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Life cycle assessment of shipping container home: A sustainable construction

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ABSTRACT

Shipping containers are manufactured exceedingly rigid and strong complying specifications for freight purposes. After ending freight spell at sea and road, shipping containers are just occupying huge spaces at ports and other places. Among all the reuses, the recent technology and construction practices have set the containers for home building purposes. This research investigates the recent usage of containers for home buildings, and determines its constructability in Australian building industry. It also investigates the effects of carbon footprint and other life cycle environmental impacts (LCEI). Life cycle assessment (LCA) approach was used to evaluate 6 LCEI category indicators: cumulative energy demand (CED), water use, solid waste, global warming potential (GWP), acidification potential, and eutrophication potential. A container-framed house is used as the base case to compare with other previous studies to evaluate the differences in those LCEI. According to Building Code Australia, the container house was complied with 6-star energy rating. Results show that operation phase has the most dominating impact for all the indicators except water use and solid waste generation. For all the impact categories, the overall contributions of the whole life cycle impacts have increased significantly if the design life of a building is increased to 100 years.

1. Introduction

Nations involved in freight exports and imports, using shipping containers through a global transportation network, are creating enormous leftover of containers at ports. It has created a double dilemma. While it is too expensive to transport the empty containers back to their origins, leaving them in the ports of destination would occupy huge spaces. As a result, there is a huge surplus of empty containers just waiting for recycling/reuse. Among all the creative practices, reuse of shipping containers for home building purposes may deserve further attention due to recent development of technological innovation. Successful cases of converting containers to youth centre, classroom, emergency shelter, office, home and hotel are rising around the globe [1–3]. This would be a sort of reimbursement in a way, which could result in cleaner and healthier coastlines without creating another problem in landfill. However, the question is how to reuse those containers sustainably for home building purposes.

Most people do not think shipping containers can be used as home building materials. Re-using shipping containers for home building purposes, reduces the need for most new materials in conventional construction. It is well known that containers are manufactured in standard dimensions with some in-built properties, which makes them an excellent modular structural component. The recent use of prefabricated shipping containers may be a substitute of traditional timber-framed construction. The study [5] stated that this has resulted into a drastic drop in embodied energy when compared to conventional building. Reusing shipping containers is the ultimate in sustainability, using far fewer materials and embodied energy than any kind of building construction [6]. Architects and builders already started to take advantage of reusing containers for home building [2,7]. However, it is important to determine its constructability as well as sustainability. There are difficulties of using shipping containers for building structures. Thermal performance of a building may vary due to local climate.

There are obvious opportunities to reduce the embodied energy through the reuse of containers as a construction material. Therefore, it is needed to ascertain the amount of energy consumption and environmental impacts reduced in container home construction. However, it is more important to ensure that the container home must be habitable like a conventional residence. It is

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common thought that because containers were not intended for home building, the operational energy required to make them habitable would restrict the aspiration of a normal residence. The study [8] pointed out that containers are relatively thin, uninsulated and acoustically inferior boxes, where comfortability might be an issue. Contrary to popular belief, however, this is not always the case. Through the measurements of internal air temperatures of two similar sized structures, one being of conventional construction, the other a modular shipping container unit, the study [5] contends that this form of construction is in fact not inferior to a conventional building. While this may be the case in hot-humid tropical climate, it may require further study for cold and temperate climate.

After ending the usable life for freight transport, cargo containers that used for building constructions, are called ISBU-Intermodal Steel Building Unit [9,10]. Due to drastic change in construction materials and methods, regulatory authorities are yet to recognize shipping containers for home building. The difficulty of using shipping containers as ISBU is that they are not catered for building codes. Majority of urban planners were against the development of ISBU construction due to conflict with present building code regulations [10]. ISBU as a living residence is typically very noisy, and insulating the interior of metal structures requires sound softening elements, which can turn out to be an additional expenditure [11,12]. However, with the use of modern insulation techniques, the performance of the building envelope improves further. Many ISBU come with industrial strength anticorrosive primer to prevent surface corrosion or future rusting. The study [13] stated that they are inherently strong, and can be stacked up to nine rows high without compromising structural integrity. Other key benefits for the reuse of containers in construction are their uniformity and modularity, which saves time [13,26]. This major advantage of using these containers opens up the opportunity for efficient building construction.

It is evident that the world is moving towards intricate environmental protocols in all sectors including building construction, which consumes huge energy and emits large quantities of greenhouse gases. Hence, reuse of shipping container would help in reducing environmental impacts. Therefore, this research will investigate the performances of constructing a container-framed house with satisfactory living spaces. It also evaluates the thermal characteristics, carbon footprint and other life cycle environmental impacts (LCEI) using life cycle assessment approach. A summary of previous life cycle assessment (LCA) studies on traditional timber framed and container residential buildings in Australia and elsewhere are given in Table 1 for major LCEI results comparison.

In order to evaluate the constructability, the existing literature is discussed critically in relation to the status of container homes along with current building practices in Australia and elsewhere. It covers contemporary technical and construction practices used in shipping container homes. It also explores the potential barriers in design and construction, sustainability and life cycle management of a home building. Finally, it provides an implication for integrating life cycle management perspective into the process of implementing low carbon construction. A conventional like container-framed house is used as the base case provided by a volume builder in Australia. The construction methods of the container-framed house are used to assess the differences in LCEI by adopting a life cycle assessment (LCA) approach using *SimaPro* software. Two life cycle impact assessment (LCIA) methods were used in this LCA approach: (i) Australian Impact Method with Normalization including cumulative energy demand (CED) and (ii) CML 2 baseline 2001 – Australian Toxicity Factors. It evaluates 6 LCEI indicators: cumulative energy demand (CED), water use, solid waste generation, global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP).

2. Current status and constructability of container homes

2.1. Shipping containers as home building blocks

Shipping containers have several dimensions. For home building purpose as shown in Table 2, the most commonly used dimensions are 6.0 m and 12.0 m long with 2.4 m width and 2.7 m high so that the container can provide a better rectangle with a high ceiling. Therefore, the height of those containers complies with the minimum clear ceiling height (i.e. 2.4m) required by many national codes for the construction of home buildings. Containers are called HC (high cube), with commercial names 20′HC-6.0 m long or 40′HC-12 m long [22]. Container comprises of composite panels including top and bottom walls, two upright sidewalls and end walls joined at their edges [23,24]. The corner posts are used to join the side and end walls in order to bear the live and dead loads. Containers also have self-supporting beams, stout and plywood flooring. Containers are made of metal sheets to form edges and its grid to support the wooden floor. The corners are rigid pieces to allow the connection between containers. To secure the house, the bottom corner blocks are generally welded to steel plates, entrenched into the concrete slab of the foundation.

The remodelling of containers homes are made of by cutting steel wall sheets to create openings for doors and windows based on architectural requirements. It also replaces original plywood floor. In recent years, insulated, painted and prefabricated doors and windows are used to fit with containers [13,25]. It is eventually delivered to the construction site. The entire high-tech construction using shipping container is regarded as a prospective modular structure that can save money and materials. Shipping containers fully equipped with fixtures and insulation make this type of construction easy and speedy [26]. Therefore, architects, designers, and homeowners are found interested in container homes due to its prefabrication and modular properties [13]. Prefabricated containers are carried with crane, and then welded down onto the foundation steel plates.

2.2. Current status and constraints

Globally over 17 million structurally sound shipping containers are sitting for further reuse after ending their first spell for freight purpose [27]. The first widely reported shipping container home (two-storied) was built in USA in 2006, which passed all of the strict guidelines of the UBC-uniform building code [28]. A 120-bedroom Travelodge hotel building was constructed at Uxbridge, London, by retrofitting 86 shipping containers onsite [29]. It was claimed that this modular construction was 40–60% quicker and produced 70% less onsite waste than traditional building methods. In addition, it does not require complicated construction processes, which helps to reduce cost substantially. In another development, four shipping containers were transformed into a children's activity centre in South Melbourne, Australia. The forms and aesthetics were generated by sustainable principle, with the aim of creating a low-cost and zero waste construction [30]. A Dutch developer converts shipping containers into 1000 units of student housing in Amsterdam [6]. It was stacked up to five levels high, bolted together and divided into 12 different buildings. Table 3 show typical container residential buildings constructed in different places globally.

Several studies reported that containers are flexible in construction system due to its modular character and rigidity [2,5,7,22]. However, it depends on the constructability and country's standard practices to comply with local regulations. Standards of Australia determine the standards to specify minimum requirements for performance, safety and constructability and the forms of construction. Constructability expresses the ease and efficiency with which structures can be built. The more constructible a structure is, the

Table 1

Summary of previous LCA studies on traditional and container residential buildings.

Study	System description, assumption and boundary	Life phases	LCEI indicators (%)			
			GHG	CED	Water	Waste
[14]	Australian climate (Brisbane), varieties of different star rating building with 50-years lifetime; excludes interior decorations and household appliances, includes renovation in maintenance; star rating specified; disposal phase includes transportation and materials to land filling only, no recycling.	Construction	34–41	35–40	54–63	4–6
		Operation	54–63	44–52	1–2	2–2
		Maintenance	7–11	10–14	35–43	6–7
		Disposal	−6 to −5	1–1	0–0	86–87
[15]	Australian climate (Brisbane), 3.6 star case study building with 50-years lifetime; excludes interior decorations and household appliances, includes renovation in maintenance; star rating specified; disposal phase includes transportation and materials to land filling only, no recycling.	Construction	34	35	63	5
		Operation	63	52	2	2
		Maintenance	8.4	12	35	6
		Disposal	−5.5	1	0	87
[16]	Australian climate (Victoria) used 0.8–5.1 star design building with 100-year lifetimes; excludes impacts of interior decorations, lighting, water heating and household appliances; includes appliances efficiency of heating and cooling; assumes 65% appliances efficiency for heating and a coefficient of performance (COP) of 3 and no duct losses for cooling; disposal phase includes dismantling of all the materials to landfill, with no carbon sequestration or material energy recovery from land fill.	Construction	7–24	4–18		
		Operation	76–93	82–96		
		Maintenance				
		Disposal				
[17]	Australian climate (Melbourne, Sydney and Brisbane), 5 star rating building with 50-year lifetime; excludes interior decorations and household appliances; assumes a COP of 3.5 with 20% ducting loss for cooling, 70% efficiency for heating; disposal phase includes dismantling of the original construction materials and their transport to recycling and landfill.	Construction	31–44	31–44	72–175	12–22
		Operation	53–68	52–64	1–3	3–6
		Maintenance	4–6	5–6	20–36	13–27
		Disposal	−1 to-4	−1 to-3	−14 to-95	55–67
[18]	New Zealand climate (Wellington), 3 different buildings (e.g. example house, concrete house, timber house); not specify star rating; 100-years lifetime; excludes interior decorations and household appliances, includes renovation in maintenance; star rating not specified; disposal phase includes waste treatment and disposal.	Construction	3.8–8.8			
		Operation	50.4–80			
		Maintenance	5.1–6.6			
		Disposal	11–35.7			
[19]	Australian climate (Newcastle), 50-years lifetime; excludes interior decorations and household appliances and major renovation; star rating and appliances energy efficiency not specified; disposal phase includes only transportation impact for construction materials to recycling and land filling.	Construction	47			
		Operation	51			
		Maintenance	2			
		Disposal				
[20]	Hungarian residential house, 50-year lifetime; includes heating and cooling, hot water, lighting; not specify star rating, excludes interior decorations; using tabulated values for gross operation energy; disposal phase includes recycling (50%) as well as their transportation.	Construction	14–21	14–20		
		Operation	67–72	68–77		
		Maintenance	7–11	6–13		
		Disposal	3–5	1–2		
[21]	United States residential house, 50-year lifetime; includes heating/cooling, lighting, decorations and household appliances; not specify star rating; excludes major renovation, recycling, incineration; energy ratings and appliances efficiency not specified.	Construction	8–21	6–16		
		Operation/use	78–92	83–94		
		Disposal	1–2	<1		
LCA of a container building						
[18]	New Zealand climate (Wellington), 3 bedrooms container stacked building; not specify star rating; internal useful area 89m^2; 100-years lifetime; excludes interior decorations and household appliances, includes renovation in maintenance; star rating not specified; disposal phase includes waste treatment and disposal.	Construction	40			
		Operation	52.4			
		Maintenance	4.1			
		Disposal	3.6			

Table 2
Specifications of 20′HC-6.0 m and 40′HC-12 m long shipping containers [22].

Model	Length (m), internal/external	Width (m), internal/external	Height (m), internal/external	Capacity volume (m^3)
20′HC-6.0 m long	5.9/6.0	2.34/2.40	2.71/2.89	37.4
40′HC-12 m long	12.0/12.2	2.34/2.40	2.71/2.89	76.1

Table 3
Container residential buildings constructed globally.

House name & country	Year	Location & climate zone	Number of container use
Stevens Container House, New Zealand	2006	Wellington, humid temperate climate	Three 40′HC
Redondo Beach House, U.S.A.	2007	California, dry climate	Nine varieties
Chalet Du Chemin Brochu, Canada	2006	Quebec, humid cold climate	Three 40′HC
Zigloo, Canada	2006	Victoria BC, humid temperate climate	Eight 20′HC
Container City I, UK	2001	London, humid temperate climate	Twenty 20′HC
Container City II, UK	2002	London, humid temperate climate	Thirty 20′HC
The Riverside Building, UK	2005	London, humid temperate climate	Seventy three 20′HC

more economical it will be [31]. As a newly developed technology, container home buildings are in the process of following the most recent Building Regulations (2006) complying with Building Code of Australia (BCA) guidelines. As a prefabricated modular structure, building of container homes has a high degree of constructability potential. Although there is flexibility in construction, the number of container homes is still quite low worldwide due to lack of skilled workforce to handle new materials and methods [13,22]. The study [13] further identified the biggest challenge in increasing the number of container homes is the stigma that is attached to these ugly metal boxes left abandoned in urban shipyards. On the other hand, salvaging of the shipping containers can slash carbon footprint from recycling these metal boxes.

It is a major challenge to achieve a suitable optimum living in container homes. It is important to create barriers that control heat loss and gain to provide a comfortable living. The study [9] pointed out that the interior of a shipping container gains exterior temperature such that in summer the container has extremely high temperatures and in winter the container has extremely low temperatures. The envelope of such design should be in compliance and thereby setting the required R-value depending on climatic conditions.

2.3. Constructability of container homes

In the last 15 years, a variety of projects using shipping containers has appeared in the building industry. These container buildings are from a single-container guesthouse/site-office to a massive 8-container family home to 86-container hotel building. Many authors pointed out that shipping container are in fact merely a structural frame, so that home building can adopt prefabricated modular characteristics according to clientele requirements, architectural plan and engineering design. It can be stacked more than eight levels high, and have the ability to resist corrosion if well coated [6,22,29]. However, the legislative guidelines for safe building of container homes are still non-existent [2]. The reason may be due to the new development with unknown structural properties of shipping container as a home building material.

Shipping container comprises of corrugated panels (roof and sides), plywood floor, purlins, front doors, frame and rails, which form an integrated structural envelop for typical home construction. In the literature, varieties of different construction systems are available. The two types of foundations commonly used in container projects are concrete raft-slab and concrete footing. A raft-slab built over the whole space of the building plan, where the container is placed over. On the other hand, the concrete footings do not cover the entire area. To get additional support, extra footings are poured in the middle of the areas and between the corner foundations. Steel rebar is used in those foundations to compensate temperature differentials in the concrete. Thick steel plates, connecting to the rebar by hooks, are embedded on to the corner footings to secure the structure firmly [2,7,13,22].

The existing plywood floors of nearly all shipping containers are treated with various pesticides. An additional physical barrier can be created by building a subfloor on top of it. This is an optional step, especially created if a physical barrier to the treatment chemicals is required, or to get above some structural remnants of the containers. Subfloor can provide a bit more insulation with a layer of foam covered by another layer of oriental strand board (OSB). Interestingly concrete can also be poured on top of the plywood. It could even be the finished floor with some dyes and/or patterns added.

Although the shipping container comes with flat roof, varieties of different roofing system can be erected atop such as shed, hip and gable roof types depending on likings for the style, insulation requirement and cost. Many people consider the existent container flat roof is more than adequate for roofing. A shed is sloped roof, simple, cheap and easy to build. A conventional hip and gable rooftops can also be secured atop of the container within a shortest possible time [11,13]. The trussed roof fastened with metal straps is welded to container steel sides. It is to be noted that the double roof consisting of container metal and trussed roof, eventually slows down the transfer of heat into the building envelope, and maintains the consistent temperature. Hence, adding an extra roof in container will clearly not save money initially, however at the end could save operational energy bills. It is also to be noted that insulation is usually placed in between metal and trussed roof. To have a better look, plasterboards are attached to the metal roof from bottom surface.

There are many ways to insulate shipping container homes. A timber frame is constructed inside or outside of the container to secure panelling and insulation materials to improve energy efficiency [25]. Container homes require minimal use of wood in exterior and interior framing because it does not carry any load. The lightweight cladding (e.g. cedar, vinyl, fibre cement) can be applied over the exterior, and plasterboard in the interior walls. It also requires opening for adding doors and windows. These activities are not identical with traditional home construction systems. It is to be noted that insulation on the exterior or interior walls depends on climatic conditions. Insulating the exterior of the containers is a better choice for cold climate, which provides a traditional outer shell aesthetically. In order to provide a thermal break to the metal walls, a layer of foil board (e.g. 25 mm) is recommended to attach to the walls. Foil board is an expanded polystyrene rigid insulating board that has reflective coatings on both sides [25].

Ceramic coating has been around for many years for insulating metal surfaces. Ceramic coating can bring huge energy savings by preventing heat transfer and heat loading onto a structure. The physics of this product is remarkable. It can be used as paint, adhesive, insulator, fireproofing and acoustic barrier. Spray of polyurethane foam works best in combination with ceramic insulation paint. With the use of ceramic insulation paint in the exterior and polyurethane foam in the interior, this high performing ISBU envelope can lead to a much smaller carbon footprint than that of typical built construction [13]. It was pointed out that both ceramic coating (i.e. supertherm) and polyurethane foam contain special gas in bubbles that gives a high thermal efficiency. The polyurethane foam is available in both open-cell and closed-cell, with differences in cost, density, strength, waterproofing and R value. Notably open-cell and closed-cell R-values vary in the ranges of R 3.5–4.0 and R 6.0–6.5 per inch thickness. Because ISBU shipping containers might be moved, closed-cell foam is well suited for its higher strength and durability.

The reusable shipping containers with existing floor, wall and roof panels can facilitate custom-fit construction in factory and then be transported to the construction site [1,13,22]. In order to improve the quality control, all the preparatory works such as disinfection, cleaning, opening, strengthening, connecting, surface preparation and painting are done in factories. It is worth noting that containers must include all necessary details for the preparation at the factory so that it avoids problems in assembly at construction site. The final changes such as the interior can be completed at construction site. There is an example in Australia of prefabricated modular dwellings with 6 containers having 7 bedrooms [1]. This design comprised of two double storied containers side by side and two single storied modules to the right as living spaces. Hence, a suitable design can be constructed in an assembly line with ease and speed.

2.4. Sustainability and low carbon construction of container homes

Current literature on reuse of shipping containers mainly focuses on its different scope and design aspects. Almost no published paper has addressed the life cycle assessment of this construction and its sustainability potential. Huge research gap exists in this aspect. Reuse of shipping containers for home construction is an innovative application to improve sustainability across the board against the typical stick-built frame construction. A container home can be constructed of about 75% recycled materials by weight as claimed by the study [32]. Creating container homes may be sustainable because of the ways the solid structure converted into a repurposed entity. Nowadays it is forging into an eco-friendly construction due to recent development of some features, such as wallboard or panelling with insulation, well-insulated flooring/ceiling options, ceramic coating and polyurethane foam insulation, low VOC paints, primers, adhesives and sealants [33]. These eco-friendly features make the container building more energy-efficient and sustainable. In addition, shipping containers are well made, which is fire, rust and mold-resistant [34]. It also saves the expenditure of labour and fuel required to ship them back to their country of origin.

Container steel is not a decomposing material to turn into compost in landfill. On the other hand, recycling requires melting of shipping container by using basic oxygen furnace (BOF) and electric arc furnace (EAF), which consumes huge amount of energy and emits greenhouse gases [35]. For example, 3.63 t shipping container requires 8000 kWh of electrical energy to convert them into steel blocks. While the process of reusing that entire 3.63 t of shipping container into a home building takes only 400 kWh of energy, which is only 5% of the energy required to melt it [36,37]. It is also found that each ton of steel making liberates approximately 2 t of CO_2 and 40 kg of other gaseous emissions [35]. According to the inventory of carbon and energy (ICE), 1 t general steel (i.e. average of all steel) recycling requires 24.4 GJ of embodied energy [41].

Assessing carbon footprints and other environmental impacts of a container building over its lifetime is a complex exercise. It requires assessment of all its products, processes and services over whole life cycle stages. Construction and maintenance phases are comprised of products, process and services of assembled building elements. Operational phase has heating and cooling requirements, which has significant environmental impact. Final disposal has hazardous land filling and/or incineration that may also have significant impact to environment.

Currently, sustainable building also often named as green building is not only reducing its environmental impacts but also creating healthy environment for occupants. Hence, the main emphasis is to select materials that are free from harmful chemicals as well as excessive environmental impacts. Prefabricated container homes may offer a number of unique opportunities to accomplish all those goals. Many previous studies have evaluated energy, carbon footprint and other environmental impacts on traditional residential buildings using life cycle assessment (LCA) approach [4,14,15,17,20]. However, there is almost no such published comprehensive LCA study of container homes in the literature in Australia and elsewhere. An architectural company (Lendager Architects) in their website claims about the use of LCA in an experimental project in Denmark using shipping container to reduce carbon emissions. The house was built with two shipping containers, where the floor, wall, roof and façade were made of different recycled and upcycled (i.e. reused with minimal modification for another purpose) materials. When the house was evaluated using LCA approach, a reduction of 86% CO_2 emission was obtained compared to a benchmark house [38]. No other detailed LCA analyses were found in the website of that company. As such, in order to fill-in the gap, this paper uses the LCA approach to evaluate environmental impacts of container homes.

3. Methodology

The methodology encompasses with data collection to evaluate carbon footprint and other life cycle environmental impacts (LCEI) using *SimaPro* LCA software. The operational heating and cooling requirements were evaluated by *AccuRate sustainability* software, which were then used as input data into the *SimaPro* model. Finally, the implications of life cycle environmental impacts of container building are reported.

Data collection and data inputs into *Simapro* and *AccuRate Sustainability* software were carried out from the actual house plans. The bill of quantity (BOQ) was calculated from house dimensions, specifications with best possible estimate and appropriate scaling factors from published industry references [17,35,39–42,50]. BOQ provides a complete quantity list of all the components used to construct the container building. The quantities were re-calculated with units suitable for *AccuRate Sustainability* and *SimaPro* using typical values by using scaling factors such as density and weighted mass. The life cycle inventory (LCI) data have been used in *Simapro* model was derived mainly from Australian AusLCI database.

3.1. LCA approach

A streamlined LCA approach was undertaken using PRé's *SimaPro* (version 7.3) software, complied with ISO 14044 guidelines. The aim of this LCA is to analyse the environmental impacts of products or processes over life cycle. This result enables a fair comparison between products or processes. *SimaPro* is particularly suitable for studies on Australian dwellings as it can be used with the Australian database AusLCI. The AusLCI database is the most accurate for this region as it contains data for Australian products and services [43,45,58]. If there are no AusLCI data available in any product process and services the ecoinvent and published data has been used. This is because Ecoinvent database has been adjusted for the Australian Building Industry [43–45]. The functional unit of this LCA is 'a house over its 60 year lifetime' including construction, operation (heating and cooling energy), maintenance and disposal. The products, process and services used for all these phases were directly entered into SimaPro LCA model.

The houses are modelled in *AccuRate Sustainability* software from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to estimate operational energy (*i.e.* heating and cooling only) requirements. This popular tool is recommended by the Australian Nationwide House Energy Rating Scheme (NatHERS) as well as Building Code of Australia, and has been validated through BESTEST [14,46]. *AccuRate Sustainability* includes an extensive database of materials that allows the user to modify building materials and its assemblages of wall, roofing and floor design options. The user can specify the materials and construction techniques, insulation levels, windows size and orientation, shading, ventilation, overshadowing, colour of indoor surfaces, geographical location, and roofing, floor and wall orientation. *AccuRate Sustainability* produces data in the format of MJ/m^2 per annum. This number is put directly into the *SimaPro* model to evaluate the life cycle environmental impacts for operation phase heating and cooling only. *AccuRate Sustainability* is suitable for this purpose, as this software contains a selection of wall, floor and roof assemblage options, and the operational energy is calculated using its default settings and standard climate data.

4. Case selection and data generation

4.1. Description of case study shipping container house

A case study house was selected for this research. The house was designed as for the Australian residential market, which was not typical in local industry. A member of the Building Designers Association has built the case study house in Melbourne, Australia. It was complied with 6 star energy rating, obtained from Australian Nationwide House Energy Rating Scheme (NatHERS) accredited energy-rating tool *AccuRate sustainability*. The general description of materials and building elements for the case study house is given in Table 4.

The residence is a double storey with three bedrooms. Reusable shipping container framing is used in this dwelling. The upper floor comprises a master bedroom with an en-suite and two smaller bedrooms and second bathroom. Ground floor comprises living and dining with an open plan kitchen with laundry space. A powder room is attached besides the stairs in the ground floor. A timber construction is also attached with container building for aesthetics. The total house dimension was 12.2 m in length and 4.9 m in width. Four standard size (i.e. 12.2 m long, 2.4 m wide and 2.6 m high) containers were attached together vertically and horizontally.

4.2. LCA system boundary, scope, data quality and assumptions

The LCA system boundary is shown in Fig. 1. Construction, operation and maintenance phases are all included in this system boundary, specifically:

- raw material extraction and production (i.e. studs)
- manufacturing of building components (i.e. doors/windows)
- transportation, from raw material extraction to part fabrication, to construction site
- construction work at the building site, including foundation, excavation
- heating and cooling energy consumed during the operation phase
- maintenance and renovations and
- demolition at the end of life and transportation of demolished materials to landfill

The system boundary excluded:

- technological improvements (i.e. recycling of container steel waste)
- interior decoration, appliances energy, staircases and inmate water consumption
- electrical wiring, plumbing, furniture, built-in cupboards, sink and kitchen utensils
- vehicle and machinery in the temporary construction site and
- urban planning infrastructure (i.e. roads, drive-way concrete and landscaping)

The goal of this study is to evaluate environmental impacts. The functional unit of this LCA is 'a house over its 60 year lifetime' including construction, operation (heating and cooling energy), maintenance and disposal. The impact of container itself was not included in this analysis, as this was used as reusable material. The life cycle inventory (LCI) data used in this study were characterized in terms of geography, technology, age, collection method and representativeness. The LCI data were documented based on relevant environmental flows associated with life cycle stage (e.g. the emissions associated with product, process or services). Data from the Australian region specific database (AusLCI) were used wherever possible. Where the data have not yet been collected from Australian sources, data from the European ecoinvent database were used, after being adjusted for Australian electricity and transportation. This approach has been used in several previous studies [15,43–45,47].

4.2.1. Construction

For construction phase, the products, process and services used were directly entered into the SimaPro LCA model. The builder's Bill of Quantity (BOQ) was used, and the quantity of each material is summed for the whole building to calculate the total amount of materials in the building. Process and services include equipment usage, transportation, fabrication and manufacturing.

4.2.2. Operational energy

AccuRate sustainability software was used in this research to evaluate the heating and cooling loads only. It estimated for continuous occupancy based on standard occupant behaviour for a four-person family, and average Melbourne weather conditions. In order to estimate heating and cooling load accurately, the efficiency and coefficient of performance (COP) of the appliance were used. COP is measured by dividing the rate at which the heat is added or removed from a room [14]. In this study, a central ducted heating system with a COP of 3 was used with a 70% heating efficiency. A central ducted heating system was chosen, as it is commonly used in the Melbourne climate [48]. The energy required to heat and cool has been estimated based on area-adjusted heating and cooling surface area (i.e. annual energy per square meter floor area per year-MJ/m^2 per annum). The heating and cooling loads are used as input data into *SimaPro* model to evaluate the life cycle environmental impacts for operation phase.

Table 4
Description of containers home case study building.

Building element	Description
Freight containers	Second-hand steel shipping container conforming to ISO 1496 and AS/NZS 3711; capable to ship in usual manners, small deformations may be permissible but all edges of walls, roofing and floor shall be straight; no deformations permitted in all the corners supports.
Foundation or basement	Foundation concretes to be minimum grade 25 MPa grade reinforced concrete for footings; construction joints properly formed comply with BCA guideline.
Floors	Total conditioned floor area 121.6 m^2, suspended timber floor, insulation in contact with floor R 1.0; carpet and underlay for living and bedroom areas; tiles for wet areas; external floor area: 2.86 m^2 with timber decking.
External & internal walls	Metal container framing external walls 163.4 m^2, reflective insulation R2 both sides with FC sheet in outer layer and plasterboard in inner; 10 mm smooth finish plasterboard internal wall (122.1 m^2).
Roof and ceiling	corrugated iron hip roof with 2 ° slope; 10 mm smooth finish plasterboard ceiling with bulk insulation R4.0; unventilated roof space cavity above ceiling; external and internal ceiling area: 80.5 m^2 and 74.6 m^2, respectively.
Insulation	Metal clad cavity panel in external wall with reflective bulk insulation R2.0; Cavity panel without insulation in internal wall, Bulk insulation R 4.0 for ceiling; Unventilated roof space cavity above ceiling; Hip roof with corrugated iron without insulation.
Doors and windows	Solid timber external and hollow core internal doors with lockset and dead bolt; aluminium frame, clear, double-glazed windows with low emissivity, total windows area 62.4 m^2, Holland blind included, no fly screens and shading.
Painting	External walls (FC sheet) with two coats of acrylic glazing; doors with two coats of gloss acrylic.

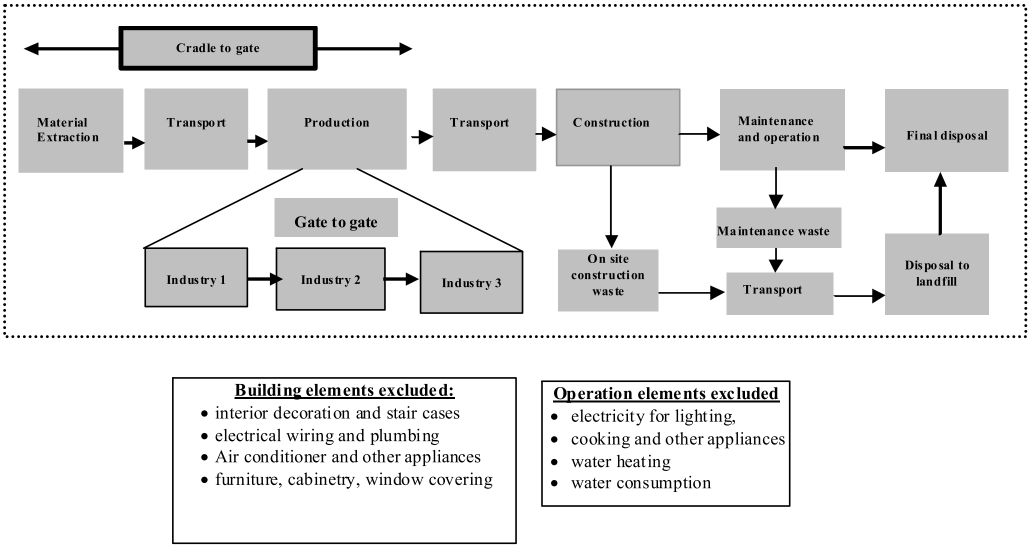

Fig. 1. LCA system boundary (dotted area included).

4.2.3. Maintenance

The definite timings for renovations used in this study were derived from standard values found mainly in the literature [20,49]. It includes a major and minor renovation that is white goods replacement and repainting, respectively. Major renovation was modelled after of 30 years interval, and external and internal envelop materials that are FC sheet, timber floor and plasterboard were replaced. In the literature, the timing for minor renovation such as repainting was observed from every 6 to 25 years in the literature [20,49]. In this study, the repainting was modelled at the median timing of 10 years as similar with first author's previous studies [14,15,49]. It means five times over a 60-year lifetime.

4.2.4. Disposal

In this study, the assumption was made to dispose off all the building materials to landfill at the end of final disposal except container steel. When materials are disposed to landfill, the main impacts are associated with transportation as well as the material that remains in landfill for extended period of time [15,17]. Disposal of timber to landfill is modelled as credit of GHG emissions, as timber materials store a significant amount of carbon for more than 100 years [15,17]. Technological improvements are certain to occur in the next 60 years in disposal process, which are difficult to predict now. Therefore, this research was not included disposal of container steel in this analysis.

4.3. LCIA and category indicators

In life cycle impact assessment (LCIA) step, *SimaPro* evaluates life cycle environmental impact (LCEI) indicators for particular interest of the research. There is no single agreed method in Australia and elsewhere under LCIA. It is advisable to assess LCEI indicators for particular interest. In this study, two LCIA methods were used: a) Australian Impact Method with Normalization including CED (cumulative energy demand) and b) CML 2 baseline 2001 – Australian Toxicity Factors. In total, there will be six LCEI indicators: CED, water use, solid waste generation, global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP), as these are categories of prime interest in Australia and elsewhere. Since this study looked at container building, other categories of interest are bio-diversity and land use impact but these are not reported here, as inventory data of suitable quality was not available [15].

5. Results and discussion

The LCA results of CED, water use, solid waste, GWP, acidification potential (AP) and eutrophication potential (EP), are shown in Table 5. The CED, GWP, AP and EP were the most dominant impact indicators for construction and operation phases for container-framed homes. While water use was the most dominant impact indicator for construction and maintenance phases and solid waste generation was the most dominant impact indicator for disposal phase. Succinctly, it can be said that operation phase has the most dominating impact in all the indicators except water use and solid waste generation.

5.1. Comparison of LCA results

5.1.1. CED

As shown in Table 5, the major impacts were found in operation (67.5%) and construction (22.7%) phases. The findings of this study are not quite similar to studies reported by the study [14,15,17] for the construction and operation phases as shown in Table 1. This may reflect there may be some dissimilarity in design life, system boundary and assumptions between this and the above-mentioned three studies. However, some studies reported fairly similar CED levels in construction and operation, even though dissimilarity exits in system boundaries. For example in the study [20], the effects of hot water and lighting were included as additional components in the operation phase, while the design life was 50 years instead of 60 years considered in container home. It is to be noted that the study [16] assumed a 100 years lifetime. As a result, operation phase has produced a higher percentage of the total impact as shown in Table 1.

In terms of unit floor area (m^2) the contribution of CED from construction phase was 3.24 GJ/m^2 which is very similar to the studies [2,51], where 3 and 3.24 GJ/m^2 were reported for traditional building, respectively. On the other hand, for steel building in New Zealand, the study [56] has found a higher value of 6.6 GJ/m^2. It is to be noted that in this study, the shipping container was used as an ‘upcycled material’ (i.e. reused with minimal modification for another purpose), which has not been counted in LCA. Overall as a whole life cycle, the CED impact of the container house of this study, when converted into per unit floor area and per annum, resulted into 238 MJ/m^2/a, which is appreciably different (376 MJ/m^2/a) from a container building in New Zealand [18]. This may be due to dissimilar inventory data, system boundary and assumption considered. For example, the study [18] considered the impact of container itself in its LCA. In contrast, the study [18] also found CED impacts for timber, concrete and traditional NZ houses (example house) as 262.6, 293.6 and 198.4 MJ/m^2/a, respectively. It is worth noting that the study [18] has not mentioned star rating considered. The study [17] reported lower life cycle CED in the range of 174.2–192.1 MJ/m^2/a for traditional buildings in Melbourne climate, due to lower star rating considered (i.e. 5 star).

5.1.2. Water use

This study like other LCA studies has not considered household water use during operation phase. The water indicator employed in this LCA is simply a summation of all water used in materials within the system boundary. For example, the water consumption of timber product is based on the water used throughout its plantation. Thus as shown in Table 5, the major water uses were found as embodied water in materials for construction (60.5%) and maintenance (38.9%) phases. These percentages are similar to the studies reported by the study [14,15] for typical Australian dwellings as shown in Table 1. This proportion of percentages (i.e. 1.5:1) between construction and maintenance is also similar as the study [53,54]. The percentages of 72–175% for construction phase as reported by the study [17] are widely varying due to consideration of different climates, system boundary and house types (e.g. timber, brick and steel). However as a whole life cycle, the water use of the container house of this study, resulted into 0.418 kL/m^2/a, which is very similar (0.417 kL/m^2/a) to the study [17] for one of the traditional buildings in Melbourne climate.

5.1.3. Solid waste generation

The generation of solid waste as shown in Table 5 is mainly during the disposal phase (89.3%), as expected. A very few studies have reported the solid waste generation. Results from this study are similar to the studies [14,15] and dissimilar to the study [17]. This was due to system boundaries and assumptions considered by those studies. For example, both the study [14,15] and this study considered landfill disposal only, while the study [17] considered both recycling and subsequent landfill in the disposal phase. As such for a whole life cycle, the solid waste generation of the container house, resulted into 6 kg/m^2/a, which is appreciably different (2.1–4.2 kg/m^2/a) from the study [17] due to quite different system boundaries considered.

5.1.4. GWP

The main impact was in the construction (24.8%) and operation (69.1%) phases. These findings on GWP are not similar to the three studies [14,15,17]. These differences originated mainly because of design life variation. The design life of this container home was 60 years while the above-mentioned 3 studies were 50 years. The study [16] has considered 100 years design life and thus the GWP deviated substantially in construction (7–24%) and operation (76–93%) phases as shown in Table 1. On the other hand, the study [19] showed even more deviations such as 47% in construction and 51% in operation. The reason may be due to exclusion of maintenance phase.

In terms of unit floor area (m^2), the contribution of GWP from construction phase was 211 kg/m^2, which is similar to the study [52], where 250 kg/m^2 were reported for a single-family wooden house in Japan. Overall as a whole life cycle, the GWP impact of the container house of this study, resulted into 14.2 kg/m^2/a, which is appreciably different (48.9 kg/m^2/a) from a container building in New Zealand [18], due to dissimilar inventory data, system boundary and assumption as discussed in CED. In contrast, the study [18] also has found GWP impacts for timber, concrete and example house as 22.3, 38 and 17.6 kg/m^2/a, respectively. As discussed in CED, the results of the study [18] were mentioned without star rating. The study [17] reported almost similar life cycle GWP in the range of 12–13.6 kg/m^2/a for traditional 5 star buildings in Melbourne climate.

5.1.5. AP

The two compounds principally involved in acidification are sulphur and nitrogen compounds. The higher the AP is the higher the risk of acid rain and environmental damage. The main impacts as shown in Table 5 were from construction (26.8%) and operation (65.7%) phases. The disposal phase has a negligible impact. Very few studies in the literature have considered AP impact in the life cycle phases of buildings. Among few reported studies, the study [20] has found AP as 26–33% in construction and 48–54% in operation, which is slightly lower in operation phase due to 50-year design life considered. In another dissimilar study [55], AP impact of an office building was 3.5-6.4% in construction and 91.6-95.5% in operation. This difference may be due to huge energy required to operate an office building.

5.1.6. EP

Phosphate and nitrate compounds are principally responsible for eutrophication. As shown in Table 5, the main impacts were

Table 5
LCA results for container home (case study) with 60-year design period.

Impacts	Unit, % and per m^2 contributions	Construction	Operation	Maintenance	Disposal	Total
CED	GJ	393.9	1172.3	162.6	8.9	1737.7
	% contribution	22.7	67.5	9.4	0.5	100
	Per m^2 contribution GJ/m^2	3.24	9.64	1.34	0.07	14.29
Water use	KL	1850.5	16.1	1188	1.7	3056.3
	% contribution	60.5	0.5	38.9	0.1	100
	Per m^2 contribution KL/m^2	15.22	0.13	9.77	0.01	25.13
Solid waste	Ton	3.6	0.4	0.7	39.2	43.9
	% contribution	8.2	0.9	1.6	89.3	100
	Per m^2 contribution Kg/m^2	30	3	6	322	361
GWP	Ton CO_2-eq	25.7	71.6	9.5	-3.2	103.6
	% contribution	24.8	69.1	9.2	-3.1	100
	Per m^2 contribution Kg/m^2	211	589	78	-26	852
AP	Kg SO_2-eq	147.7	362.4	40.6	0.8	551.5
	% contribution	26.8	65.7	7.4	0.1	100
	Per m^2 contribution Kg/m^2	1.21	2.98	0.33	0.01	4.54
EP	Kg PO_4- eq	15.7	74.6	5.8	0.8	96.9
	% contribution	16.2	77.0	6.0	0.8	100
	Per m^2 contribution Kg/m^2	0.13	0.61	0.05	0.01	0.80

Gray shade- for easy identification of the highest value.

from construction (16.2%) and operation (77%) phases. The maintenance phase impact was 6%. Very few studies considered EP impact. The contribution of construction, operation and maintenance phases were (11–16%), (82–87%) and (2–3%) respectively reported in Melbourne climate in the study [17], which is very similar with this study. The contributions of construction, operation and maintenance phases were (22.4–29.3%), (66.4–70.3%) and (4.2–7.3%) respectively reported by the study [55] for an office building. Overall as a whole life cycle, the EP impact of the container house of this study, resulted into 0.013 kg/m^2/a, which is very similar (0.011 kg/m^2/a) to the study [17] for a traditional building in Melbourne climate.

Therefore, it can be summarised that operation phase was the major contributor of CED (67.5%), GWP (69.1%), AP (65.7%) and EP (77%). These results were mostly associated with the energy (i.e. CED) consumed in heating and cooling operations, which results in emissions such as CO_2 (main cause of GWP), sulphur and nitrogen compounds (main cause of AP), and phosphates and nitrates (main causes of EP). While construction and disposal phases were the main contributors of embodied water consumption (60.5%) and solid waste generation (89.3%), respectively. It is worth to note that embodied water quantification is not so accurate due to provisional method and still improving [57]. However, water measure provides a useful guidance to assess the likely environmental stress if not managed appropriately. For CED, water use, AP and EP, the results showed that the impacts are very similar with published literature. The contribution of solid waste in the disposal phase was varied widely with literature due to differences in the consideration of recycling and upcycling issues. The variation of GWP is originated mainly because of design life, dissimilar inventory data, system boundary and assumption considered.

5.2. *Sensitivity analysis*

Due to data uncertainty, sensitivity analysis was undertaken to assess the LCA robustness of the case study container building. In this study, lifespan, transportation distance and maintenance scenarios were evaluated for the sensitivity to LCA.

5.2.1. *Lifespan scenario*

The effects of changing the container building lifespan on LCA impacts are shown in Table 6. In this sensitivity analysis, the impacts of lifespan was analysed by considering 100 years instead of 60 years for the case study house. Standard maintenance was considered during 100 years design life, which consists of 3 major renovations at a 25-year interval and 9 times painting at a 10-year interval. It is to note that the impacts of construction phase remain same, as these are not time-dependent, and they have one-off impacts.

For all impact categories, the overall contributions of the whole life cycle impacts have increased significantly in the range of 55.4–74%. The maximum overall impact 74% came from water use. In terms of life cycle phases, although a maximum of 205.9% increase in water use came from disposal phase but the quantity

Table 6
Sensitivity LCA results and% difference with container case study house.

Home	Impacts	Unit & %	Construction	Operation	Maintenance	Disposal	Total
100 yr life Container farmed-home	CED	GJ	393.9	1953.9	401.6	17.4	2766.8
		% diff	0.0	66.7	147.0	95.5	59.2
	Water use	KL	1850.5	26.8	3434.1	5.2	5316.6
		% diff	0.0	66.5	189.1	205.9	74.0
	Solid waste	Ton	3.6	0.7	2.0	63.8	70.1
		% diff	0.0	75.0	185.7	62.8	59.7
	GWP	Ton CO_2-eq	25.7	119.3	25.2	-6.4	163.8
		% diff	0.0	66.6	165.3	100.0	58.1
	AP	Kg SO_2-eq	147.7	604.1	104.1	1.2	857.1
		% diff	0.0	66.7	156.4	50.0	55.4
	EP	Kg PO_4- eq	15.7	124.3	13.8	1.3	155.2
		% diff	0.0	66.6	137.9	62.5	60.2
Container farmed-home: 100 km Transportation distance	CED	GJ	402.5	1172.3	163.6	9.7	1749
		% diff	2.2	0.0	0.6	9.0	0.7
	Water use	KL	1850.5	16.1	1188.0	1.6	3056.2
		% diff	0.0	0.0	0.0	0.0	0.0
	Solid waste	Ton	3.6	0.4	0.7	39.2	43.9
		% diff	0.0	0.0	0.0	0.0	0.0
	GWP	Ton CO_2-eq	26.2	71.6	9.5	-3.1	104.2
		% diff	1.9	0.0	0.0	-3.1	0.6
	AP	Kg SO_2-eq	150.4	362.4	40.9	1.1	554.8
		% diff	1.8	0.0	0.7	37.5	0.6
	EP	Kg PO_4- eq	16.1	74.6	5.9	0.9	97.5
		% diff	2.5	0.0	1.7	12.5	0.6
Low maintenance container home	CED	GJ	393.9	1172.3	58.4	8.9	1633.5
		% diff	0.0	0.0	-64.1	0.0	-6.0
	Water use	KL	1850.5	16.1	1030.4	1.7	2898.7
		% diff	0.0	0.0	-13.3	0.0	-5.2
	Solid waste	Ton	3.6	0.4	0.04	39.2	43.2
		% diff	0.0	0.0	-94.3	0.0	-1.6
	GWP	Ton CO_2-eq	25.7	71.6	3.3	-3.2	97.4
		% diff	0.0	0.0	-65.3	0.0	-6.0
	AP	Kg SO_2-eq	147.7	362.4	18.1	0.8	529.1
		% diff	0.0	0.0	-55.4	0.0	-4.1
	EP	Kg PO_4- eq	15.7	74.6	2.1	0.8	93.2
		% diff	0.0	0.0	-63.8	0.0	-3.8

Gray shade- for easy identification of the highest value; % diff- difference with case study

wise major increase came from maintenance phase. The reason is due to additional major and minor renovations in the span of 100 years life cycle. On the other hand, the quantity wise contributions of CED, GWP, AP and EP were higher in operation phase, while percent wise maximum contributions were in maintenance phase (137.9–189.1%). Impacts in both operation and maintenance phases were increased significantly, in proportion to the lifespan due to major and minor renovations. Also because of renovations, 100 years design life container home produced 62.8% additional solid waste during disposal phase. Hence, the proportions of the contribution of different life cycle phases were sensitive to design life of a building except construction phase.

The study [14] has reported on sensitivity of LCA impacts when the 3.6-star building lifetime was analysed for 50 and 100 years in Brisbane climate. It was reported that the whole life GHG and CED were increased by 71 and 64% respectively. This is slightly higher than this container house mainly because of lifespan increase from 60 to 100 years and also due to dissimilarities in star-rating and annual heating/cooling loads between Melbourne and Brisbane climates. Due to variation in annual heating/cooling loads, differential star-band score thresholds are used for Melbourne and Brisbane climates. For example, a 6-star home in Melbourne and Brisbane must achieve different annual heating/cooling requirements of less than 114 and 43 MJ/m^2, respectively, while for 3.6-star housing, these figures jumps to 226 and 83 MJ/m^2, respectively. In a similar sensitivity study [16] for 50 and 100 years lifespan, the reported whole life GHG and CED for eight heritage buildings (e.g. 0.8–5.1 star) in Melbourne climate, were increased by averages of 47 and 46% respectively. This is slightly lower than this container house of 60 years lifespan.

5.2.2. Transportation distance scenario

In the container case study building, the construction materials were assumed to be transported 50 km from the manufacturing gate to the construction site using an articulated 30-ton truck. Demolition wastes were assumed to be transported 30 km from the construction site to the landfill using a garbage transit truck. In order to analyse the sensitivity of transportation impact, 100 km distances were assumed in both the construction and demolition cases into the *SimaPro* LCA model. The variation in transport distance as shown in Table 6 indicates insignificant differences as a whole life cycle in any impact categories. Although disposal phase showed appreciable variations in AP (37.5%), EP (12.5%) and CED (9%), the variations of absolute quantities were low. In construction phase, although the CED, GWP, EP and EP showed slight differences (e.g. 1.8–2.5%), water use and solid waste showed no differences. On the other hand, operation and maintenance phases showed very negligible variations.

5.2.3. Low maintenance scenario

A low maintenance scenario was evaluated compared to standard maintenance to show the sensitivity of impacts. In the low maintenance scenario, the major renovation (e.g. replacement of plasterboard, ceramic tiles, plaster render, timber floors and ceilings) at 30-year time was changed with replacement of plasterboard only. Maintenance comprised of repainting, was changed from 10 year to 20 year interval. Therefore, it means that 1 time in plasterboard replacement and 2 times in painting.

The differences of impacts between standard and low maintenance scenarios are shown in Table 6. Significant decreases of impacts are apparent in the maintenance phase only, while construction, operation and disposal phases remain same as expected. In whole of life cycle for all the impact categories, the decreases were between 1.6 and 6%. The study [20] has reported a similar result for low maintenance on CED (5%).

Succinctly, for all impact categories, the overall contributions of the whole life cycle impacts have increased significantly due to design life of a building. While low maintenance scenarios show up to 6%, transportation distance scenarios show a negligible difference.

6. Implication of shipping container home

The shortfall of the balance of trade between Western and Asian countries has created a surplus of shipping containers in Western countries. It is more expensive to ship back rather than to build a new container in Asia. Hence, shipping containers can be attributed to widely called ‘upcycled’ (i.e. reused with minimal modification for another purpose) building materials. Although shipping containers can be modified to create complex and luxurious homes, it is not so practical for permanent residential dwelling to occupy in Australia and elsewhere. Some qualities of container home such as strength, reusability and constructability provide a range of flexibility that enables the occupant to make it their own. To have better performance, container homes not only utilize shipping containers itself, but it uses a variety of prefabricated building elements in their assemblies of floors, walls and roofing designs. All these processes may have higher economic and environmental impacts.

After considering construction costs, stakeholders generally select the building material complying star rating for local climate. The higher star rating means the lesser energy required for heating and cooling. Several authors pointed that comparatively less amount of energy will be required to repurpose the shipping containers into home buildings [11,5]. It allows some possibility of energy-saving designs with upcyled options rather than to recycle or dispose-off in landfill. However, what is the certainty that the shipping container provide better design from life cycle energy and environmental perspective? Is the shipping container providing the same with traditional building material if container considered as home building assemblages? Is the upcycled shipping container significant, compared to traditional timber framing building? What would be the value for stakeholders, if environmental indicators were considered? What change would be significant for the industry?

A container home offers a fast, green, and sustainable approach to building because of its standardized and reliable factory-controlled manufacturing. An average sized home can be built with almost no wood. If the upcycled container is used as framing in this container case study, an additional 1.98-ton timber framing material can be saved, as estimated from bill of quantity (BOQ). According to the inventory of carbon and energy (ICE), 1.98-ton softwood requires 891 MJ energy, and consumes 14.7-ton CO_2-eq [41]. On the other hand, container building involves energy intensive steps. Before reaching the construction site, the container building requires some modification and manufacturing process to produce finished product, so environmental impacts may be high. A major issue is that a large amount of materials and construction techniques may be required for the production processes. Transporting the prefabricated container home may also generate substantial energy input.

Although the upcycling of shipping containers is appeared to be a green construction, there is mixed arguments regarding the sustainability of using containers for home building purposes, due to the additional cost and energy which may be needed to make it a habitable space comparing with traditional building. However, there is still lack of an in-depth sustainability study to evaluate life cycle environmental impacts and costs required to make a shipping container home liveable, comparing with traditional building method. In order to draw a full picture, further work is planned to investigate the effect of life cycle environmental impacts and cost considering both traditional and container home buildings.

7. Conclusions

The sustainability of a new product like ‘upcycled’ shipping container in building industry primarily depends on environmental benefit of the materials and methods used. The prospect of using shipping container in building was assessed in terms of its constructability and life cycle environmental impacts. This was tested in this research by investigating a case study container dwelling for 60 years design life. The results show that the CED, GWP, AP and EP were the most dominant impact indicators for the operation phase, while water use was for the construction phase, and solid waste was for the disposal phase. The impact contributions of CED, embodied water, AP and EP are very similar with published literature, while the variation of GWP was mainly because of dissimilarity in design life, inventory data and system boundary considered. Due to differences in the consideration of recycling and upcycling, solid waste in disposal phase was also varied widely. If the design life of a building is increased from 60 to 100 years, the overall whole life cycle impact indicators have increased significantly in the range of 55.4–74%. The impact between standard and low maintenance scenarios were varied by marginal decrease in the range of 1.6–6.8%, while transportation scenario shows a negligible difference. Further work is planned to investigate of the effect of life cycle environmental impacts and cost of traditional and shipping container buildings.

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