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Effect of Star Rating Improvement of Residential Buildings on Life Cycle Environmental Impacts and Costs

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Abstract: A diagnostic framework is proposed to assess the influence of star rating improvement for residential buildings on life cycle environmental impacts and life cycle costs (LCEI and LCC) using life cycle assessment (LCA) and life cycle costing methods, respectively, on all life cycle phases (i.e., construction, operation, maintenance, and disposal). A reference house was modified on the basis of six alternative designs to deliver a particular star rating in order to demonstrate the analysis framework. Two LCIA methods (i.e., material flows/add masses and eco-indicator 99 Australian substances) were used to estimate ten LCEI indicators under two categories: seven from problem-oriented (i.e., raw material, air emission, water emission, eco-toxicity, acidification/eutrophication potential, ozone depletion, and climate change) and three from damage-oriented (i.e., resource depletion, ecosystem quality, and effect on human health) categories. The three damage-oriented indicators were combined to evaluate environmental and economic wellbeing on a single eco-point basis. All these combinations of impact indicators can offer three lines of analytical options along with star rating: problem-oriented, damage-oriented, and a variety of problem and damage-oriented LCEIs with LCCs. Hence, the optimum house selection is-based not only on cost or star rating, but also on LCEIs.

Keywords: eco-indicator 99 method; material flows/add masses; star rating; life cycle cost; life cycle environmental impacts; ecosystem quality

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1. Introduction

In recent years, the building industry has made considerable efforts to minimize the use of energy throughout the life cycle by increasing a building's star rating. The primary emphasis is on reducing the energy consumption in every life cycle phase of a building. The overall energy consumption depends on the operational stage and integrated setup of all of the life cycle phases of a building. A building's star rating mainly depends on its fabric/envelope components (i.e., wall, floor, and roofing), along with ancillary elements like window glazing and shading, sealing, ventilation, orientation, etc. Building materials with varying heat conduction and retention properties may create comfort for inhabitants. Climatic conditions worldwide also influence the proportions of embodied energy versus operational energy due to the materials [1]. It has been reported that a lower proportion of embodied energy can be found in colder climates compared to warmer climates [2]. Previous studies have focused on optimizing environmental impacts and costs associated with materials and construction methods throughout the life cycle [3–6]. Some studies have described zero-energy or nearly-zero-energy homes [7–10], which require additional insulation, higher-performance green materials, glazing, airtightness, and solar PV. However, it is necessary to justify the integration of insulation materials with PV installation (storage facility) through an exhaustive sensitivity analysis. Maximizing the installed PV and using vacuum insulation panels have been identified as feasible solutions for nullifying environmental impacts and ensuring energy efficiency [11]. Green materials might have fewer environmental impacts, although they require additional costs during building and throughout the whole life cycle [12,13]. The life cycle of a building consists of the construction, operation, maintenance, and disposal phases. Therefore, optimizing life cycle cost (LCC) and life cycle environmental impact (LCEI) throughout the whole building design is crucial.

House energy rating is a key indicator of a building's thermal performance. Currently, it is required that residential dwellings in several states of Australia be constructed with a 6-star rating. Higher-rated homes provide better thermal comfort, which reduces heating and cooling requirements [14,15]. A building's thermal comfort, energy efficiency, and conservation are interrelated matters. There are many ways to incorporate thermal comfort into building design. Previous studies have focused on thermal comfort and energy efficiency by incorporating improved insulation, glazing, and building orientation to increase star ratings. Some of them have considered aspects of insulation and building orientation [16], solar gain and the use of daylighting [17], and green elements, e.g., solar systems, green roof technology, and low-E (low-emissivity) windows [18]. Meanwhile, some studies have discussed the sustainable construction of zero-energy homes, while anticipating cost to be a barrier to implementing green and energy-saving elements.

Both costs and environmental impacts in building [19–23] and building-related energy system [24] designs have been reported without consideration of star rating. Several recent studies [25–27] have described the optimization of the life cycle cost and environmental impact of buildings. The study by Stephan [28] estimated the life cycle costs and energy requirements related to varying energy reduction events. The review by Saynajoki et al. [29] summarized the findings of many case studies on the variation in GHG emissions resulting from methodological choices. Star rating improvements during the operational heating and cooling phases of buildings have been reported both with LCC [30,31] and without LCC [32]. A life cycle green cost assessment (LCGCA) concept was proposed to promote a standard monetary unit for collectively measuring life cycle costs and environmental effects [33]. However, discussions of star rating improvements using fabric elements and other ancillary elements are very limited in the literature. In this study, the star rating of the building is modified by changing the insulation and cladding materials, assemblies, and a few specific ancillary elements as a trade-off with LCC and LCEI for the entire building and throughout its entire life cycle. Base House, a reference study house in Brisbane, Australia, was adapted to achieve different star ratings.

LCC and LCEI will be evaluated using the life cycle costing and life cycle assessment (LCA) methods. The outcome of any LCA is to assess the possible environmental impacts connected to products, processes, or services [34–36]. Region- or country-specific life cycle impact assessment (LCIA) procedures are also accessible by using LCA software. SimaPro, one of the most widely used LCA software packages, incorporates many LCIA methods for Australia and elsewhere. Several of these LCIA methods are specific to the Australian region. The range of impact indicators is the main difference among different LCIA methods. Hence, the selection of the LCIA method is contingent on the environmental issues that are the prerequisites for the study. However, there are no approved LCIA methods in Australia or elsewhere [37]. ISO 14044 provides standardized guidelines for LCIA [38]. This study applies two LCIA procedures: (a) Material flows/add masses; and (b) Eco-indicator 99 (H) Australian substances. The impacts are characterized under two categories: (i) the problem-oriented category (i.e., raw material, air emission, water emission, eco-toxicity, acidification/eutrophication (AP/EP), ozone layer depletion, and climate change); and (ii) the damage-oriented category (i.e., resource depletion, ecosystem quality, and effects on human health). In the Eco-indicator 99 (H) method, the damage-oriented indicators are combined into a single scored value to evaluate environmental and economic wellbeing ranges into easily comprehensible units (eco-points). Hence, all ten of these indicators are able to offer three choices for optimization along with different star ratings: problem-oriented LCEI with LCC, damage-oriented LCEI with LCC, and the combination of the problem- and damage-oriented LCEI with LCC, to compensate for the different designs under consideration. It should be noted that although Eco-indicator 99 is an old method, it was used here for the purposes of comparative study. The relative magnitude would not vary much if other LCIA methods were used.

2. Star Rating of Residential Buildings—A Critical Review

Buildings with higher star ratings require a smaller amount of energy to achieve the preferred thermal competence. This section critically reviews contemporary issues related to the star rating and some provisions, e.g., deemed-to-satisfy (DTS), along with tools, e.g., environmentally sustainable design (ESD), of buildings. It also discusses the implications of the star rating on the building design's economic and environmental performance.

2.1. StarRating, DTS Provisions, and ESD Tools

To increase the energy efficiency of buildings, the Building Code of Australia (BCA) offers incentives for adopting a star rating system and DTS provisions [39]. The star rating is a benchmark that specifies thermal performance on the basis of a number of stars. A generic term called the home energy rating system (HERS) was proposed to assess this. It is also a nationally recognized system under NatHERS (nationwide house energy rating scheme) in Australia. It encourages energy-saving design and construction by providing a consistent approach to estimating and ranking residential buildings' potential thermal performance. Most Australian states and territories enacted a minimum star rating of 3.5–4 for new homes starting from July 2003. This was increased to a 5-star minimum in 2006 [40]. Since May 2011, in several Australian states, all new houses, extensions, and modifications must attain a 6-star energy rating [41].

Several star rating software systems are available to establish compliance for the residential sector of Australia. In this regard, AccuRate Sustainability, FirstRate5, and BERS Pro are used to assess the star rating of a building enclosure. The use of these star rating systems is mandatory, and they are accredited under NatHERS protocol. The annual heating and cooling loads of a building project are assessed using these energy rating tools in order to provide a star rating [42].

BCA introduced DTS provisions to assist people who were unable to achieve 6-star compliance for some classes of building in Australia. The DTS provisions include a range of commonly practiced cost-effective building applications, for instance, insulation in the wall, floor, and roofing, and low-solar-heat-conductance glazing. It also includes energy-saving lighting and air conditioning, shading, and ventilation. Alternatively, some building assessment tools, for example, BASIX, Green Star, NABERS, BESS, and eTool, can be used for the ESD system. The principle behind ESD is to provide support for the construction of buildings that will lessen their environmental impact due to their ongoing use. Some ESD tools are mandatory in some states in Australia, such as BASIX for New South Wales. Several ESD ratings are voluntary, dealing with energy performance and a number of other variables. In the case of Green Star, NABERS, and BESS, these variables include material selection and construction, water consumption, environmental impacts, waste generation, and indoor environmental situations. These tools allow owners, tenants, property agents, and managers to review and improve environmental performance throughout the design, construction, and life of a building. ESD rating tools are designed according to local climatic and geographic conditions. When comparing the effectiveness of these rating tools, the local climate and geography need to be considered. For example, a Korean green building certification system was proposed in [43], allowing the integrated application of LCA results with green standards for environmental design.

2.2. Star Improvement Options

The primary goal of star improvement is to increase the thermal comfort of homes throughout the year. The temperature exceeds the comfort threshold in many parts of Australia due to its large diurnal and seasonal ambient temperature ranges [44–47]. For example, discomfort in Melbourne and Hobart occurs due to winter cold, while in Brisbane and Sydney this is due to warmness much of the year. Due to these differences, building typologies are often varied, and thus demand considerable cooling or heating.

According to the Energy Smart Housing Manual [46], inhabitants' energy efficiency and comfort can be achieved by implementing the highest and lowest comfortable temperatures in summer and winter, respectively. Residential buildings lose an average of 60%, 10%, and 30% of their heat during winter through their roofing, floors, and walls, respectively, necessitating supplemental heating to achieve the desired thermal comfort. These heating losses can be minimized by implementing 'tight design' (e.g., airtight windows). On the other hand, for the convenience of inhabitants, buildings require substantial air exchange in the summer. Well-fitted windows and doors, walls, roofing, and floors, considerably impact the thermal comfort of buildings. A well-designed ventilation system can save a substantial cooling load (up to 30%) in summer [48].

The star rating of a building depends on the thermal characteristics of the building fabrics, which can be improved by adding adequate insulation [49]. Effective insulation can save about 45–55% of the energy required for cooling and heating [50]. Insulation can be used in roofing, walls, and under floors to significantly impact energy savings [51]. Other adjustments such as size and windows, glazing type, sealing of doors and windows, shading by eaves and external blinds, and use of ceiling fans may considerably reduce energy consumption [52]. The most increase in star rating has been reported to be a result of the glazing type, which increases the star rating by an average of 0.49. Double-glazed windows are hermetically sealed insulated glass units (IGUs), which significantly beat standard single-glazed windows in terms of both insulation and noise reduction [45]. The extra two inner surfaces of the unit and the resulting sealed cavity are able to meet a wide range of performance criteria, such as higher insulation attributes, reduced solar heat transmittance, and improved resistance to UV light entry. However, window performance can be severely compromised if air or water infiltrates through the gaps between the frame and the sash.

2.3. Life Cycle Environmental Impacts and Cost Assessment Studies

The system description, assumptions, boundaries, and results of impact categories from previous life cycle environmental assessment studies are summarized in Table 1. A high degree of dissimilarities is apparent among these studies, particularly with respect to building life span, star rating, location, and climatic impact contribution in different life cycle phases. The median value building lifespan was 50 years. The results of each study depend on building typology, construction material, star rating, and whether the impacts of appliances (e.g., water heating, lighting, and cooking) are included in the operation phase along with heating and cooling loads. Each study concentrates on various environmental impacts depending on the research focus in the considered life cycle phases. For example, ref. [53] presented the outcomes during the construction, product, use, end of life, and beyond building life cycle phases, while [54] presented outcomes in the material, construction, use, and disposal phases. On the other hand, refs. [55–57] presented impact results for the construction, operation, maintenance, and disposal phases, while [58] presented them in the construction, use, and disposal phases only.

Table 1. Summary of recent life cycle environmental assessment studies of buildings.

Study	System Description, Assumption, and System Boundary	LCEI (%)	Life Phases			
			C	O	M	D
[46]	Australian climate (Melbourne), two multi-storey residential apartment buildings, 7-star rating with 60-year lifetime; includes five different life cycle stages: product, construction, use, end of life and beyond building life cycle; use phase includes the effect of maintenance and operational heating/cooling, lighting, water use, and hot water; end-of-life phase includes waste in landfill and recovery from recycling; beyond building life cycle phase includes recovery of materials after the building is demolished; excludes onsite installation processes and apartment appliances, lift systems, etc.	Climate change	The % contribution ranges for the construction, product, use, end of life, and beyond building life cycle phases are 1–1, 8–12, 88–91, 1–2, and −2 to −2.			
		Oz. dep.	The % contribution ranges for the construction, product, use, end of life, and beyond building life cycle phases are 12–13, 35–39, 43–52, 5–9, and −3 to −4.			
[1]	Australian climate (Brisbane), variety of buildings with different star ratings with 50-years lifetime; excludes interior decorations and household appliances, includes renovation in maintenance; star rating specified; disposal phase includes transportation and materials to landfilling only, no recycling.	GHG	34–41	54–63	7–11	−5 to −6
		CED	35–40	44–52	10–14	1–1
		Water	54–63	1–2	35–43	0–0
		Waste	4–6	2–2	6–7	86–87
[47]	Australian climate (Melbourne), 9-storey apartment building and 6-star fictitious reference building, an average of 6.8-star rating apartment with 50-year lifetime; includes four different life cycle stages: materials, construction, use, and disposal; construction waste is omitted from the system boundary; use phase includes heating, ventilation, and cooling (HVAC), lighting and (hot) water use; disposal phase includes demolition of the building at the end of life and subsequent waste management (i.e., landfill and recycling); excludes maintenance, appliances, human labor, and capital equipment.	GWP	The % contribution ranges for the material, construction, use, and disposal phases are 10–12, 1–2, 83–88, and −1 to 5.			
		EP	The % contribution ranges for the material, construction, use, and disposal phases are 21–27, 1–2, 75–77, and −1 to −3.			
		Water use	The % contribution ranges for the material, construction, use, and disposal phases are 5–7, 0–0, 94–96, and −2 to −2.			
[9]	Australian climate (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.	GWP	31–39	53–68	4–6	−1 to −4
		EP	34–44	51–61	6–8	−1 to −4
		R. Dep.	30–46	50–66	4–6	−1 to −3
[48]	Spain and Columbian climate, two houses, 50-year lifetime; includes HVAC, illumination, domestic hot water, electrical equipment, and cooking; star rating and appliance energy efficiency not specified; disposal phase includes transportation and landfilling. Note: results are approximated from graphs.	GWP	9–28	62–88	2–7.5	1–2.5
		AP	1.5–7	90–97.5	0–2	1–1
		ODP	8.5–27.5	52.5–87	2–11	2.5–9

Table 1. *Cont.*

Study	System Description, Assumption, and System Boundary	LCEI (%)	Life Phases C	O	M	D
[49]	Hungarian residential house, 50-year lifetime; includes heating and cooling, hot water, lighting; does not specify star rating; excludes interior decorations; uses tabulated values for gross operation energy; disposal phase includes recycling (50 and their transportation.	GHG	14–21	67–72	7–11	3–5
		CED	14–20	68–77	6–13	1–2
		AP	26–33	48–54	14–23	2–3
		ODP		85–88		
		EP	35–42	31–38	17–28	−6 to 8
		Eco. Q		15–27		
		H Health R. Dep.		37–43 76–81		10–20
		T. point	17–20	62–69	9–16	3–6
[50]	European climate with three different zones; multifamily building; does not specify star rating; 50-year lifetime; use phase includes the operation (heating and cooling) and maintenance phases; disposal phase includes waste treatment and disposal.	GWP	8.2–34.7	65.3–91.8		0.7–5.5
		AP	8.3–35.9	64.6–91.7		−1.3–1.1
		EP	13.8–47.7	52.3–86.2		−0.6 to–1.9
		Oz. dep.	5.1–20.6	79.4–94.9		−2.3 to −0.3

Oz. dep: ozone depletion; GHG: greenhouse gas; CED: cumulative energy demand; water: embodied water use; waste: solid waste generation; GWP: global warming potential; EP: eutrophication potential; R. Dep: resource depletion; AP: acidification potential; ODP: ozone depletion potential; Eco. Q: ecosystem quality; H. Health: Human health; T. point: total eco-point.

The dissimilarities in terms of findings between these studies are due to the variance in the system assumptions with respect to maintenance and carbon sequestration on disposal. Due to the desire for consistent data, some studies did not report material replacement as part of maintenance, or omitted demolition from their processes [59]. While a few studies included maintenance, transport, and landfill, as well as the impacts of recycling and reuse, during the disposal phase, many other studies included transport impacts for the operation of landfill sites only [14]. The energy consumed during the operational phase indicates a considerable degree of variance, while that consumed during the construction phase was proportionally smaller.

The system description, study focuses, assumptions, limitations, and results from previous life cycle cost assessments are shown in Table 2, where dissimilarities are evident among those studies. The evidence regarding dissimilarities is dependent on a given location and climate, the lifespan of the building, star rating, and impact contribution in different life cycle phases.

Table 2. Summary of previous cost studies on residential buildings.

Study	Country, Study Focus, Assumption, and Limitations	Major Findings
[2]	Australian study; applied a life cycle costing modeling approach within an LCC framework of the whole building; 3.6- to 3.9-star design building; discount rate of 6%; 50-year lifetime; construction, operation, maintenance, and disposal costs are reported.	The average construction, operation, maintenance, and disposal costs are 62.8, 8.8, 25.7, and 2.7%, respectively.
[4]	Australian study; applied a life cycle costing modeling approach within an LCC framework of the whole building; 3.6- to 4.4-star design building; discount rate 6%; 50-year lifetime; construction, operation, maintenance, and disposal costs are reported.	Construction, operation, maintenance, and disposal cost ranges are 62–65, 8–10, 24–26, and 3–3%, respectively.
[23]	Australian study; applied a thermal performance modeling approach within an LCC framework; discount rate of 3.5% over 0–30 years; 3% over 30–70 years; only operating costs are reported; costs from other life cycle stages are not specified.	The energy-efficient building is the most cost-effective design.
[24]	Australian study; estimated retrofit cost to achieve a 6 star from existing lower rating houses; discount rate not specified; costs in each life cycle phase are not specified; house and land package are specified.	The average cost per star rating was $3415 ± 46%; an increase in construction cost of 1–2% results in a 6-star rating from the previous 4.9-star.
[33]	Australian study; examined the cost-effectiveness of thermal performance improvement measures; the discount rate is not specified; only construction costs are included; whole life cycle costs are not specified.	The construction cost is approximately $150,000 for a 4-star house; the average cost per star rating improvement is around $2600 for 5–6-star, and $9000 for 6–7-star, respectively.
[52]	Australian study; applied lifetime economic and environmental costs and benefits analysis by varying energy efficiency performance; discount rate 3.5% over 0–30 years; 3% over 30–70 years; operation costs are reported only; costs from other life cycle stages are not specified.	Zero-emission housing would be an achievable goal.
[53]	European study; estimated LCC of dwelling, including construction, operation, and maintenance; discount rate 4% over 50 years; disposal costs are not estimated separately.	Construction, operation, and maintenance costs are 65, 25, and 10%, respectively.
[54]	European study; estimated LCC of multifamily dwellings including periodic maintenance; discount rate 2.5% over 60 years; construction costs are not included.	Construction, operation, and maintenance costs are 50–60%, 23–34% and 13–20%, respectively.
[55]	European study; estimated LCC of residential dwellings; discount rate 4% over 50 years; disposal cost is not specified.	Construction, operation, and maintenance costs are about 56, 22, and 2%, respectively.
[16]	North American study; estimated LCC value of buildings, including construction, operation, and disposal costs; discount rate 2, 4, 6, 8% over 35 years; LCC is sensitive to discount rate; maintenance cost is not included.	Construction, operation, and disposal cost are 88, 11, and 2%, respectively.
[56]	North American study; estimated LCC of residential buildings, including mortgage (land and construction), operational and maintenance or improvement costs; discount rate 4% over 50 years; disposal costs are not included.	Mortgage, operation, and maintenance costs contributed 68–79, 3–9, and 20–22%, respectively.

Improved building star ratings not only have a positive outcome in terms of thermal performance, they can also ultimately significantly minimize environmental impacts and costs. Environmental and cost associations for buildings need to be analyzed in order to comply with the current 6-star rating. There is a link between energy efficiency and sustainable housing development in terms of social, economic, and environmental performance.

3. Methodology

Throughout a building's whole life cycle, i.e., the construction, operation, maintenance, and disposal phases, life cycle costing and life cycle assessment (LCA) methods were respectively applied to assess life cycle costs and environmental impacts (LCC & LCEI).

An existing house with a 3.6-star rating was identified as a Base House. This Base House was adjusted on the basis of six alternative designs for the purposes of this study. The star ratings of these six alternative houses were evaluated using AccuRate Sustainability software, developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation), Australia. AccuRate Sustainability was used to estimate the operational heating and cooling demands, which were then input into SimaPro LCA software. As such, the impact of star rating on LCEI & LCC was determined, and the optimal design was identified.

3.1. Life Cycle Assessment (LCA) Approach

PRé's *SimaPro* (v7.3) software for LCA conformed to ISO 14044 guidelines and was used to assess the LCEI of all of the life cycle phases of a complete building. SimaPro is particularly appropriate for studies on Australian dwellings, because of its inclusion of AusLCI, the Australian database [60,61]. The AusLCI database contains reasonably accurate data for Australian products and services [37]. The working object of the SimaPro software for the assessment of LCEI is a residential building with a 50-year design life, including all life cycle phases [62]. The products, processes, and services applicable for all life cycle phases were incorporated into the SimaPro software package.

The AccuRate Sustainability software package, endorsed by the Australian nationwide house energy rating scheme (NatHERS) and BCA and validated through BESTEST, has been widely accepted for estimating energy consumption during the operational phase. It includes a materials database that permits users to change building constituents and the assemblies of roofing, floor, and wall designs. Users can stipulate the construction technique and material, insulation level, window type and size, opening area, glazing, shading, sealing, ventilation, geographical location, and building orientation. It yields a value in MJ/m^2/year required to produce the desired level of thermal comfort. These outputs were then input into the SimaPro model for a design period of 50 years to evaluate the LCEI.

3.2. Life Cycle Costing Approach

Throughout the life cycle period, all pertinent costs related to construction, operation, maintenance, disposal, and residuals were obtained for the purposes of LCC analysis. All of the costs were estimated on the basis of present values (PV). Equation (1) was used to estimate future operation, maintenance, and disposal costs using present values. The estimates of future inflation were discounted using an appropriate discount rate [63], as shown in Equation (2).

$$FC = PV \times (1 + f)^n \tag{1}$$

$$DPV = FC/(1 + d)^n \tag{2}$$

where PV = present value, FC = future cost, DPV = discounted present value, d = discount rate, f = inflation rate, and n = number of years.

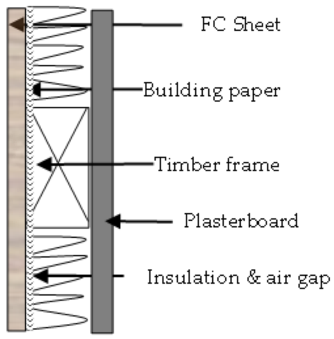
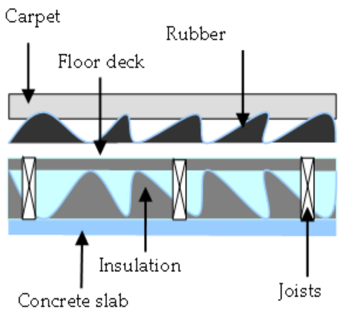
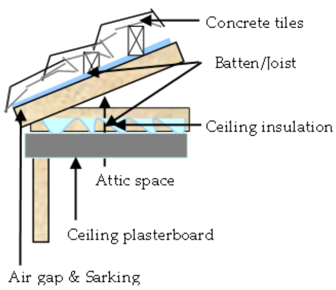
The standard construction cost guides adopted the LCC data for construction, maintenance, and disposal [64,65]. The operational energy heating and cooling costs were estimated using local utility rates [66,67]. The material and labor costs constituted the construction cost, while the cost of repainting and material replacement over a 50-year life cycle period was entered for maintenance cost. For all those modified houses considered, the costs associated with lighting, household water use, and water heating were omitted, as these were assumed to be identical [67].

4. Case Study House Selection

4.1. Case Study House

In light of recent housing industry trends in Australian capital cities [68], a standard residential townhouse/unit in Brisbane, constructed by a participant of the Building Designers Association, Queensland, was selected as the reference house for this study (referred to as the Base House). The house was given a 3.6-star rating, as determined by the energy rating software AccuRate Sustainability. The essential features and assemblies of the components (i.e., roofing, floor, and walls) of the Base House are described in Table 3. The sketches shown in the table are not to scale; these only portray the assembly arrangements used for the purposes of analyzing the building's floor, walls, and roofing (roof + ceiling) systems. The dwelling is an attached timber-framed double-story veneered brick building with three bedrooms, an attached garage, and a concrete-slabbed ground floor. The living room, kitchen, and laundry area with a lavatory are all situated on the ground floor, while a master bedroom with an attached ensuite, two small bedrooms, and another bathroom are all included on the upper floor.

Table 3. Assemblies, descriptions, and sketches of wall, roofing, and floor designs of the Base House.

Assemblies of Building Elements	Not to Scale Sketches	Description of (Base House)
External walls Fiber cement (FC) Sheet Building paper (reflective foil) Insulation and air gap Timber plates, studs, noggins Plasterboard		External walls (101 m^2) with FC sheet; face brick at the front wall (only 11 m^2) with uncolored mortar; timber frame; internal walls (52 m^2): 10 mm smooth finish plasterboard on studs, no insulation, and acrylic paint finish except for wet area walls.
Floors Carpeted top/timber floorboard Carpet underlay Plywood floor deck (12 mm) Reflective insulation Timber floor joists Concrete slab on ground		Carpet in bedrooms; timber floorboard on concrete slab in living and family room; tiles in kitchen and wet areas; plywood in upper floor decking; joist spacing and fixing under the tiled floor as manufacturer specifications; 101 m^2 total house floor area with 21 m^2 garage floor area; reinforced concrete strip footing and 100 mm concrete slab on the ground; 20 MPa grade reinforced concrete.
Roof and ceiling Concrete roof tile Air gap (40 mm) Sarking (reflective insulation) Timber rafters, battens Ceiling joists Ceiling insulation Plasterboard		Gable roof with 25° pitch; color-coated concrete roof tiles; total roof area: 125 m^2; 10 mm smooth finish plasterboard ceiling with R2.5 glass wool batt insulation over the plasterboard.

4.2. Alternative House Designs

The case study house was adapted using six alternative designs, using modified floor, wall, and roofing assemblages. Tables 4–6 illustrate the assemblages of the modified floor (e.g., F1, F2, and F3), wall (W1, W2, and W3), and roofing (R1, R2, and R3) designs. These modified floor, wall, and roofing designs were assembled in combination to build the above six alternative houses, as outlined in Table 7. These alternative houses and the Base House are abbreviated as H followed by their star rating, as determined using AccuRate software. The star ratings achieved by the alternative houses were all in the range of 3.6 to 4.9. It can be noted that there are two 3.9-star rating houses obtained, which are denoted as H3.9a and H3.9b, to differentiate their assemblages.

Table 4. Description of floor types.

Floor-Type	Ground Floor (Dining and Living)	Ground Floor (Wet Areas and Kitchen)	Upper Floor (Bedrooms and Corridors)	Upper Floor (Wet Areas)
F1 (BH—carpeted floor with less insulation)	Carpeted top Underlay (10 mm) Plywood deck (12 mm) Vapor barrier Concrete slab on ground	Ceramic tiles (8 mm) Plywood deck (12 mm) Vapor barrier Concrete slab on ground	Carpeted top Underlay (10 mm) Plywood deck (12 mm) Reflective insulation Timber floor bearers, joists Plasterboard	Ceramic tiles (8 mm) Vapor barrier Plywood deck (12 mm) Reflective insulation Timber floor bearers, joists Plasterboard
F2 (Timber floor)	T&G hardwood (19 mm) Underlay (10 mm) Plywood deck (12 mm) Glass fiber batt: R1.0 Vapor barrier Concrete slab on ground	Ceramic tiles (8 mm) Plywood deck (12 mm) Vapor barrier Concrete slab on ground	T&G timber board pine Underlay (10 mm) Plywood deck (12 mm) Reflective insulation Glass fiber batt: R1.5 Timber floor bearers, joists Plasterboard	Ceramic tiles (8 mm) Vapor barrier Plywood deck (12mm) Reflective insulation Timber floor bearers, joists Plasterboard
F3 (Mixed floor)	Ceramic tiles (8 mm) Plywood deck (12 mm) Glass fiber batt: R1.0 Vapor barrier Concrete slab on ground	Ceramic tiles (8 mm) Plywood deck (12 mm) Vapor barrier Concrete slab on ground	T&G timber board pine Underlay (10 mm) Plywood deck (12mm) Reflective insulation Glass fiber batt: R1.5 Timber floor bearers, joists Plasterboard	Ceramic tiles (8 mm) Vapor barrier Plywood deck (12 mm) Reflective insulation Timber floor bearers, joists Plasterboard

Table 5. Description of different wall assemblages.

Wall Type	Description of Assemblage
W1 (BH—FC sheet with less insulation)	Fiber cement (FC) sheet Building paper (reflective foil) Air gap (40 mm) Glass fiber batt R1.0 Timber frame, studs, noggins Plasterboard
W2 (Weatherboard wall)	Weatherboard (12 mm) Building paper (vapor barrier) Air gap (40 mm) Glass fiber batt: R1.5 Timber frame, studs, noggins Glass fiber batt: R1.5 Particleboard: 33 mm Plasterboard

Table 5. *Cont.*

Wall Type	Description of Assemblage
W3 (FC sheet wall)	Fiber cement (FC) sheet Building paper (vapor barrier) Air gap (40 mm) Glass fiber batt: R1.5 Timber frame, studs, noggins Glass fiber batt: R1.5 Particleboard: 33 mm Plasterboard

Table 6. Description of different roofing (roof + ceiling) assemblages.

Roofing Type	Description of Assemblage	
	Roof	Ceiling
R1 (BH—Gable tile roofing with less insulation)	Concrete roof tile (20 mm) Air gap (40 mm) Sarking (RFL) Softwood rafters, battens	Glass wool batt: R2.5 Softwood ceiling joists Plasterboard
R2 (Gable tile roofing)	Concrete roof tile (20 mm) Air gap (40 mm) Sarking (RFL) Softwood rafters, battens Glass fiber batt: R2.5	Polystyrene extruded: R3.0 Softwood ceiling joists Glass fiber batt: R1.0 Plasterboard
R3 (Skillion flat roofing)	Steel metal roof (2 mm) Air gap (40 mm) Sarking (RFL) Glass fiber batt: R1.5 Softwood rafters, battens Polystyrene extruded: R3.0	Rock wool batt: R3.0 Softwood ceiling joists Glass fiber batt: R1.5 Plasterboard

Table 7. Description of assemblages used to form different alternative houses.

House Name	Floor	Wall	Roofing	Description of Houses
H3.6	F1	W1	R1	Base House (BH) formed with F1, W1, and R1 combination
H3.9a	F1	W2	R1	BH modified with W2 weatherboard wall
H3.9b	F1	W1	R3	BH modified with R3 skillion flat roofing
H4.4	F3	W1	R1	BH modified with F3 mixed type floor
H4.6	F2	W2	R2	BH modified with F2 timber floor, W2 weatherboard wall, and R2 gable tile roofing
H4.8	F3	W3	R3	BH modified with F3 composite floor, W3 FC sheet wall, and R3 skillion flat roofing
H4.9	F3	W2	R3	BH modified with F3 composite floor, W2 weatherboard wall, and R3 skillion flat roofing

The modified floor assemblages included variations in floor tops and insulation materials. The selected floor tops included carpet, timber, and ceramic tiles. The Base House floor F1 used a carpeted floor with less insulation, while F2 and F3 used timber and composite floor (timber + ceramics) tops with higher levels of insulation.

The wall assembly's modification involved deviations in wall cladding in terms insulation, gaps, and positions in the array. The designated wall claddings were composed of fiber cement (FC) sheets and weatherboard. The Base House wall W1 used FC sheets with a lower level of insulation, while W2 and W3 were employed with higher levels of insulation.

The modified roofing assemblages include variations in the roof type, top material, and R-value of the insulations. The selected roof types and top materials were gable tiles and skillion metals. The Base House roofing R1 used gable tiles with less insulation, while R2 and R3 roofing used gable tiles and skillion metal with higher levels of insulation.

4.3. Data Generation

A complete list of the constituents and costs for the construction of the Base House was entered into the builder's Bill of Quantity (BoQ). The total amounts of materials used in the Base House were obtained by summing the quantities of each material used. Appropriate units were applied to the BoQ for LCC, LCA, and AccuRate inputs. The amounts obtained were estimated using representative values via conversion factors, for example, mass density and weight density sourced from customary industry references [64,69] and other published sources [70,71]. Operational energies, cooling, and heating only, were estimated in AccuRate and adapted to units fitting for the LCA input. For all of the modified houses, a similar approach was employed.

4.4. LCA System Boundary

The LCA system boundary, which comprised the phases related to construction, operation, maintenance, and disposal, is shown in Figure 1. The construction phase includes several activities: raw material extraction, basic building element production (e.g., timber studs, steel plates), and building part fabrication (e.g., timber floor, windows, doors). The related transport to the construction site of raw materials for elements/parts produced and fabricated is also included. The building site construction work may also include excavation, erection, and composition of different building components (i.e., walls, floors, roofing). Energy consumption during the operation phase, major/minor maintenance, and renovation work during the design life are all key modules included within the system boundary. At the end of the design life, the system boundary of the stated LCA also included demolition and transport of waste materials to landfill.

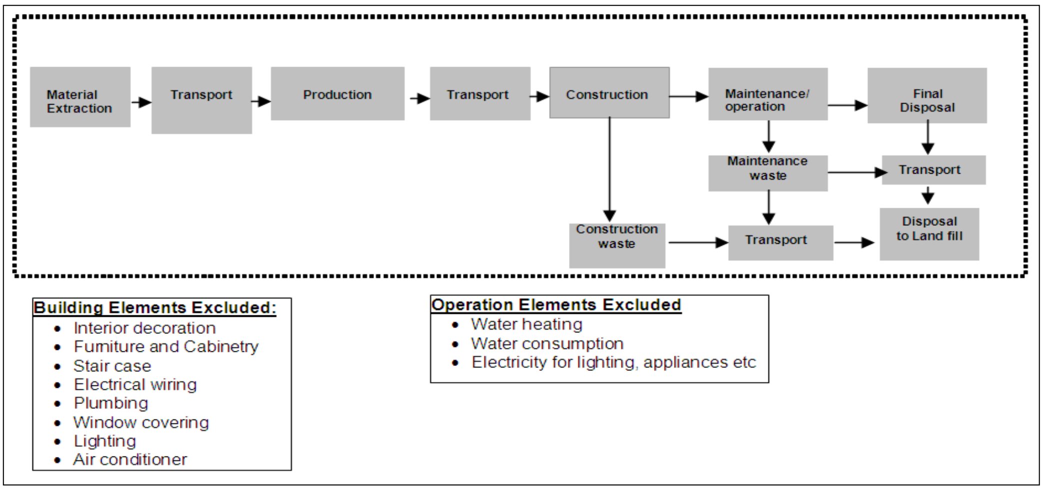


Figure 1. LCA system boundary.

In this study, the life cycle inventory (LCI) data used were categorized on the basis of technology, geography, collection method, age, source, and representativeness. AusLCI, an Australia-specific database, was used wherever applicable. The database on building materials was updated by the Building Product Innovation Council (BPIC) [62]. After the Australian electricity, and transport data had been adjusted, where the data was not yet available from the Australian sources, the European Eco-invent database was employed. This methodology has been used in several previous studies [72,73].

The assumptions and scope of previous LCA studies varied widely, leading to differences in emissions and other impact factors [74]. A comprehensive LCA can be performed in SimaPro by collecting data from real construction sites for proper outcomes. Interior decoration, technological improvement (construction waste recycling and reuse), water supply, and electrical appliances are excluded from the scope of this LCA. Electrical wiring, plumbing fixtures, accessories, furniture, sinks, kitchenware, built-in cabinets, machinery, and vehicles used temporarily on the construction site are outside the system boundary. The conducted LCA presents the emissions of construction materials extracted from the site's bills of quantities (BoQ). Moreover, urban infrastructure (i.e., roads, footpaths, and landscaping) are outside the scope of this project.

4.5. Construction

Data related to products, processes, and services used in the construction phase were entered directly into the LCA model SimaPro. Using the BoQ of the builders, the amount of each material was summed in order to estimate the total quantity of materials used in the building. Processes and services were included in the fabrication and manufacturing of the building components.

4.6. Operational Energy

The heating and cooling operational energies were calculated for average Brisbane weather conditions assuming continuous occupancy of standard four-person family occupant functions. The efficiencies of the heating and cooling machines and their coefficients of performance (COP) were employed to evaluate the precise energy requirements of the building. COP measures the rate of heat removed or added from an enclosed area. The Australian Minimum Energy Performance Standard (AS/NZS 3823.2) [75] was employed in this approach for air-conditioners [76]. An efficiency of 70% for a heating system and a COP of 2.79 for a ducted cooling system having a loss of 30% (equivalent to a COP of 1.96) were applied in this study. The AS/NZS 3823.2 [75] standard identifies a COP of 2.79 in Australian states for air conditioners [76,77]. Additionally, ducted cooling devices are Brisbane's most frequently applied system.

4.7. Maintenance

The average time interval required to arrange a renovation was determined from the existing literature. Major restoration work was launched in this study after 25 years, where interior materials, such as ceramic tiles, tiled roofs, ceilingsg, plasterboard, plaster render, and timber floors, were renewed. The outer envelope materials, for example, FC sheets, were also restored in this major restoration work. However, no replacement was considered for bricks due to their high durability. Repainting was regarded as minor renovation work. For repainting, there is a selection of timing in the literature of every 6 to 25 years. In this study, repainting work was considered to occur four times over a 50-year design life, every 10-year median time interval.

4.8. Disposal

All the building materials were assumed to be laid in a landfill at the conclusion of the designed lifespan. These building wastes remain in a landfill for a prolonged period, significantly impacting the environment. In this study, the transport of building materials 30 km to landfill was also assumed in carrying out the impact investigation. It is recognized that disposal technology will improve in the coming 50 years, which is challenging to anticipate now. Demolition and transport of waste constituents to landfills at the end of the design life were considered for this life cycle analysis.

4.9. LCIA Method and Indicators

For the evaluation of life cycle environmental impact (LCEI) indicators, SimaPro was applied during the life cycle impact assessment (LCIA) stage. There is no universally accepted method available for LCIA in Australia or elsewhere. The two LCIA methods used in this study were: (a) Material flows/add masses; and (b) Eco-indicator 99 (H). Ten impact indicators, including raw material, water emission, air emission, acidification/eutrophication (AP/EP), ozone layer depletion, eco-toxicity, climate change, resources, ecosystem quality, and human health, were considered in this study. At the endpoint of cause and effect, a damage-oriented approach under Eco-indicator 99 aims to combine the

LCA outputs into user-friendly, readily understandable units (i.e., eco-points). Effects on resources, ecosystem quality, and human health were the three damage categories considered in this study. Resource damage was estimated on the basis of surplus energy per kg (MJ surplus) resulting from extracted fossil fuels or minerals. Human health damage was evaluated on the basis of disability-adjusted life years (DALY). Damage due to ecosystem quality is reported as a potentially disappearing fraction of species in a specific space and time (PDF$\times$m^{2}yr). More specifically, this is the percentage of species that have died in a particular area and time due to environmental loading. Since this study looked at alternative buildings, the other categories of interest in terms of indicators could be land use impact and bio-diversity, which could not be included here due to the lack of appropriate inventory data [5,62].

4.10. LCC Modeling Assumptions

The future operation, maintenance, and disposal costs were estimated using today's prices and anticipated inflation rate. Therefore, these future costs were converted into present values using a discount rate. To avoid complexity and to be within the scope of this study, costs such as property taxes, settlement costs related to land and other fees, electrical wiring, plumbing, interior decoration, furnishing, cabinetry, staircase, and air conditioning were not incorporated into the costing analysis. It was anticipated that those costs would all remain similar for the different variations of the considered building. The salvage value (resale cost) was also not incorporated in this study due to the lack of reliable and valid data. An average inflation rate of 3% based on the last ten years of Australian inflation rates [78] was considered for this study. A discount rate of 6% was contemplated, as per the suggestion of the Department of Infrastructure [79]. All costs were estimated in Australian dollars for the purposes of this study.

5. Results and Discussion

5.1. LCA Results

The LCA outcomes of ten impact indicators, including raw material, air emission, water emission, eco-toxicity, acidification/eutrophication, climate change, ozone layer depletion, resources, ecosystem quality, and human health, are given in Table 8. All these impacts are shown for all life cycle phases (i.e., construction, operation, maintenance, and disposal). The individual score of resources, ecosystem quality, and human health are also shown in the last row of Table 8. The effects on resources, ecosystem quality, and human health were determined by means of normalization and weighting processes.

In particular, the results of different scenarios when varying the materials used to obtain different star ratings are compared to the reference Base House H3.6. Upgrading the star rating leads to a significant reduction in midpoint and endpoint impacts. However, beyond a specific threshold, damage categories tend to increase, such as by 4%, 11.4%, and 2% for climate change, ecosystem damage, and resources, respectively, when upgrading H4.8 to H4.9. These values range between 7% and 17% with respect to the Base House, showing that the improvement of energy rating in H4.8 represents the optimum solution, as discussed in the paragraphs on the different impact categories, below.

Raw material: Table 9 shows that the main impacts were found to occur during construction (74.4–78.9%), operation (12.3–16.8%), and maintenance (8.1–8.7%). The disposal phase presented a negligible impact. There are almost no studies reporting the raw materials employed in each of the different life phases of buildings. Compared to the Base House, the maximum change (i.e., total change, %) was found for the H3.9b house, as shown in Table 10. The reason for this may be the use of a skillion metal roof, which is much lighter than a gable roof. The required quantity of raw material expressed per unit of livable floor area (i.e., excluding the garage), was 1.57–1.67 ton/m^2. The improvement per star rating was found to be in the range of 1.5 and 35.7 tons.

Table 8. LCA results for all the house designs.

Category/LCEI Method		Impact & Unit	Life Cycle Phase	LCA Results of All Houses						
				H3.6	**H3.9a**	**H3.9b**	**H4.4**	**H4.6**	**H4.8**	**H4.9**
Mid-Point Category	Material flows /add masses	Raw material (ton)	C	125.7	127.2	120.9	125.8	128.1	127	131.5
			O	28.4	27.0	24.4	20.2	20.7	20.8	22.0
			M	14.7	13.5	12.8	18.1	14.2	13.1	13.5
			D	0.1	0.038	0.040	0.131	0.036	0.067	0.006
			T	168.9	167.7	158.2	164.3	163.0	160.9	167.0
		Air emission (ton)	C	30.5	30.4	31.3	30.5	33.5	32.5	32.3
			O	47.5	43.8	40.9	34.6	33.9	33.8	35.9
			M	8.9	8.6	7.5	7.9	9.0	8.0	8.6
			D	8.4	10.0	8.6	7.9	9.6	9.3	10.6
			T	95.3	92.9	88.4	80.9	85.9	83.6	87.5
		Water emission (kg)	C	385.2	385.3	357.0	385.2	398.1	390.4	447.3
			O	15.7	14.9	13.4	11.2	11.4	11.5	12.1
			M	315.2	308.0	264.8	331.8	305.2	297.5	308.0
			D	5.3	5.4	5.1	5.4	5.2	5.2	5.4
			T	721.3	713.6	640.4	733.6	719.9	704.6	772.8
	Eco-Indicator 99 (H) Australian Substances	Eco-toxicity (PDF×m^{2}yr)	C	15,132.3	14,731.9	1511.9	15,132.3	1602.4	1544.2	1526.7
			O	6389.5	6065.4	548.7	4560.4	465.7	468.5	493.9
			M	2166.9	1579.7	144.4	2538.5	212.7	154.5	158.0
			D	−71.0	−84.7	−8.3	−63.9	−8.5	−7.8	−9.0
			T	23,617.8	22,292.2	2196.7	22,167.3	2272.2	2159.4	2169.6
		AP/EP (PDF×m^{2}yr)	C	589.9	596.5	641.2	589.9	683.2	671.7	634.4
			O	1205.8	1078.4	1044.3	897.9	838.7	831.4	891.9
			M	153.8	142.8	130.5	148.2	146.8	135.3	142.8
			D	40.8	42.0	40.6	33.8	37.5	33.4	42.6
			T	1990.4	1859.7	1856.6	1669.8	1706.3	1671.8	1711.7
		Ozone layer depletion (DALY) × 10^{-5}	C	0.1	0.1	1.9	0.1	1.9	1.9	2.4
			O	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
			M	0.08	0.07	0.07	0.09	0.08	0.08	0.08
			D	0.0006	0.0006	0.0005	0.0006	0.0005	0.0005	0.0006
			T	0.1807	0.1707	1.9706	0.1907	1.9806	1.9806	2.4807
		Climate change (DALY) × 10^{-5}	C	433.4	384.4	467.6	433.4	478.6	500.0	435.0
			O	1017.0	938.9	876.9	740.8	725.2	700.0	770.0
			M	165.7	145.0	137.2	170.1	166.2	100.0	145.0
			D	88.3	101.0	97.6	92.6	105.4	100.0	106.0
			T	1704.5	1569.4	1579.3	1437.0	1475.3	1400.0	1456.0
Damage Category	Eco-Indicator 99 (H) Australian Substances	Human health (Pt)	C	834.0	832.4	753.3	834.0	970.0	958.7	914.5
			O	832.8	765.1	718.6	608.7	591.6	590.4	628.4
			M	224.6	214.5	204.2	319.3	218.7	207.4	214.5
			D	26.1	28.4	27.1	26.7	28.5	27.9	29.3
			T	1917.5	1840.4	1703.1	1788.7	1808.7	1784.3	1786.6
		Ecosystem quality (Pt)	C	1086.5	1133.5	1079.4	1086.5	1055.4	1094.5	1191.7
			O	152.4	139.5	131.5	111.7	107.9	107.6	114.7
			M	193.9	233.2	176.2	99.2	140.7	179.8	233.2
			D	3.4	3.6	3.4	3.1	3.3	3.1	3.6
			T	1436.2	1509.8	1390.6	1300.5	1307.4	1385.1	1543.2
		Resource (Pt)	C	1163.4	1188.6	1243.5	1163.4	1373.7	1356.5	1330.9
			O	939.6	771.4	822.8	738.4	611.9	593.1	653.3
			M	439.6	422.9	375.0	476.9	427.0	409.8	422.9
			D	41.1	41.6	40.1	42.8	41.4	41.5	41.9
			T	2583.6	2424.6	2481.4	2421.4	2453.9	2400.9	2449.0
		Single score (Pt)		5937.4	5774.7	5575.1	5510.6	5570.0	5570.3	5778.8

C: construction; O: operation; M: maintenance; D: disposal, T: whole life. Light & dark gray shades to indicate minimum & maximum values in that row (T: whole life).

Table 9. Percent contribution in each life cycle for different impact categories.

Phases %	Raw Material	Air Emission	Water Emission	Eco-Toxicity	AP/EP	Ozone Depletion	Climate Change	Human Health	Ecosystem Quality	Resource
C (%)	74.4–78.9	32.0–39.0	52.5–57.9	64.1–71.5	29.6–40.2	52.4–96.7	24.5–35.7	43.5–53.7	75.1–83.5	48.0–56.5
O (%)	12.3–16.8	39.5–49.8	1.5–2.2	20.5–27.2	49.2–60.6	negligible	49.2–59.8	32.7–43.4	7.4–10.6	24.7–36.4
M (%)	8.1–8.7	8.5–10.5	39.9–45.2	6.6–11.5	7.0–8.9	3.2–47.2	7.1–11.8	11.6–17.9	7.6–15.4	15.1–19.7
D (%)	negligible	8.8–12.1	negligible	negligible	2–2.5	negligible	5.2–7.3	1.4–1.6	negligible	1.6–1.8

C: construction; O: operation; M: maintenance; D: disposal, T: whole life. Gray shade to indicate the maximum value in that column (impact category).

Air emission: The major impacts were found for construction (32–39%) and operation (39.5–49.8%), as shown in Table 9. The maintenance and disposal phases accounted for (8.5–10.5%) and (8.8–12.1%), respectively. The maximum total change (%) compared to the Base House was found for H4.4, followed by H4.8, as shown in Table 10, which may be due to the use of a composite floor. Houses H4.4 and H4.8 had minimal air emissions in the operation and maintenance phases. Throughout the whole life cycle, the required quantity of air emission per unit of livable floor area was 0.80–0.94 ton/m^2. The improvement per star rating was found to be in the range of 6 and 23 tons.

Water emission: The major impacts were found for construction (52.5–57.9%) and maintenance (39.9–45.2%). The operation and disposal phases were negligible. The maximum total change (%) was found for H3.9b (Table 10). The reason for this may be that a skillion metal roof produces much lower water emissions than a roof of gable tiles. Throughout the whole life cycle, the required quantity of water emission was 6.3–7.7 ton/m^2. The improvement per star rating was found to be up to 269.7 tons.

Eco-toxicity: The major impacts were found for construction (64.1–71.5%), operation (20.5–27.2%), and maintenance (6.6–11.5%). Disposal was negligible. A hugely different maximum total change (−90.9%) was found for H4.8 (Table 10). The H3.9b, H4.6, and H4.9 houses also produced less eco-toxicity than the Base House. The reason for this may be the skillion metal roof, which produces much less eco-toxicity than a roof of gable tiles. The emission of eco-toxicity in all phases was several times lower than for the Base House and the H3.9a and H4.4 houses. Throughout the whole life cycle, the required quantity of eco-toxicity per square meter of the livable area was 21.4–233.8 PDF×yr. The improvement per star rating was found to be up to 71,403.7 PDF×m^2yr for the H3.9b house.

AP/EP: The mid-point impact category AP/EP is the combined response obtained using the Eco-indicator 99 (H) method. However, most previous studies have reported AP and EP separately. The impact of AP in all life phases except disposal is several times higher than that of EP. In this study, the major impacts of the combined AP/EP were found for construction (29.6–40.2%), operation (49.2–60.6%), and maintenance (7–8.9%), as shown in Table 9. Table 1 shows that the EP results obtained in [80] for construction, operation, and maintenance were similar to the results reported in this study. This conclusion could be due to the similarities between the studies in terms of the assumptions, design life, and system boundaries adopted. In the disposal phase, the study found a negative value due to recycling (i.e., credit), as shown in Table 1, which is not similar to the results of this study. Ref. [54] determined the EP impact be 22–29% for the production and construction and 75–77% for the use (i.e., operation and maintenance) phases, which may be due to dissimilarities in the effects of HVAC, lighting, and hot water considered in the operation phase. Again, in the disposal phase, the negative values of the study were due to recycling. The AP/EP, when measured per unit livable floor area, was 16.5–19.7 PDF*yr. Using different units, ref. [53] reported the impact of EP to be 0.011 kg $PO_4/m^2/yr$ for a customary building in the Melbourne climate. The improvement per star rating was found to be up to 446 PDF×m^2yr for the H3.9b house.

Table 10. Changes in different houses with respect to the Base House for different impact categories.

Impact Category	Impact Feature	H3.6	H3.9a	H3.9b	H4.4	H4.6	H4.8	H4.9
Raw material (ton)	* Total change, %	-	−0.7	−6.3	−2.7	−3.5	−4.7	−1.1
	Per m^2 contribution	1.67	1.66	1.57	1.63	1.61	1.59	1.65
	† Per star change	-	−4.0	−35.7	−5.7	−5.9	−6.7	−1.5
Air emission (ton)	Total change, %	-	−2.5	−7.2	−15.1	−9.9	−12.3	−8.2
	Per m^2 contribution	0.94	0.92	0.88	0.80	0.85	0.83	0.87
	Per star change	-	−8.0	−23.0	−18.0	−9.4	−9.8	−6.0
Water emission (ton)	Total change, %	-	−1.1	−11.2	1.7	−0.2	−2.3	7.1
	Per m^2 contribution	7.1	7.1	6.3	7.3	7.1	7.0	7.7
	Per star change	-	−25.7	−269.7	15.4	−1.4	−13.9	39.6
Eco-toxicity (PDF×m^{2}yr)	Total change, %	-	−5.6	−90.7	−6.1	−90.4	−90.9	−90.8
	Per m^2 contribution	233.8	220.7	21.7	219.5	22.5	21.4	21.5
	Per star change	-	−4418.7	−71,403.7	−1813.1	−21,345.6	−17,882.0	−16,498.6
AP/EP (PDF×m^{2}yr)	Total change, %	-	−6.6	−6.7	−16.1	−14.3	−16.0	−14.0
	Per m^2 contribution	19.7	18.4	18.4	16.5	16.9	16.6	16.9
	Per star change	-	−435.7	−446.0	−400.8	−284.1	−265.5	−214.4
Ozone depletion (DALY)	Total change, %	-	−5.5	990.5	5.5	996.1	996.1	1272.8
	Per m^2 contribution	0.002	0.002	0.020	0.002	0.02	0.02	0.02
	Per star change	-	−0.03	6.0	0.0	1.8	1.5	1.8
Climate change (DALY)	Total change, %	-	−7.9	−7.3	−15.7	−13.4	−17.9	−14.6
	Per m^2 contribution	16.9	15.5	15.6	14.2	14.6	13.9	14.4
	Per star change	-	−450.3	−417.3	−334.4	−229.2	−253.8	−191.2
Human health (Pt)	Total change, %	-	−4.0	−11.2	−6.7	−5.7	−6.9	−6.8
	Per m^2 contribution	19.0	18.2	16.9	17.7	17.9	17.7	17.7
	Per star change	-	−257.0	−714.7	−161.0	−108.8	−111.0	−100.7
Ecosystem quality (Pt)	Total change, %	-	5.1	−3.2	−9.4	−9.0	−3.6	7.5
	Per m^2 contribution	14.2	14.9	13.8	12.9	12.9	13.7	15.3
	Per star change	-	245.3	−152.0	−169.6	−128.8	−42.6	82.3
Resources (Pt)	Total change, %	-	−6.2	−4.0	−6.3	−5.0	−7.1	−5.2
	Per m^2 contribution	25.6	24.0	24.6	24.0	24.3	23.8	24.2
	Per star change	-	−530.0	−340.7	−202.8	−129.7	−152.3	−103.5
Single score (Pt)	Total change, %	-	−2.7	−6.1	−7.2	−6.2	−6.2	−2.7
	Per m^2 contribution	58.8	57.2	55.2	54.6	55.1	55.2	57.2
	Per star change	-	−542.3	−1207.7	−533.5	−367.4	−305.9	−122.0

* Total change, % compared to Base House (H3.6). † Per star change with Base House (H3.6). Light & dark gray shades to indicate minimum & maximum values in that row (for each house).

Ozone depletion: Table 9 shows that the main impacts were found for construction (52.4–96.7%) and maintenance (3.2–47.2%). As shown in Table 1, the findings reported in [55] for the construction phase (52.5–87%) were similar to those obtained in this study. This finding indicates similarities in the assumptions, system boundaries, and design life adopted. Another study [53], conversely, found a dissimilar 47–48% in the production and construction phases in a multi-storey apartment building. Several studies, such as [53,56], have reported dissimilar values of ozone depletion in the operation phase, reporting 43–52%, 85–88%, and 79.4–94.9%, respectively. These dissimilarities may be due to the additional inclusion of the maintenance phase along with operational hot water and lighting effects. The contribution of ozone depletion throughout the whole life cycle was 0.002 to 0.02 DALY per unit of livable floor area (m^2). The improvement per star rating was found to be up to 0.03 DALY for the H3.9a house.

Climate change: Table 9 shows that the main impacts were found for construction (24.5–35.7%), operation (49.2–59.8%), and maintenance (7.1–11.8%). The contribution of the disposal phase was (5.2–7.3%). The findings for climate change in this study were much lower than those presented in the study by Ballinger [44] for the use phase (i.e., operation and maintenance together), as shown in Table 1 (88–91%), due to the effects of the addition of operational hot water, lighting, and water use. Ballinger's study [44] evaluated climate change on the basis of kg CO_2-eq. Several other studies [5,14,80] in which GWP/GHG was obtained as kg CO_2-eq reported similar findings for all life cycle phases except the disposal phase. The difference in the disposal phase was due to the consideration of the carbon sequestration of timber materials during landfilling. On the other hand, refs. [53,58] found quite a high variation, in the 64–95% range, during the operation and maintenance phases because of the effect of the addition of operational hot water, lighting, and electrical appliances. The required quantity of climate change was shown to be 13.9–16.9 DALY when reported per m^2 livable floor area on a whole life cycle basis. In different units, ref. [81] estimated the GWP impacts of the container, timber, and concrete houses as 48.9, 22.3, and 38 kg CO_2-eq/m^2/a, respectively. The improvement per star rating was found to be 450.3 DALY for the H3.9a house.

Human health: The major impacts were found for construction (43.5–53.7%), operation (32.7–43.4%), and maintenance (11.6–17.9%), while the disposal phase was negligible (1.4–1.6%). The study findings by Islam et al. [14] for the operational phase (37–43%) were quite similar to those reported in this study, but their results for the disposal phase were dissimilar (10–20%). These findings may be due to the similarity in the design life and the dissimilarity in recycling at the disposal phase. The maximum change (i.e., total change, %) was found for H3.9b, followed by the H4.8 house, as shown in Table 10. This can be attributed to the construction phase, which reduced the impact on human health significantly compared to the Base House H3.6. Meanwhile, in the H4.8 house, the operation phase was considerably lower than in the Base House. It can also be noted that with an increasing star rating, the contribution of the operation phase progressively decreased for all the houses except H4.9. Throughout the whole life cycle, the impact on human health per unit of livable floor area was 16.9–19 Pt/m^2. The improvement range per star rating was 100.7–714.7 Pt.

Ecosystem quality: The major impact was found for construction (75.1–83.5%). Operation and maintenance were (7.4–10.6%) and (7.6–15.4%), respectively, while the disposal phase was negligible. As shown in Table 1, the findings reported in [56] for the operational phase (15–27%) were quite dissimilar to this study, which may be due to the effect of the addition of operational hot water and lighting. The maximum change (i.e., total change, %) was found for H4.4, followed by the H4.6 house, as shown in Table 10. This change may be due to the huge improvement in the ecosystem quality during the operation and maintenance phases compared to the Base House. It can also be noted that with an increasing star rating, the contribution of the operation phase progressively decreased for all the houses except H4.9. The impact of ecosystem quality per unit of livable floor area throughout the entire life cycle was 12.9–15.3 Pt/m^2. The improvement range per star rating was found to be up to 169.6 Pt.

Resources: The major impacts were found for construction, operation, and maintenance (48.0–56.5%, 24.7–36.4%, and 15.1–19.7%, respectively), while the disposal phase was negligible (1.6–1.8%). Szalay's [56] study reported findings of 76–81%, as shown in Table 1, which is quite dissimilar to this study. This contrast may be due to the different choices for the system boundary. On the other hand, Islam et al. [14] reported 50–66%, which may be due to the IMPACT 2002+ LCIA method's weighting/normalization set. The maximum change (i.e., total change, %) was found for H4.8, followed by the H4.4 house, as shown in Table 10. The reason for this may be the operation phase, which significantly reduces the impact of resources compared to the Base House. The impact of resources per unit of livable floor area throughout the whole life cycle was 23.8–25.6 Pt/m^2. The improvement range per star rating was 103.5–530 Pt.

Single score: This score was obtained by adding the corresponding points from resources, ecosystem quality, and human health to generate a single score indicating overall ecological wellbeing. In this regard, as shown in Table 10, the maximum change (%) was found for H4.4, followed by H4.6 and H4.8, compared to the Base House. The single score per unit of livable floor area throughout the whole life cycle was 54.6–58.8 Pt/m^2. The improvement range per star rating was 122.0–1207.7 Pt compared with the Base House. The key purpose of this point score is to describe the relative differences among houses, where 1 Pt is computed by dividing the whole environmental load in a region by the sum of residents and multiplying it by 1000 (scale factor).

Therefore, it can be concluded that the construction phase was the major contributor to all impact categories except air emission, AP/EP, and climate change. These three impact indicators were found to be the predominating contributors during the operation phase, as expected. When considering the results of resources, ecosystem quality, and human health, the construction phase was also a major contributor. These results are primarily associated with the products, processes, and services of material used in the construction phase. On the other hand, during the operation phase, the outcomes were commonly related to the energy consumed (i.e., heating and cooling), which generates CO_2 emissions (main source of air emission and climate change), nitrogen and sulfur compounds (key sources of AP), and nitrates and phosphates (major sources of EP). Some environmental impacts were observed in the literature due to differences in the system boundary, assumptions, LCIA methods, and weighting/normalization set adopted.

The prominence of life cycle phases is dependent on the environmental impacts considered. In many previous studies, the operational phase became more prominent due to the consideration of the impacts of GHG (or equivalent GWP) and cumulative energy demand (CED). On the other hand, in this study, construction became more prominent than the operation phase due to the major contribution made by other environmental impacts (e.g., the raw material, water emission, eco-toxicity, and damage category impact indicators). Therefore, the conclusions of different studies depend on which environmental impact indicators were focused on.

5.2. LCC Results

The LCC of all seven houses, including the Base House, are shown in Table 11. The costs of all items were estimated in Australian dollars (AUD). Construction alone had a contribution of 62–65%, compared to the total cost in the last column. Operation and maintenance were 7–10% and 25–26%, respectively, while disposal cost was relatively low. These contribution ranges are highly comparable (in %) to the results presented in Table 2. The reasons for this might be similarities in the assumptions, design life, and discounted rate adopted.

Table 11. Life cycle cost (AUD) for all house designs.

Life Cycle Phase	LCC Results of all Houses							
	H3.6	**H3.9a**	**H3.9b**	**H4.4**	**H4.6**	**H4.8**	**H4.9**	**Range, % ****
Construction	128,774	135,000 * (4.8%)	128,387 (−0.3%)	128,739 (0.0%)	138,000 (7.2%)	132,000 (2.5%)	134,000 (4.1%)	62–65
Operation	20,317	18,400 (−9.4%)	18,398 (−9.4%)	15,681 (−22.8%)	15,200 (−25.2%)	14,300 (−29.6%)	14,200 (−30.1%)	7–10
Maintenance	53,947	55,000 (2.0%)	53,122 (−1.5%)	50,525 (−6.3%)	55,000 (2.0%)	53,900 (−0.1%)	54,500 (1.0%)	25–26
Disposal	5618	5800 (3.2%)	6851 (21.9%)	6656 (18.5%)	5800 (3.2%)	6660 (18.5%)	6620 (17.8%)	3–3
Total	208,656	214,000 (2.6%)	206,758 (−0.9%)	201,601 (−3.4%)	214,000 (2.6%)	206,860 (−0.9%)	209,320 (0.3%)	-
† Difference per star rating	-	17,813 (8.7%)	−6327 (−3.0%)	−8819 (−4.3%)	5344 (2.6%)	−1497 (−0.8%)	511 (0.2%)	-
AUD/m^2	2066	2119	2047	1996	2119	2048	2072	-

* Total change in % compared to the Base House (H3.6). ** Lowest to highest contribution range of life cycle phases in % of all the houses, including the Base House (H3.6). † Cost amount and % differences compare to Base House (H3.6). Gray shade to indicate the lowest LCC house of that life cycle phase (row).

For different life cycle phases, the % variations of different houses compared to the Base House are shown in Table 11 (within brackets). The operation phase showed increased savings with an increasing star rating compared to the BH, with the highest savings being obtained for the H4.9 house (−30.1%). On the other hand, construction and maintenance, the highest cost contributors, showed comparatively smaller savings for houses H3.9b (−0.3%) and H4.4 (−6.3%), respectively. The disposal phase showed increasing costs for all houses, but the differences were smaller in terms of dollar value. In total value, the H4.4 house presented the highest saving (3.4%). The second highest savings were obtained for two houses: a higher star rating house (H4.8) and a relatively lower star rating house (H3.9b). House H3.9b had the lowest construction cost because of the skillion flat roof component, offering higher compensation for the operation, maintenance, and disposal costs. House H4.8 also used a skillion flat roof, a composite floor, and FC sheet walls, thus increasing the construction costs. Still, the total cost was ultimately reduced due to comparatively high savings (−29.6%) during operation. House H4.9 used weatherboard walls with extra insulation to increase the star rating, thus increasing construction, maintenance, and disposal costs, which was, however, insufficient to surpass the highest saving (30.1%) made with respect to the operation cost. It is intuitively evident that from among the second (H3.9b and H4.8) and third (H4.9) cheapest houses compared to the Base House, house H4.8 should be chosen not only from a cost point of view but also on the basis of life cycle environmental impact, as discussed in Section 5.1.

Hence, the influence of the star rating exposed an interesting trend in terms of LCC. While the LCC exhibited a steady decreasing trend in the operation phase with an increasing star rating, it did not follow any trend during the construction, maintenance, and disposal phases. This trend is due to the random selection of construction materials in order to achieve a star rating.

Cost saving per difference in star rating was also the highest (4.3%) in the H4.4 house compared to the Base House, while the H3.9b house was ranked second (3%), ahead of H4.8. A small investment of AUD 5226 (4.1% in H4.9 houses) or even AUD 3226 (2.5% in H4.8 houses) was enough to increase the star rating from 3.6 to 4.9 and 4.8, respectively, in order to achieve a higher star rating. When converted into a per star rating (e.g., AUD 2688–AUD 4020), these incremental investments were similar to those presented in the study by Islam et al. [5], where a necessary investment of around AUD 2300–AUD 5800 per star rating was reported. Furthermore, McLeod and Fay [40] also reported a similar investment of about AUD 2600 per star rating improvement. When the star rating of the houses was improved from 5 to 6 and 6 to 7, Moore [82] reported investments of around AUD 1300 and AUD 4200 per star rating improvement, respectively. Throughout the whole life cycle, the cost per unit of livable floor area for H4.4 was AUD 1996, while for the Base House, it was AUD 2066, resulting in savings of AUD 70/m^2.

6. Multi-Criterion Trade-Off between Star Rating, LCEI, and LCC

Customers generally select houses with a star rating in consideration of local climate and cost. A higher star rating requires less energy for heating and cooling, which eventually reduces greenhouse gas emissions. Recent developments in the building industry demonstrate that it is moving towards the adoption of complex environmental protocols for all life cycle phases. The environmental impacts of residential buildings were evaluated for each life cycle phase in order to indicate their loading on the environment. For optimized housing selection, a multi-criterion decision-making process was used to determine a trade-off between the results for star rating, life cycle environmental impacts, and cost. Hence, this multi-criterion process constituted the basis of an analytical life cycle framework system. The multi-criterion trade-off process is useful for housing selection, because the simultaneous consideration of star rating, life cycle environmental impact, and cost may result in a compromise solution that is able to fulfill the needs of legislative compliance, as well as customer and environmental requirements.

Regarding the eco-toxicity, climate change, and damage to resources categories, the best house obtained was H4.8. In comparison, H3.9b was the best house with respect to the raw material, water emission, and human health categories, as shown in Table 8. In terms of air emission, AP/EP, and damage to ecosystem quality, the best house was determined to be H4.4. This H4.4 house was also the best when all damage categories were converted into a single score. Likewise, H4.4 was also the best house with respect to LCC. However, when considering all life cycle environmental impacts, costs, and star rating, intuitively, the H4.8 house was at a clear advantage, because H4.8 was the second best choice in all impact indicators except ozone layer depletion and damage to ecosystem quality, as shown in Table 8. Hence, to select the optimum house, it is necessary to consider not only cost and star rating but also the life cycle environmental impacts.

Building typology, material variations, design elements, construction techniques, and climatic zones are the driving forces influencing these results. Future works can be elaborated by developing a series of reference studies and performing uncertainty for design variables. Affordable active and passive designs must be optimized for broader applications in the building industry, and the outcomes converted into tools for implementation. Manufacturers and architects can use these to make more informed design decisions in the future.

7. Conclusions

This study evaluated the environmental impact and cost of residential buildings throughout their life cycle when improving their star ratings. An analytical life cycle framework for the construction, operation, maintenance, and disposal of buildings was used to evaluate the environmental impacts and costs of a range of selected star-rated buildings. The construction phase was the major contributor to seven impact categories: the raw materials used, water emission, eco-toxicity, ozone layer depletion, resource damage, ecosystem quality, and human health. On the other hand, the operation phase was a major contributor to the remaining three impact categories: air emission, acidification/eutrophication potential, and climate change. The construction phase receives the highest ranking due to the products, processes, and services of materials used in this phase. On the other hand, energy consumed for heating and cooling during the operational phase resulted in CO_2 emissions (the key source of air emission and climate change), as well as the emission of nitrogen and sulfur compounds (the main sources of acidification potential), and nitrates and phosphates (the main sources of eutrophication potential). The proportion of costs incurred during construction alone was 62–65%, while costs during operation and maintenance were 7–10% and 25–26%, respectively, and disposal costs were relatively low.

This study used a trade-off between multiple criteria, which is useful for the evaluation of residential buildings, because star rating, life cycle environmental impacts, and cost together may produce a compromised solution that is able to fulfill the needs of legislative compliance, customer, and environmental requirements. The house presented in the case study was modified with only a composite-type floor (i.e., H4.4), and was found to be a better house in terms of air emission, acidification/eutrophication, damage to ecosystem quality, and cost.

As such, the life cycle environmental impacts (LCEI) and costing (LCC) represented the two best methods for determining ways to improve the building materials used in the case study building. A score of 4.9 stars with a composite floor (ceramic tiles/plywood deck) over the concrete slab, an insulated weatherboard wall cladding, and insulated skillion flat roofing provided an environmental impact score of 5779 and a cost of AUD 209,320. However, the second possible option, for a 4.8-star house, had identical assemblies, except for the use of an insulated fiber cement wall as an effective building component. The associated cost of AUD 206,860 and the relevant impact score of 5570, resulting in a 4.8-star rating, identify this as the optimum assembly of the building fabric.

A conjugate approach to environmental impacts and costing, along with a star rating, shows that H4.8 represented an attractive trade-off compared to the other rated houses. H4.9 was the second most feasible provision in consideration of overall cost, eco-toxicity, climate change, and resource extractions. The study combined a multi-objective approach to identify optimal assemblies for the selected criteria. The findings of this study reflect the preference of materials during the decision-making stage in line with the national energy rating system.

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References

1. Karimpour, M.; Belusko, M.; Xing, K.; Bruno, F. Minimising the life cycle energy of buildings: Review and analysis. *Build. Environ.* **2014**, *73*, 106–114. [CrossRef]
2. Cuéllar-Franca, R.M.; Azapagic, A. Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Build. Environ.* **2012**, *54*, 86–99. [CrossRef]
3. Robati, M.; McCarthy, T.J.; Kokogiannakis, G. Integrated life cycle cost method for sustainable structural design by focusing on a benchmark office building in Australia. *Energy Build.* **2018**, *166*, 525–537. [CrossRef]
4. Kaziolas, D.; Bekas, G.; Zygomalas, I.; Stavroulakis, G. Life cycle analysis and optimization of a timber building. *Energy Procedia* **2015**, *83*, 41–49. [CrossRef]
5. Islam, H.; Jollands, M.; Setunge, S.; Bhuiyan, M.A. Optimization approach of balancing life cycle cost and environmental impacts on residential building design. *Energy Build.* **2015**, *87*, 282–292. [CrossRef]
6. Aye, L.; Ngo, T.; Crawford, R.H.; Gammampila, R.; Mendis, P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy Build.* **2012**, *47*, 159–168. [CrossRef]
7. Berry, S.; Whaley, D.; Davidson, K.; Saman, W. Near zero energy homes–What do users think? *Energy Policy* **2014**, *73*, 127–137. [CrossRef]
8. Sartori, I.; Napolitano, A.; Voss, K. Net zero energy buildings: A consistent definition framework. *Energy Build.* **2012**, *48*, 220–232. [CrossRef]
9. Bribián, I.Z.; Capilla, A.V.; Usón, A.A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build. Environ.* **2011**, *46*, 1133–1140. [CrossRef]
10. González-Mahecha, R.E.; Lucena, A.F.; Szklo, A.; Ferreira, P.; Vaz, A.I.F. Optimization model for evaluating on-site renewable technologies with storage in zero/nearly zero energy buildings. *Energy Build.* **2018**, *172*, 505–516. [CrossRef]
11. De Masi, R.F.; Gigante, A.; Vanoli, G.P. Are nZEB design solutions environmental sustainable? Sensitive analysis for building envelope configurations and photovoltaic integration in different climates. *J. Build. Eng.* **2021**, *39*, 102292. [CrossRef]
12. Gold, S.; Rubik, F. Consumer attitudes towards timber as a construction material and towards timber frame houses–selected findings of a representative survey among the German population. *J. Clean. Prod.* **2009**, *17*, 303–309. [CrossRef]
13. Tushar, Q.; Bhuiyan, M.A.; Zhang, G. Energy simulation and modeling for window system: A comparative study of life cycle assessment and life cycle costing. *J. Clean. Prod.* **2022**, *330*, 129936. [CrossRef]
14. Islam, H.; Jollands, M.; Setunge, S.; Haque, N.; Bhuiyan, M.A. Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings. *Energy Build.* **2015**, *104*, 250–263. [CrossRef]
15. Tushar, Q.; Bhuiyan, M.A.; Zhang, G.; Maqsood, T. An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development. *J. Clean. Prod.* **2021**, *289*, 125622. [CrossRef]
16. Oktay, D. Design with the climate in housing environments: An analysis in Northern Cyprus. *Build. Environ.* **2002**, *37*, 1003–1012. [CrossRef]
17. Seyfang, G. Community action for sustainable housing: Building a low-carbon future. *Energy Policy* **2010**, *38*, 7624–7633. [CrossRef]
18. Zhang, X.; Shen, L.; Wu, Y. Green strategy for gaining competitive advantage in housing development: A China study. *J. Clean. Prod.* **2011**, *19*, 157–167. [CrossRef]
19. Asadi, E.; Da Silva, M.G.; Antunes, C.H.; Dias, L. Multi-objective optimization for building retrofit strategies: A model and an application. *Energy Build.* **2012**, *44*, 81–87. [CrossRef]
20. Wang, W. A Simulation-Based Optimization System for Green Building Design. Ph.D. Thesis, Concordia University, Montreal, QC, Canada, 2005.
21. Zachariah, J.-A.L. Towards Sustainable Homes through Optimization: An Approach to Balancing Life Cycle Environmental Impacts and Life Cycle Costs in Residential Buildings. Ph.D. Thesis, University of Toronto, Toronto, ON, Canada, 2003.

22. Atmaca, A. Life cycle assessment and cost analysis of residential buildings in south east of Turkey: Part 1—Review and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 831–846. [CrossRef]
23. Pombo, O.; Allacker, K.; Rivela, B.; Neila, J. Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting—A case study of the Spanish housing stock. *Energy Build.* **2016**, *116*, 384–394. [CrossRef]
24. Ristimäki, M.; Säynäjoki, A.; Heinonen, J.; Junnila, S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* **2013**, *63*, 168–179. [CrossRef]
25. Wang, R.; Lu, S.; Feng, W.; Zhai, X.; Li, X. Sustainable framework for buildings in cold regions of China considering life cycle cost and environmental impact as well as thermal comfort. *Energy Rep.* **2020**, *6*, 3036–3050. [CrossRef]
26. Lu, K.; Jiang, X.; Yu, J.; Tam, V.W.; Skitmore, M. Integration of life cycle assessment and life cycle cost using building information modeling: A critical review. *J. Clean. Prod.* **2021**, *285*, 125438. [CrossRef]
27. Konstantinidou, C.A.; Lang, W.; Papadopoulos, A.M.; Santamouris, M. Life cycle and life cycle cost implications of integrated phase change materials in office buildings. *Int. J. Energy Res.* **2019**, *43*, 150–166. [CrossRef]
28. Stephan, A.; Stephan, L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Appl. Energy* **2016**, *161*, 445–464. [CrossRef]
29. Säynäjoki, A.; Heinonen, J.; Junnila, S.; Horvath, A. Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environ. Res. Lett.* **2017**, *12*, 013001. [CrossRef]
30. Morrissey, J.; Horne, R. Life cycle cost implications of energy efficiency measures in new residential buildings. *Energy Build.* **2011**, *43*, 915–924. [CrossRef]
31. Belusko, M.; O'Leary, T. Cost analyses of measures to improve residential energy ratings to 6 stars-playford North Development, South Australia. *Australas. J. Constr. Econ. Build.* **2010**, *10*, 48–59. [CrossRef]
32. Iyer-Raniga, U.; Wong, J.P.C. Evaluation of whole life cycle assessment for heritage buildings in Australia. *Build. Environ.* **2012**, *47*, 138–149. [CrossRef]
33. Gu, L.; Lin, B.; Zhu, Y.; Gu, D.; Huang, M.; Gai, J. Integrated assessment method for building life cycle environmental and economic performance. *Build. Simul.* **2008**, *1*, 169–177. [CrossRef]
34. Guinée, J.B. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2002; Volume 7.
35. Nissinen, A.; Grönroos, J.; Heiskanen, E.; Honkanen, A.; Katajajuuri, J.-M.; Kurppa, S.; Mäkinen, T.; Mäenpää, I.; Seppälä, J.; Timonen, P. Developing benchmarks for consumer-oriented life cycle assessment-based environmental information on products, services and consumption patterns. *J. Clean. Prod.* **2007**, *15*, 538–549. [CrossRef]
36. Xing, S.; Xu, Z.; Jun, G. Inventory analysis of LCA on steel-and concrete-construction office buildings. *Energy Build.* **2008**, *40*, 1188–1193. [CrossRef]
37. Renouf, M.; Grant, T.; Sevenster, M.; Logie, J.; Ridoutt, B.; Ximenes, F.; Bengtsson, J.; Cowie, A.; Lane, J. Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia. Australian Life Cycle Assessment Society. 2015. Available online: www.alcas.asn.au (accessed on 3 August 2022).
38. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006; pp. 235–248.
39. Building Code of Australia. *National Construction Code (NCC) 2016*; Australian Building Codes Board: Canberra, Australia, 2016.
40. McLeod, P.; Fay, R. The cost effectiveness of housing thermal performance improvements in saving CO_2-e. *Archit. Sci. Rev.* **2011**, *54*, 117–123. [CrossRef]
41. Warren-Myers, G.; Bartak, E.; Cradduck, L. Observing energy rating stars through the Australian Consumer Law lens: How volume home builders' advertising can fail consumers. *Energy Policy* **2020**, *139*, 111370. [CrossRef]
42. Warren-Myers, G.; Kain, C.; Davidson, K. The wandering energy stars: The challenges of valuing energy efficiency in Australian housing. *Energy Res. Soc. Sci.* **2020**, *67*, 101505. [CrossRef]
43. Roh, S.; Tae, S.; Kim, R. Developing a Green Building Index (GBI) certification system to effectively reduce carbon emissions in South Korea's building industry. *Sustainability* **2018**, *10*, 1872. [CrossRef]
44. Ballinger, J.A. The 5 star design rating system for thermally efficient, comfortable housing in Australia. *Energy Build.* **1988**, *11*, 65–72. [CrossRef]
45. Reardon, C.; Milne, G.; McGee, C.; Downton, P. *Your Home Technical Manual*; Department of Climate Change and Energy Efficiency; Australian Government: Canberra, Australia, 2010.
46. State of Victoria. *Energy Smart Housing Manual*; Sustainability Victoria: Melbourne, Australia, 2002.
47. Kile, G.; Nambiar, E.; Brown, A. The rise and fall of research and development for the forest industry in Australia. *Aust. For.* **2014**, *77*, 142–152. [CrossRef]
48. Santamouris, M.; Mihalakakou, G.; Argiriou, A.; Asimakopoulos, D. On the efficiency of night ventilation techniques for thermostatically controlled buildings. *Sol. Energy* **1996**, *56*, 479–483. [CrossRef]
49. Shrapnel, B. *Scoping Study to Investigate Measures for Improving the Environmental Sustainability of Building Materials*; Department of the Environment and Heritage; Australian Greenhouse Office: Canberra, Australia, 2006.
50. Tushar, Q.; Bhuiyan, M.; Sandanayake, M.; Zhang, G. Optimizing the energy consumption in a residential building at different climate zones: Towards sustainable decision making. *J. Clean. Prod.* **2019**, *233*, 634–649. [CrossRef]
51. ICANZ. *Insulation Handbook*; Insulation Council of Australia and New Zealand: Melbourne, Australia, 2008.

52. Australian Building Codes Board. Building Codes Board. Building Improvements to raise house energy ratings from 5.0 stars. In *Constructive Concepts*; Australian Building Codes Board: Canberra, Australia, 2009.
53. Carre, A.; Crossin, E. *A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings*; Forest & Wood Products Australia: Melbourne, Australia, 2015.
54. Durlinger, B.; Crossin, E.; Wong, J.P.C. *Life Cycle Assessment of a Cross Laminated Timber Building*; Forest and Wood Products Australia: Melbourne, Australia, 2013.
55. Ortiz-Rodríguez, O.; Castells, F.; Sonnemann, G. Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. *Sci. Total Environ.* **2010**, *408*, 2435–2443. [CrossRef] [PubMed]
56. Szalay, Z. *Life Cycle Environmental Impacts of Residential Buildings*; Department of Building Energetics and Building Services; Budapest University of Technology and Economics: Budapest, Hungary, 2007.
57. Islam, H.; Jollands, M.; Setunge, S.; Ahmed, I.; Haque, N. Life cycle assessment and life cycle cost implications of wall assemblages designs. *Energy Build.* **2014**, *84*, 33–45. [CrossRef]
58. Nemry, F.; Uihlein, A.; Colodel, C.M.; Wetzel, C.; Braune, A.; Wittstock, B.; Hasan, I.; Kreißig, J.; Gallon, N.; Niemeier, S. Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs. *Energy Build.* **2010**, *42*, 976–984. [CrossRef]
59. Muneron, L.M.; Hammad, A.W.; Najjar, M.K.; Haddad, A.; Vazquez, E.G. Comparison of the environmental performance of ceramic brick and concrete blocks in the vertical seals' subsystem in residential buildings using life cycle assessment. *Clean. Eng. Technol.* **2021**, *5*, 100243. [CrossRef]
60. Tharumarajah, A.; Grant, T. Australian national life cycle inventory database: Moving forward. In Proceedings of the Fifth ALCAS Conference, Melbourne, Australia, 22–24 November 2006.
61. Newton, P.; Hampson, K.; Drogemuller, R. *Technology, Design and Process Innovation in the Built Environment*; Routledge: London, UK, 2009; Volume 10.
62. Delsante, A. *A Validation of the AccuRate Simulation Engine Using BESTEST*; CSIRO: Canberra, Australia, 2004.
63. Deans, D.J. *Discount Rates for Commonwealth Infrastructure Projects*; Parliament House: Canberra, Australia, 2018.
64. Rawlinsons Group. *Rawlinsons Australian Construction Handbook*; Rawlhouse Publishing: Perth, Australia, 2018.
65. Maxted, K. *Rawlinsons Construction Cost Estimating*; Rawlinsons (W.A): Rivervale, Australia, 2021.
66. Hyland, J. *Price Comparison Report Update 2011*; Office of the Tasmanian Economic Regulator: Tasmania, Australia, 2011.
67. AEMC. *2016 Residential Electricity Price Trends*; Australian Energy Market Commission: Sydney, Australia, 2016.
68. Shi, S.; Valadkhani, A.; Smyth, R.; Vahid, F. Dating the timeline of house price bubbles in Australian capital cities. *Econ. Rec.* **2016**, *92*, 590–605. [CrossRef]
69. Staines, A. *The Australian House Building Manual*; Pinedale Press: Port Macquarie, Australia, 2001.
70. Hammond, G.; Jones, C. *Inventory of Carbon & Energy: ICE*; Sustainable Energy Research Team, Department of Mechanical Engineering; University of Bath: Bath, UK, 2008; Volume 5.
71. Lawson, W.R. *Timber in Building Construction-Ecological Implications*; Bond University: Robina, Australia, 1996.
72. Chen, D.; Syme, M.; Seo, S.; Chan, W.Y.; Zhou, M.; Meddings, S. *Development of an Embodied CO_2 Emissions Module for AccuRate*; Forest & Wood Products Australia: Melbourne, Australia, 2010.
73. Henriksen, J.E. The Value of Design in Reducing Energy Use and CO_2-e Impact over the Life Cycle of a Detached Dwelling in a Temperate Climate. Ph.D. Thesis, University of Newcastle, Callaghan, Australia, 2006.
74. Tushar, Q.; Bhuiyan, M.A.; Zhang, G.; Maqsood, T.; Tasmin, T. Application of a harmonized life cycle assessment method for supplementary cementitious materials in structural concrete. *Constr. Build. Mater.* **2022**, *316*, 125850. [CrossRef]
75. *AS/NZS 3823.2*; Performance of Electrical Appliances—Air Conditioners and Heat Pumps Energy Labelling and Minimum Energy Performance Standards (MEPS) Requirements. Standards Australia: Sydney, Australia, 2013.
76. Teter, L. Bill for the Energy Efficiency of Electrical Appliances Equipment and Lighting Product Act No. 24 of 2016. Attorney General's Office, Government Act, Republic of Vanuatu. 2017. Available online: http://eparliamentresource.gov.vu/jspui/handle/1/1299 (accessed on 27 September 2022).
77. Wu, J.; Xu, Z.; Jiang, F. Analysis and development trends of Chinese energy efficiency standards for room air conditioners. *Energy Policy* **2019**, *125*, 368–383. [CrossRef]
78. IPART. *Local Government Discount Rate. Independent Pricing and Regulatory Tribunal*; IPART: Sydney, Australia, 2022.
79. McDougall, A. Melbourne 2030: A preliminary cost benefit assessment. *Aust. Plan.* **2007**, *44*, 16–25.
80. Carre, A. *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*; Forest and Wood Products Australia: Melbourne, Australia, 2011.
81. Olivares, A.A.P.; Andres, A. Sustainability in Prefabricated Architecture: A Comparative Life Cycle Analysis of Container Architecture for Residential Structures: A Thesis Submitted to the Victoria University of Wellington in Fulfilment of the Requirements for the Degree of Master of Architecture. Ph.D. Thesis, Victoria University of Wellington, Wellington, New Zealand, 2010.
82. Trivess, M. *The Costs and Benefits of Zero Emission Housing; Modelling of Single Detached Houses in Melbourne*; RMIT University: Melbourne, Australia, 2010.