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"Sustaining the Resilient, Beautiful and Safe Cities for a Better Quality of Life"

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ORGANISED BY

Gresafe_Cities RIG
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LIFE CYCLE ANALYSIS OF BUILDING MATERIALS AS A TOOL IN DECISION MAKING FOR URBAN REDEVELOPMENT

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Abstract

A combination of increasing population and increasing rates of urbanisation is placing enormous development pressure on the physical and social infrastructure of cities and forcing the rapid redevelopment of many urban sites. Unless carefully managed, rapid redevelopment of urban sites is likely to result in substantial environmental damage in addition to disruption or displacement of existing social relationships, local heritage, and community infrastructure. This paper suggests that life cycle assessment could be a useful tool to assess the environmental impacts of urban redevelopment. It reports on a detailed assessment of the environmental impacts of a group of similar, older apartment towers in Brisbane, Australia over their full physical lifespans. The detailed life cycle assessment provides clear data on the total environmental impact of these buildings, as well as which of their materials and components and which parts of their lifecycle create the largest environmental impacts. The life cycle assessment identifies that even though the massive, reinforced concrete and cavity brickwork structures of these buildings are the greatest cause of environmental impact at the time of construction, it is the ongoing replacement of apartment interiors that is ultimately responsible for a substantially larger environmental impact over the full lifespan of these buildings. Even though the total environmental impact of these buildings can only grow throughout their lifespans, this study finds that their total impact per year of operation is reducing, making them very good candidates for retention rather than demolition and redevelopment. Finally, this study proposes that a progressive reduction in environmental impacts per year of occupation as buildings age is likely to be a feature of much of the existing built environment. In turn, this suggests life cycle assessment can be a useful tool to determine which parts of the existing built environment are most damaging and are therefore most suitable for redevelopment.

Keywords: *life cycle energy analysis, embodied energy, environmental impacts, sustainability,*

INTRODUCTION

In 1950, less than 30% of the world's population lived in cities (United Nations Department of Economic and Social Affairs, 2018b). By 2020, this had increased to more than 55% of global population, and by 2050 it is predicted that nearly 70% of the world's people will live in cities (United Nations Department of Economic and Social Affairs, 2018a).

The combination of increasing population and increasing rates of urbanisation puts enormous development pressure on both the physical and social infrastructure of cities, as more and more people come to depend on the often limited resources and services that existing cities provide (Hadi, Mazdak, Travis, & Sybil, 2021; Zurich, 2015). While the rapid redevelopment of existing cities in order to accommodate this increasing population has the potential to improve access to infrastructure and services, and to improve quality of life (Palanivel, 2017), it can also result in the destruction of urban green spaces, disruption of existing social relationships and the demolition of local history and cultural heritage (Mehdipanah, Marra, Melis, & Gelormino, 2018).

The rapid redevelopment of urban areas also creates significant environmental damage from the production of materials used in new buildings and infrastructure. The construction and occupation of the build environment is estimated to responsible for around 40% of global energy use (Dixit, 2019), as well as being the single largest waste stream in many countries (Cheshire, 2016). While we are generally aware of the large environmental footprint of common construction materials such as cement, steel and aluminium (R. Crawford, Stephan, & Prideaux, 2019), there is less certainty about which parts of the built environment, and which stages of the built environment's lifecycle have the greatest overall impacts (Dixit, 2019). Until we have a better idea of when and where most of the environmental impacts of the built environment occur, it will be difficult or impossible to both increase urban population and reduce the impact of cities on the environment.

This study examines a large group of similar older apartments buildings in Brisbane that are currently subject to redevelopment pressure due to increasing urban population and density. It aims to understand which parts of these building and which parts of their lifecycle have the greatest and least environmental impacts, and whether this group of buildings has a low, average or high environmental impact. Once a complete picture of the whole of life environmental impacts of these buildings has been developed and understood, it will be possible to determine how they can best be managed over their remaining physical lifespans.

Should these buildings be exceedingly expensive (financially or environmentally) then perhaps they should be replaced with new, low cost and low environmental impact buildings, taking care to protect existing amenity of the area and resident's connections to family and friends. If they are relatively low cost, then their place in the city should be carefully preserved and improved, along with the existing social relationships, local history, and community infrastructure that exists alongside and within these buildings.

LITERATURE REVIEW

Life cycle assessment is generally seen as the most reliable method of quantifying the environmental impacts of a building across its whole lifespan (R. Crawford, 2011, p. 38; König & Hellstern, 2010, pp. 38-40). Life cycle assessment of the energy used by and embodied in a building is further acknowledged as an accurate way to determine the total environmental impact of buildings in countries which are heavily dependent on fossil fuel use (R. Crawford et al., 2019, pp. 6-8, 36), such as Australia (Department of the Environment and Energy, 2019, p. 8), Japan, Malaysia, Singapore and Vietnam (The World Bank, 2022). This is partially because energy use is a good proxy for overall environmental impact (Steinmann et al., 2017) but also because embodied energy data is more widely available for building materials and products than data on other environmental impacts (Steinmann et al., 2017, pp. 6360-6362).

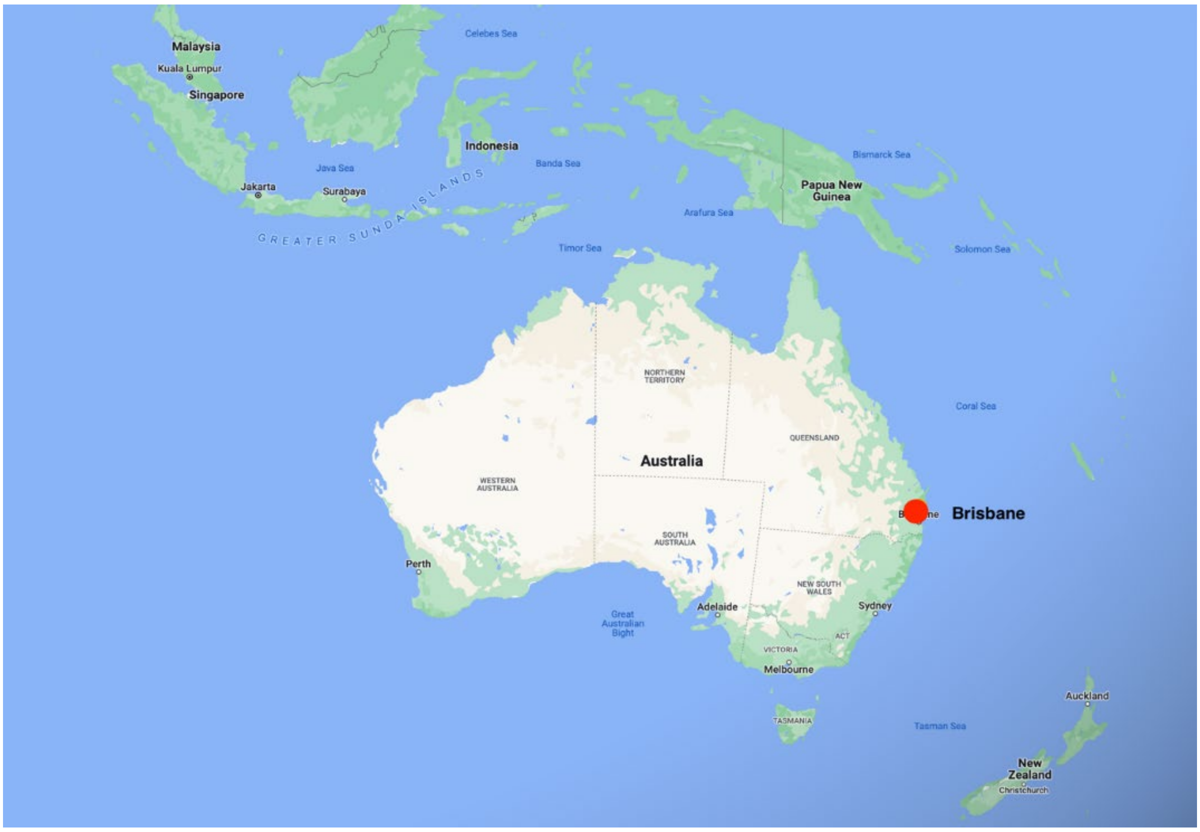
In this paper, the life cycle energy assessment (LCEA) of a case study building is used to establish the overall environmental impact of a large group of similar, older apartment buildings in Brisbane. The accuracy and resolution of any LCEA study is highly dependent on high quality data about the quantities and types of materials used in the building (R. Crawford, 2011; König & Hellstern, 2010), so careful selection of the case study building was required.

In this instance effort was made to ensure the case study building is truly representative of its type, and that sufficient detail was available on the building to make an accurate assessment of the building materials that have gone into its construction and maintenance. The selected case study building has all eight physical features identified as common to this group of buildings in a physical survey: cavity brick load bearing walls, a simple rectangular floor plan, a single lift servicing all levels, a metal sheet roof, aluminium framed single glazed windows, an overall height between 4 and 9 storeys with between 2 and 4 apartments per storey, no more than one storey of basement and no non-residential components (such as shops, offices or studios). Additionally, an almost complete set of architectural and structural engineering drawings was available for the case study building, making an accurate calculation of the total materials used in its construction and ongoing maintenance possible.

The case study building is located in Brisbane, a sprawling city of nearly 2.3 million inhabitants on the east coast of Australia, as shown in Figure 1 (below). The case study building is located on river front land approximately 4km from the city centre and is one of eleven very similar older apartment towers on its street. As shown in Figure 2 (below), it is surrounded by low rise apartment buildings to the south and a local government facility to the west. The case study building is named Belvedere, and will be referred to by this name throughout this paper.

Figure 1

The city of Brisbane



(Google, 2022)

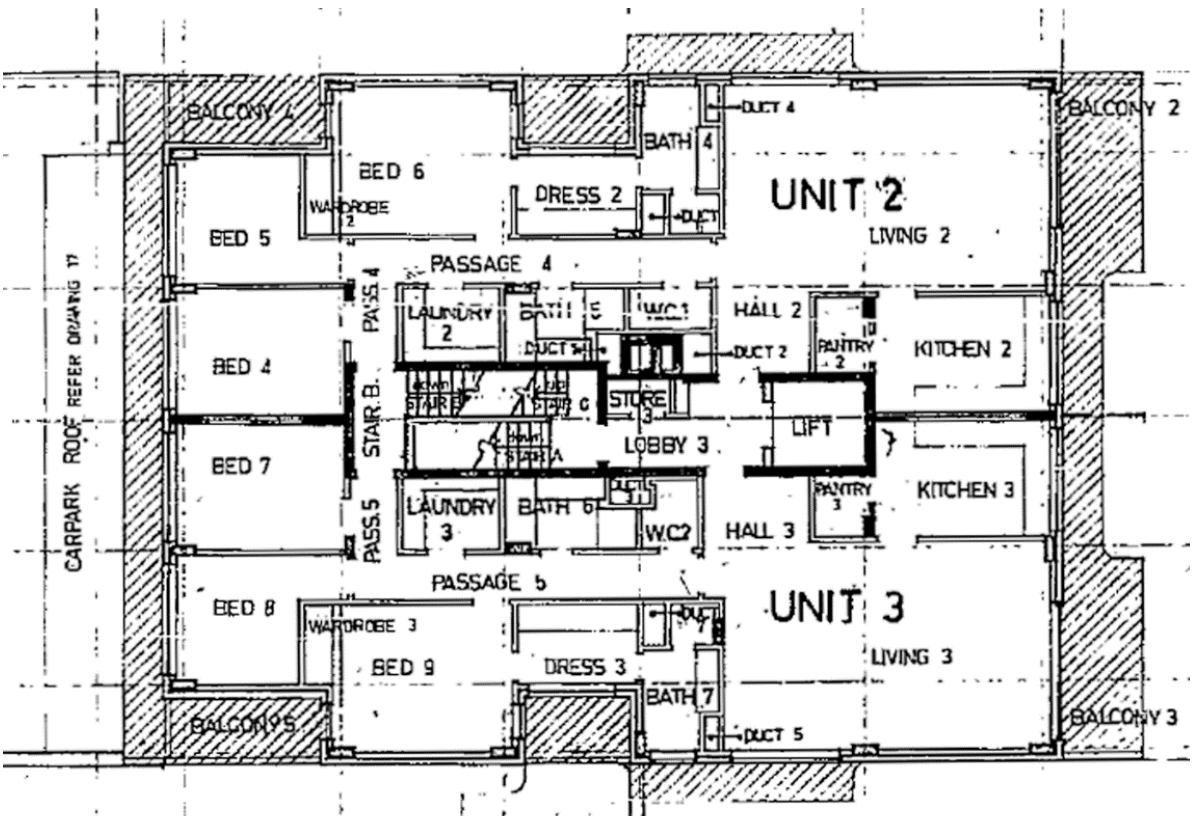
Belvedere was constructed in 1972 and contains 9 storeys of identical apartments over a ground floor with a single unique apartment. Belvedere also has a single level of basement, which contains car parking spaces, common rooms and an undercroft. Figures 3 (below) shows the general arrangement of a typical storey, while Figures 4 and 5 (below) show the and the street and river frontage of the building respectively.

Structurally, Belvedere is founded on deep concrete piles and thick ground beams to provide stability in the deep riverside mud. The ground level and storeys above have cavity brick external walls, double brick internal party walls and single brick walls which divide rooms in individual apartments. Fire escape stairs and the lift shaft are in-situ concrete, while lobby walls are core filled concrete blockwork. The roof cladding is metal sheeting, supported by cold formed steel purlins and hot rolled steel universal beams and parallel flange channels.

Figure 2
Area around the case study building

(Nearmap.com, 2020)

Figure 3:
Typical apartment floor plan



(Brisbane City Council Archives, 1973)

Figure 4 (left) and Figure 5 (right)
Case study building river and street elevations

(Photos by author)

Each apartment in Belvedere has a large balcony facing north east, as well as a smaller balcony facing south west. Large aluminium framed sliding glass doors connect the living and dining spaces to the north facing balconies. These glass sliding doors are shaded by the balcony of the apartment above, and by the roof at the top level. All balconies have steel framed balustrades, with wire reinforced glass infill panels. Masonry surfaces on the interior of the building have an applied render finish, which has been painted. Apartment interiors are generally carpeted, except for an entry space and wet areas, which are tiled. Kitchens and other wet areas are fitted with ceramic baths, basins and toilets as well as laminate covered medium density fibreboard cabinetwork.

METHODOLOGY

The goal of the LCEA is to identify the whole of life embodied energy use of the case study building and to understand which elements and processes have the greatest environmental impacts. The study includes the initial embodied energy (IEE) of the original construction and the recurrent embodied energy (REE) of maintenance and component replacement throughout the building's full lifespan.

While many life cycle assessments examine the impact of buildings over an assumed economic lifespan of 50 years, this study will assess the case study building over the 200 year physical lifespan predicted for Belvedere by the Physical Lifespan Calculator developed by Professor Craig Langston (Langston, 2011). While not all buildings will live out their full physical lifespans, it is important to assess environmental impacts across their full physical lifespan to determine whether the building becomes increasingly energy intensive over time. A building that becomes increasingly energy intensive over time is becoming less sustainable and may be a good candidate for either refurbishment and retrofitting with lower energy components and systems, or demolition and replacement with a lower energy building, depending on the degree of increase in energy intensity and the cultural and social value of the building.

This study will quantify the whole of life embodied energy of the case study building in gigajoules (GJ). The total embodied energy of the building will be converted to energy per square meter of the complete floor area of the building (GJ/m^2) for comparison to other LCEA studies, and to embodied per year of use (GJ.a) in order to compare the building at different stages of its lifespan.

The scope and extent of the study, known as a 'system boundary' (European Standards, 2011), has been determined by the available drawings for the case study building. The available drawings describe the types and quantities of materials used to construct the building but contain little information on their origins or how they were transported to the construction site. Similarly, there is no information on the types or quantities of labour, tools or machinery used in the construction. As a consequence, the energy involved in transporting materials to site and in construction of the building have been excluded from the study. As the building is currently less than 50 years old and has a further 150 years of use ahead of it, there is no way to determine the energy that will be used by labour, tools and machinery in the demolition or disassembly of the building. Accordingly, de-construction energy, and disposal of the waste products from de-construction have also been excluded from the study.

While the architectural drawings accurately describe the building's structure, envelope and internal fittings and fixtures, they contain no information on the extent or type of wiring, conduit and pipework used in the building's electrical, mechanical or hydraulic systems. Further, no information is available on the lift used in the original building, and little information is available on the embodied energy in new lifts that could be incorporated into the building over the course of its lifespan. This lack of information has resulted in the building's services being excluded from the study.

This study will use the embodied energy values for materials found in the Environmental Performance in Construction (EPiC) database (R. Crawford et al., 2019) to calculate the total embodied energy of the materials used in the construction of the case study building. Determining the initial embodied energy of the case study building requires calculating the embodied energy of all the individual materials and components that went into the original construction of the building.

Following the examples of Crawford (2011), Rauf (2015), Treloar et al. (2000) and others, the embodied energy of individual materials and components were calculated by multiplying the net quantity of a building element or component incorporated in the building by a construction wastage factor, to determine the gross quantity of that element or component used during construction. The gross quantity of a material is then multiplied by the embodied energy of that element or component per unit of volume, area, or item.

The final quantities of individual building materials and components incorporated into the building were calculated from a CAD model of the building based on the available architectural and structural drawings. Automated scheduling functions were used to calculate the total volume, area or count of individual building elements and components from this CAD model.

The wastage rates used in the embodied energy calculations were drawn from a literature review conducted by Crawford (2004, pp. 147-148), and are a synthesis of data from Wainwright and Wood (1981) and CSIRO (1994) . Rauf (2015, p. 58) adds that over-ordering of materials and on-site wastage represents around 10% of total waste produced by the construction industry and can make a considerable contribution to total embodied energy.

RESULTS

The results of the initial embodied energy (IEE) calculations of the case study building are graphed in Figure 6 (below) and summarised by element group in Table 1 (below),. The total IEE of the case study building is 24,751.84 GJ, or 4.983 GJ/m^2.

Figure 6

Initial embodied energy by building element group

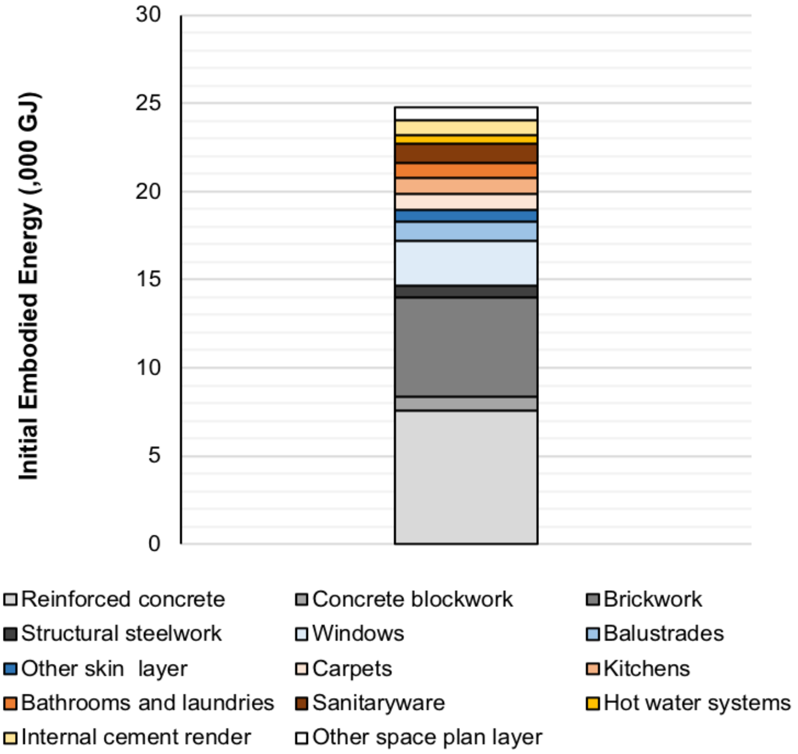


Table 1

Initial embodied energy by building element and shear layer

Shear Layer	Building Element	Embodied Energy (GJ)	Embodied Energy (%)
Structure		14,767.29 GJ	59.29%
	Reinforced concrete	7,567.61 GJ	30.57%
	Concrete blockwork	809.42 GJ	3.27%
	Brickwork	5616.82 GJ	22.69%
	Structural steelwork	684.45 GJ	2.77%
Skin		4,301.76 GJ	17.38%
	Roof and rainwater goods	309.38 GJ	1.24%
	Asbestos Panels	95.41 GJ	0.38%
	Paint (exterior)	20.80 GJ	0.08%
	Windows	2,527.74 GJ	10.21%
	Doors	266.77 GJ	1.07%
	Balustrade	1,081.66 GJ	4.37%
Space Plan		5,773.79 GJ	23.33%
	Internal Cement Render	839.32 GJ	3.39%
	Paint (interior)	99.35 GJ	0.40%

	Doors (interior)	274.65 GJ	1.11%
	Floor Tiles	349.23 GJ	1.41%
	Carpets	896.07 GJ	3.62%
	Kitchens (cabinetwork, appliances and tiles)	912.11 GJ	3.69%
	Bathrooms and laundries (ex. sanitaryware)	855.36 GJ	3.46%
	Sanitaryware (WC, basin, bathtub)	1,056.89 GJ	4.27%
	Hot water systems	490.80 GJ	1.98%
Total embodied energy		**24,751.84 GJ**	**100%**
Building area:	**4967.71 m^2**	**4.982 GJ/m^2**	

This is comfortably within the 4.32-7.26 GJ/m^2 range for IEE established in literature reviews by Ramesh et al (2014) and Karimpour et al (2014) for typical buildings in developed countries, although their studies used older methods to calculate embodied energy. It is more difficult to position this result in relation to other LCEA studies that use current methods to determine embodied energy values, such as the EPiC database. This database is relatively new and few published LCEA studies which make use of it.

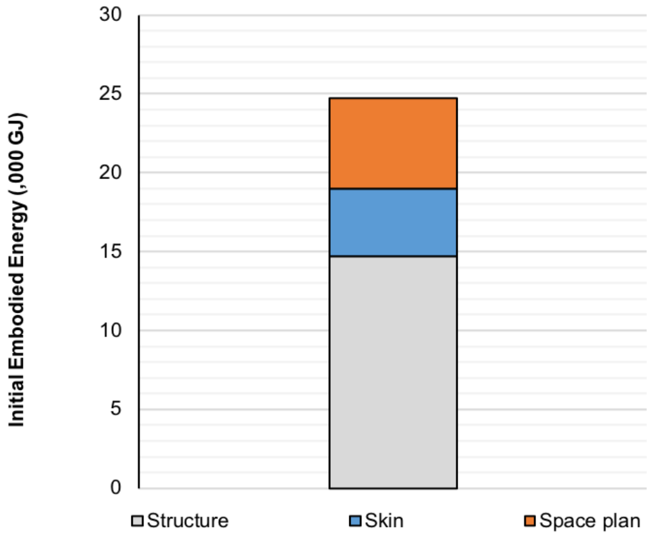
Table 1 (above) and Figure 6 (above) also indicate that the majority of the IEE in the case study building comes from the reinforced concrete structure and brick internal and external walls. This is not surprising, as the structure of the building comprises the greatest part of the building both by weight and volume and is comprised of high embodied energy materials such as steel reinforcing, concrete and clay bricks. It is also interesting to note that the extensive concrete piles and pile caps that were required to stabilise the building in the deep riverside mud of the site only account for 2.77% of the total IEE of the building. This suggests that other similar apartment buildings constructed elsewhere in Brisbane (and throughout Australia) with stable soils will have substantially similar initial embodied energy profiles to the case study building.

Table 1 (above) and Figure 6 (above) also indicates a clear hierarchy in the IEE of the case study building, with three element groups contributing a total of 63.47% of the total embodied energy. Reinforced concrete (30.57%) and brickwork (22.69%) clearly dominate, while windows (10.21%) also make a substantial contribution. Beyond this, another eight element groups make smaller, but roughly equal contributions: concrete blockwork (3.27%), structural steelwork (2.77%), balustrades (4.37%), internal cement render (3.39%), carpets (3.62%), kitchens (3.69%), bathrooms and laundries (3.46%) and sanitaryware (4.27%). Together, these eight element groups account for a further 28.84% of the total IEE. The remaining seven element groups, which includes Asbestos Panels, Doors, Paint, Floor Tiles (excluding wet areas) and Hot water systems, account for the remaining 7.69% of the building's IEE.

Table 1 (above) and Figure 7 (below) aggregate the embodied energy of building elements into structure, skin and space plan 'shear layers' along the lines suggested by Francis Duffy (1990) and Stuart Brand (1995). In Brand's '6S' shear layer system, structure consists of the footings and load bearing elements. In most buildings the structure is difficult to modify and it defines potential physical lifespan, which may range from as little as 25 years to 300 years or more depending on site conditions, level of care and maintenance, and protection from the elements (Boardman, 2005; Langston, 2011).

The skin shear layer is the building envelope, including roof cladding, windows, shading systems, balustrades, vents and surface treatments. While the structure shear layer is constant and generally defines the lifespan of the building, skin elements are frequently replaced when exposure to the elements cause them to break down or fail.

Figure 7
Initial embodied energy by shear layer



The space plan shear layer refers to the interior layout, ceilings, wall and floor coverings, as well as the fixtures and fittings that define individual spaces such as the sink and stove of a kitchen. Generally, the space plan shear layer is relatively quick and easy to change to match changes in living arrangements or occupant expectations.

Unsurprisingly, the structure shear layer is responsible for the clear majority of IEE, but it is interesting to note that the space plan shear layer's contribution is larger than that of the skin shear layer. It is also important to note that the load bearing cavity brick walls of the case study building are technically both structure and skin, but in this case they have been included under structure in Figure 7 (above).

Recurrent Embodied Energy Calculations

With the initial embodied energy of each element group in the building calculated, the recurrent embodied energy (REE) of the building can be determined by applying material and component replacement rates from existing literature over the 200 year physical lifespan of the case study building. Table 2 (below) outlines the material and component lifespans that have been used in the REE study. In this REE calculation the replacement of interior elements has been separated and offset so that all elements in all apartments are not replaced at the same time, but instead take place progressively.

A summary of the embodied energy calculations over the 200 year physical lifespan of the building are provided in Table 3 (below). Table 3 indicates the rapidly growing REE at 50 year intervals, as building components and apartment interiors are progressively replaced. Table 3 (below) shows that in the first 50 years of the building's life, IEE forms the largest portion of total embodied energy, but over the following 150 years this share of total embodied energy rapidly reduces and by the end of the building's lifespan IEE forms only 27.95% of total embodied energy. Table 3 also hints that it is the frequently replaced elements, such as carpets, kitchens and bathrooms, that make an increasing substantial contribution to the building's total embodied energy at the end of its lifespan. Carpets expand from 3.62% to 12.85% of total embodied energy over the life of the building, while kitchens expand from 4.69% to 13.15% and bathrooms and laundries increase from 3.46% to 10.79%.

Table 2
Building element and sub element lifespans

Element:	Sub-element:	IEE (GJ)	Element lifespan
Reinforced concrete		7,567.61	Life of building
Concrete blockwork		809.42	Life of building
Brickwork		5,616.82	Life of building
Structural steelwork		684.45	Life of building
Roofing and rain water goods		309.38	40 years
Asbestos Panels		95.41	50 years
Paint (exterior)		20.80	10 years
Windows		2,527.74	50 years
Doors (unit entry doors and garage doors)		227.77	50 years
Balustrade		1,081.66	45 years
Internal cement render		839.32	Life of building
Paint (interior)		99.35	10 years
Doors (unit interior)		274.65	50 years
Floor tiles (outside of apartment wet areas)		349.23	50 years
Apartment Interiors			17.5 years
	Carpets	896.07	17.5 years
	Kitchens	912.11	17.5 years
	Bathrooms and laundries (excluding sanitaryware)	830.81	17.5 years
	Sanitaryware	1056.89	17.5 years
Hot water systems		490.80	35 years

Table 3:
Embodied energy calculations and proportions at 50 year intervals

Element:	At construction (1973)	At 50 years (2023)	At 100 years (2073)	At 150 years (2123)	At 200 years (2173)
Reinforced concrete	7,566.61 30.57%	7,566.61 18.66%	7,566.61 12.78%	7,566.61 9.80%	7,566.61 8.54%
Concrete blockwork	809.42 GJ 3.27%	809.42 GJ 2.00%	809.42 GJ 1.37%	809.42 GJ 1.05%	809.42 GJ 0.91%
Brickwork	5,615.82 GJ 22.69%	5,615.82 GJ 13.85%	5,615.82 GJ 9.48%	5,615.82 GJ 7.27%	5,615.82 GJ 6.34%
Structural steelwork	684.45 GJ 2.77%	684.45 GJ 1.69%	684.45 GJ 1.16%	684.45 GJ 0.89%	684.45 GJ 0.77%
Windows	2,527.74 GJ 10.21%	4,945.60 GJ 12.20%	7,363.46 GJ 12.43%	9,781.32 GJ 12.67%	9,781.32 GJ 11.05%
Balustrade	1,081.66 GJ 4.37%	2,142.48 GJ 5.28%	3,203.31 GJ 5.41%	4,264.13 GJ 5.52%	5,324.96 GJ 6.04%
Other skin elements	692.37 GJ 2.80%	1783.65 GJ 4.40%	2952.10 GJ 4.98%	4,120.56 GJ 5.34%	4,738.87 GJ 5.35%
Carpets	896.07 GJ 3.62%	3,447.06 GJ 8.50%	6,281.03 GJ 10.60%	9,114.99 GJ 11.81%	11,378.74 GJ 12.85%

Kitchens	912.11 GJ 4.69%	3,414.71 GJ 8.42%	6,581.73 GJ 11.11%	9,555.04 GJ 12.83%	11,648.58 GJ 13.15%
Bathrooms, laundries	855.36 GJ 3.46%	2866.94 GJ 7.07%	5,478.53 GJ 9.25%	7,827.39 GJ 10.14%	9,552.87 GJ 10.79%
Sanitaryware	1056.89 GJ 4.27%	3643.80 GJ 8.99%	7023.52 GJ 11.86%	10,069.48 GJ 13.04%	12,322.62 GJ 13.92%
Hot water systems	490.80 GJ 1.98%	970.10 GJ 2.39%	1,603.16 GJ 2.71%	2,408.00 GJ 3.12%	2,887.30GJ 3.267%
Other space plan elements	1562.55 GJ 6.31%	2,655.82 GJ 6.55%	4,065.67 GJ 6.86%	5,388.99 GJ 6.98%	6,239.13 GJ 7.05%
Total Embodied Energy	24,751.85 GJ 100%	40,546.46 GJ 100%	59,228.80 GJ 100%	77,205.99 GJ 100%	88,550.69 GJ 100%
Initial Embodied Energy	**24,751.85 GJ 100%**	**24,751.85 GJ 61.04%**	**24,751.85 GJ 41.79%**	**24,751.85 GJ 32.06%**	**24,751.85 GJ 27.95%**
Recurrent Embodied Energy	**0.00 GJ 0%**	**15,794.61 GJ 38.96%**	**34,476.95 GJ 58.20%**	**52,454.14 GJ 67.94%**	**63,798.84 GJ 72.05%**
Annual REE rate	**N/A**	**1.28% per annum**	**1.39% per annum**	**1.41% per annum**	**1.26% per annum**

DISCUSSION

Figure 8 (below) presents the progressive and incremental growth of REE over the life of the case study building. At present, in 2022, REE is approximately half the size of IEE but by 2063, REE and IEE will be roughly equal, and by 2113, REE is forecast to be double IEE. This graph clearly shows that over a 200 year building lifespan, REE makes a far larger contribution to total embodied energy that IEE.

The size and proportion of REE is perhaps surprising and may suggest that Brisbane's older apartment towers require unacceptably high levels of maintenance and component replacement. If this were true, it could be a compelling reason for their early demolition, and replacement with lower maintenance buildings in order to reduce the overall environmental impact of the city.

Comparisons of maintenance and component replacement rates between buildings are most easily made using the annual REE rate of a building. This is the percentage of the initial embodied energy that is added to the building in each year of its lifespan as recurrent embodied energy (Dixit, 2019; Abdul Rauf & Crawford, 2015b). Annual REE rates have been calculated for the case study building and are shown on the bottom line of Table 3 (above).

While the REE rate changes over the life of a building alongside the intensity of component replacements, at the end of the 200 year lifespan of the case study building, the final REE rate is only 1.26% per annum. This indicates that the case study building is well within the typical range of REE rates established by Rauf and Crawford (A Rauf & Crawford, 2014; Abdul Rauf & Crawford, 2015a). Expected REE rates range from 1% per annum for well-maintained buildings that are able to obtain a maximum lifespan from building components to 2% per annum for poorly cared for buildings that require frequent component replacements. The 1.26% REE rate for the case study building indicates that the overall IEE and REE ratios seen in Figure 8 are typical, and indicate that the case study building has substantially lower than average maintenance requirements.

Figure 8

Initial and recurrent embodied energy over a 200 year building lifespan

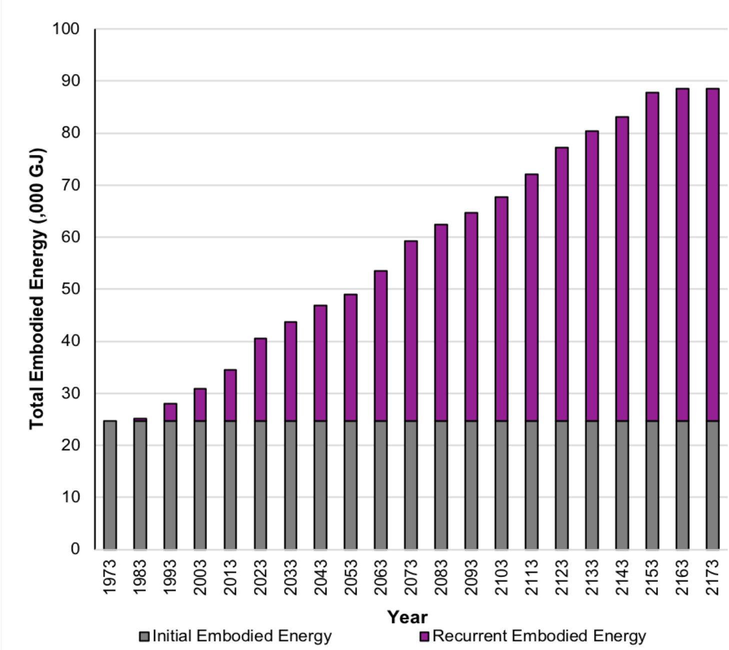


Figure 9 (below) delves deeper into the distribution of total embodied energy over the life of the building, and compares the embodied energy in the structure, skin and space plan layers. Figure 9 clearly identifies that the space plan shear layer is responsible for the majority of total embodied energy once the building is more than 100 years old, and for 61.02% of total embodied energy at the end of the building's lifespan in 2173. Figure 9 also illustrates that the space plan layer sees a continuous and incremental increase through the whole building lifespan, while the skin layer has a series of noticeable jumps in embodied energy at 50, 100 and 150 years of age.

Figure 9

Total embodied energy by shear layer over a 200 year building lifespan

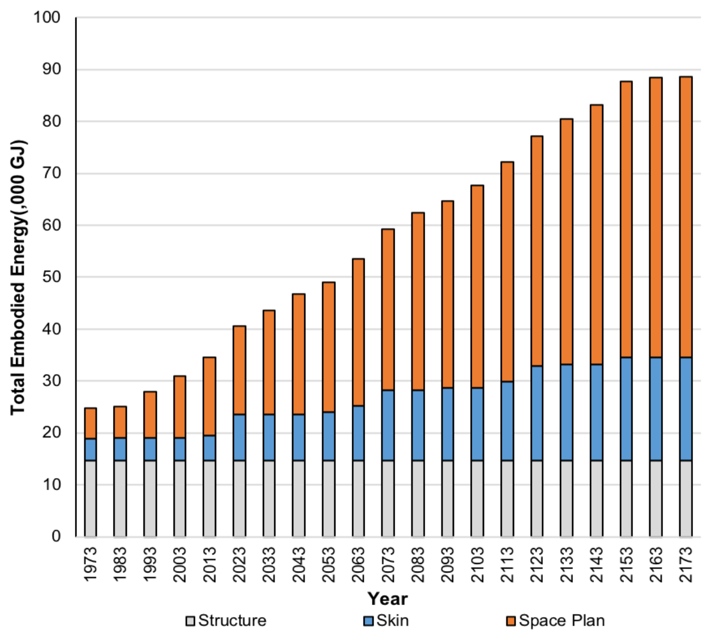
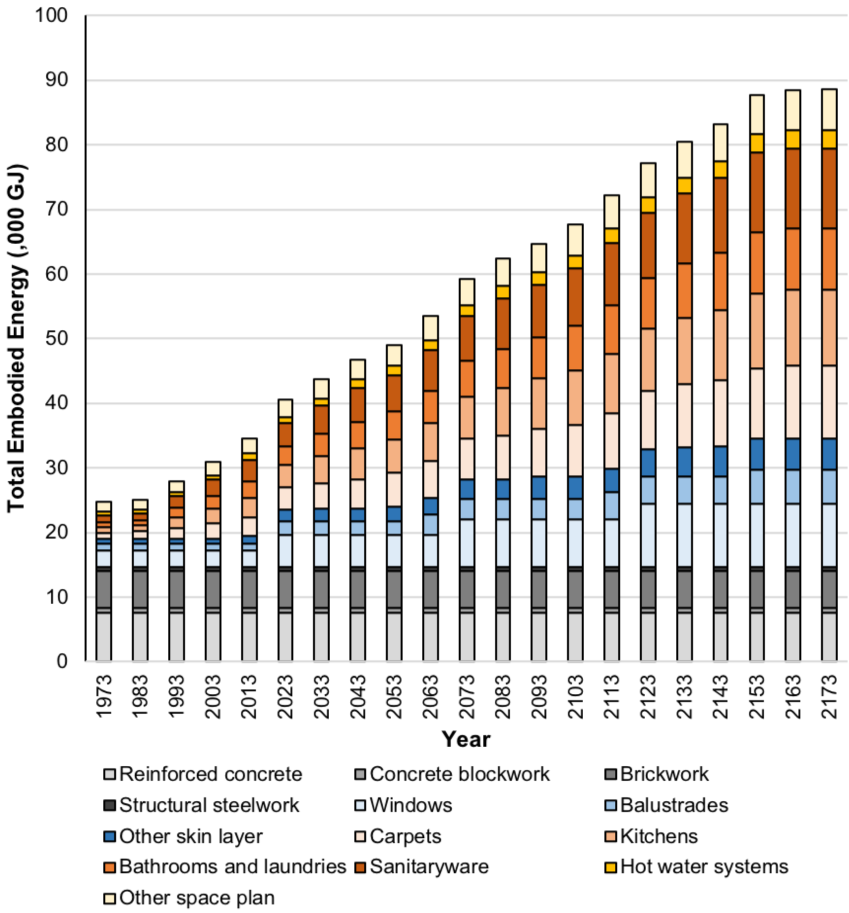


Figure 10 (below) examines total embodied energy by building element group to determine which elements are most responsible for the increase in REE over the full life of the building. Figure 10 shows that interior fittings and finishes are indeed the source of most of the embodied energy in the building throughout most of its lifespan. At 100 years of age the embodied energy of the interior fittings and finishes is roughly equal to the embodied energy of the rest of the building, and at the end of the building's lifespan in 2173, apartment interiors are responsible for more than 60% of total embodied energy. Bathrooms, laundries and sanitaryware in particular are responsible for a large share of embodied energy over the full building lifespan.

Figure 10

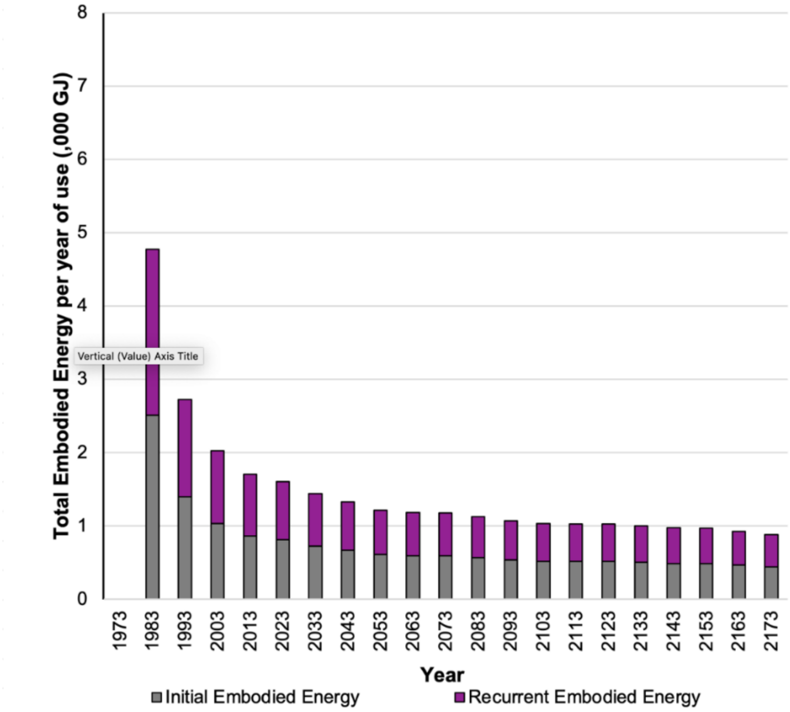
Total embodied energy by building element group over a 200 year building lifespan



A final point to make is that because the total embodied energy of a building can only ever increase, it is of limited value in determining the relative environment impacts, and whether it might be suitable to retain, or to demolish and redevelop any individual building. Instead, total embodied energy divided by the age of a building provides a far clearer measure of the current impact of a building at any point of its lifespan.

Figure 11 (below), graphs the total embodied energy of the case study building divided by its age across its predicted physical lifespan, and clearly indicates that the ongoing impact of the building reduces substantially over time. The separation of IEE and REE further underscores that this is due to the IEE of the reinforced concrete and brick structure of the building are progressively spread over a longer and longer period.

Figure 11
Initial and recurrent embodied energy per annum over a 200 year building lifespan



As the case study building has a below average REE rate of 1.26% per annum, we would expect a truly average building with a REE rate of 1.5% per annum to have a very similar graph, with a slightly higher REE bar for each period but a substantially similar reduction in total embodied energy per year of occupation across its lifespan.

CONCLUSION

This study of the embodied energy of a building representative of the group of Brisbane's older apartment buildings has revealed three key insights into the total life cycle embodied energy of this group of buildings, and one general principle for managing urban redevelopment.

The first insight is that over a typical 200 year physical lifespan, REE accounts for a far greater proportion of total embodied energy than IEE. After 50 years of occupation, REE accounts for 40.69% of total embodied energy, which rises to 60.05% after 100 years and 73.67% after 200 years. This increase in the proportion of REE reflects the large amount of additional embodied energy that is added to these buildings during their lives by the process of replacement of building parts and components as they age.

Even though this steadily mounting REE forms the largest part of the total embodied energy once the building reaches the end of its life, analysis of the annual REE rate suggests that these buildings are not actually high maintenance buildings. Instead, their overall REE rate of 1.26% per annum places them below the average REE rate of 1.5% determined by Rauf and Crawford (2013, 2015a).

The second important insight gained from this study is about the sources of this embodied energy. It seems obvious that the large quantity of high embodied energy materials in the masonry structure shear layer of these buildings should be the most important factor in their total embodied energy, but this is not the case. The structure shear layer of the case study building accounts for 59.29% of IEE but is only 36.20% of embodied energy at 50 years, 24.78% at 100 years and 19.01% at 200 years. Instead, it is the progressive replacement of complete apartment interiors in the space plan shear layer that contributes most to total embodied energy at the end of the building's lifespan. The space plan shear layer grows from 23.33% of IEE to 41.98% of total embodied energy at 50 years, 52.46% at 100 years and 61.02% at 200 years.

The third insight gained from this study is that even though the total embodied energy and environmental impact of the case study building increases over time, its environmental impact per year of occupation is actually reducing as the initial embodied energy of construction is being spread over a longer and longer period.

Taken together, these insights suggest that the case study building, and other similar older apartment towers are relatively benign. The energy embodied in their massive concrete and cavity brick structures has already been expended and will contribute towards a long, low maintenance lifespan, while their durable skins require little energy to maintain.

While the environmental impact of the ongoing replacement of apartment interiors is significant, it seems highly unlikely that there is anything about these buildings that results in an exceptionally high rate of apartment interior replacement, and that this level of interior component replacement also occurs in a wide range of other apartment towers, low rise apartment buildings and detached dwellings of all ages and conditions.

If the relationship between initial embodied energy, recurrent embodied energy and building lifespan established in this study hold for a substantial part of the built environment, then it suggests a general principle for managing urban redevelopment: in addition to their embedded social networks, local history and culture, existing buildings may also have the lowest embodied environmental impacts in our built environment.

While it is risky to extrapolate the results of a single case study to the wider existing built environment, it does seem safe to say that we cannot simply assume that the replacement of existing buildings with new 'high performance' buildings will reduce the overall environmental impact of cities and the built environment.

In fact, this study suggests that the opposite might be true, at least for residential buildings. If the largest embodied environmental impacts of buildings are in fact due to the regular replacement of carpets and other interior finishes, and the rate of replacement of these items is similar regardless of the age, structure or style of the residential building, then these embodied impacts will simply be reproduced in any new residential buildings that are constructed, regardless of any new low embodied energy structural system, high performance building skins or energy efficient services that replacement buildings might offer.

Finally, this study hints that a viable method of reducing the environmental impacts of cities might be to carefully maintain and preserve the materials and embodied energy that has been invested in existing buildings, and to manage their repair and component replacement processes. This, in turn, might allow the personal connections, family ties, local history and community infrastructure which are embodied in existing buildings to remain in place and to continue to develop.

REFERENCES

Boardman, B. (2005). *40% house*: Oxford : Environmental Change Insititute, University of Oxford.

Brand, S. (1995). *How buildings learn : what happens after they're built*: New York : Penguin Books.

Brisbane City Council Archives. (1973). Building Approval 6460-73 at 2 Sandford Street, St Lucia, Queensland. In.

Cheshire, D. (2016). *Building revolutions : applying the circular economy to the built environment / David Cheshire*. Newcastle upon Tyne: Newcastle upon Tyne : RIBA Publishing.

Crawford, R. (2011). *Life Cycle Assessment in the Built Environment*: Hoboken : Taylor & Francis.

Crawford, R., Stephan, A., & Prideaux, F. (2019). *EPiC Database*. University of Melbourne,: https://doi.org/10.26188/5dc228ef98c5a.

Crawford, R. H. (2004). Using input-output data in life cycle inventory analysis. In R. H. Crawford (Ed.).

CSIRO. (1994). *Quote: Cost Estimating System for House Builders*. Australia, Highett.: CSIRO Division of Building Construction and Engineering.

Department of the Environment and Energy. (2019). *Australian Energy Update 2019*. Australian Energy Statistics: Canberra

Dixit, M. K. (2019). Life cycle recurrent embodied energy calculation of buildings: A review. *Journal of Cleaner Production, 209*, 731-754. doi:10.1016/j.jclepro.2018.10.230

Duffy, F. (1990). Measuring building performance. *Facilities, 8*(5), 17-20. doi:10.1108/eb006518

European Standards. (2011). EN 15978:2011. In *EN 15978:2011: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*: British Standards Institute.

Google. (2022). Google Maps. Retrieved from https://www.google.com/maps/@-23.401772,135.867232,5.09z

Hadi, H., Mazdak, A., Travis, W., & Sybil, S. (2021). Effects of Urban Development Patterns on Municipal Water Shortage. *Frontiers in water, 3*. doi:10.3389/frwa.2021.694817

Karimpour, M., Belusko, M., Xing, K., & Bruno, F. (2014). Minimising the life cycle energy of buildings: Review and analysis. *Building and Environment, 73*(C), 106-114. doi:10.1016/j.buildenv.2013.11.019

König, H., & Hellstern, C. (2010). *A life cycle approach to buildings : principles, calculations, design tools* (1st ed.. ed.). Munich : : Edition Detail, Institut für Internationale Architektur-Dokumentation.

Langston, C. (2011). Estimating the useful life of buildings. *Conference Papers*, Paper 30. Retrieved from http://epublications.bond.edu.au/aubea_2011/30

Mehdipanah, R., Marra, G., Melis, G., & Gelormino, E. (2018). Urban renewal, gentrification and health equity: A realist perspective. *Eur J Public Health, 28*(2), 243-248. doi:10.1093/eurpub/ckx202

Nearmap.com. (2020). Satellite Image of area around 2 Sandford Street, St Lucia. *Image date: Thursday 17 September 2020.*

Palanivel, T. (2017). Rapid urbanisation: opportunities and challenges to improve the well-being of societies. Retrieved from https://hdr.undp.org/content/rapid-urbanisation-opportunities-and-challenges-improve-well-being-societies

Rauf, A. (2015). *The effect of building and material service life on building life cycle embodied energy.* Retrieved from http://hdl.handle.net/11343/116138

Rauf, A., & Crawford, R. H. (2013). The relationship between material service life and the life cycle energy of contemporary residential buildings in Australia. *Architectural science review, 56*(3), 252-261. doi:10.1080/00038628.2013.810548

Rauf, A., & Crawford, R. H. (2014). *The Effect of Material Service Life on the Life Cycle Embodied Energy of Multi-Unit Residential Buildings*. Paper presented at the World Sustainable Buildings Conference 2014, Barcelona.

Rauf, A., & Crawford, R. H. (2015a). Building service life and its effect on the life cycle embodied energy of buildings. *Energy, 79*, 140-148. doi:10.1016/j.energy.2014.10.093

Rauf, A., & Crawford, R. H. (2015b). *The effect of building and material service life on the life cycle embodied energy of an apartment building*. Paper presented at the Living and Learning: Research for a Better Built Environment, 49th International Conference of the Architectural Science Association, Melbourne, Australia. http://anzasca.net/2015-conference-papers/

Steinmann, Z. J. N., Schipper, A. M., Hauck, M., Giljum, S., Wernet, G., & Huijbregts, M. A. J. (2017). Resource Footprints are Good Proxies of Environmental Damage. *Environ. Sci. Technol, 51*(11), 6360-6366. doi:10.1021/acs.est.7b00698

The World Bank. (2022). Fossil fuel energy consumption (% of total). Retrieved from https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS?end=2015&most_recent_value_desc=false&start=2010

Treloar, G., Fay, R., Love, P. E. D., & Iyer-Raniga, U. (2000). Analysing the life-cycle energy of an Australian residential building and its householders. *Building Research & Information, 28*(3), 184-195. doi:10.1080/096132100368957

United Nations Department of Economic and Social Affairs. (2018a). 68% of the world population projected to live in urban areas by 2050, says UN. Retrieved from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

United Nations Department of Economic and Social Affairs. (2018b). Population Facts. Retrieved from https://population.un.org/wup/publications/Files/WUP2018-PopFacts_2018-1.pdf

Wainwright, W. H., & Wood, A. A. B. (1981). *Practical Builder's Estimating*. London: Hutchinson.

Zurich. (2015). The risks of rapid urbanization in developing countries. *Global risks report.* Retrieved from https://www.zurich.com/en/knowledge/topics/global-risks/the-risks-of-rapid-urbanization-in-developing-countries

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