stage can potentially be avoided by replacing 30% of cement with fly ash, new aluminium with recycled aluminium and new steel with recycled steel. These material substitutions reduced the total GHG's emitted during the 'cradle to use' life cycle of Building 216 by a further 7% (i.e., 13, 241 kg CO_2-e).

5. Conclusions

Life cycle assessment is increasingly being used to determine the environmental impacts of building and construction projects. The Life cycle GHG emissions and embodied energy of Stage 2 of Building 216 are 14,229 tonne CO_2-e and 172 TJ, respectively. The 'usage stage' of this building produces 63% less GHG emissions than the University's building average, due to the implementation of an energy efficient Building Management System. As a result of the introduction of this system, embodied energy consumption of the life cycle of the building is 20% less than the university average. The current research estimated that there is a potential for saving around 60% carbon footprint associated with the replacement of a traditional commercial building with this Building 216 in Australia.

However, opportunities for GHG mitigation still exist in the construction and material life cycle of a new building with the use of revised cement formulations and recycled aluminium and steel where possible. Applying these mitigation strategies could further reduce the total life cycle GHG emissions of Building 216 by a further 7%.

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