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Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings

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ABSTRACT

This paper describes life cycle assessment (LCA) and life cycle cost (LCC) analysis for typical Australian houses. It reports how different roofing (i.e. roof and ceiling) and floor designs affect the life cycle environmental impacts and cost (LCEI & LCC) over the various life stages of buildings (i.e. construction, operation, maintenance and final disposal). A case study house, called Base House, was modified with 8 alternative roofing and 4 floor designs to generate 12 variant houses. Specifically, one variable either from roofing or from floor was varied at a time while keeping wall and other components as in the Base House. The four life cycle environmental impacts were greenhouse gas (GHG) emission, cumulative energy demand (CED), water use, and solid waste generation, evaluated by LCA approach. The LCC was estimated based on life cycle costing approach. The results of LCEI & LCC of each house were evaluated on a whole of life cycle basis. A number of trades-off on the houses modified with roofing and floor designs were identified based on LCEI & LCC results. For the houses modified with roofing and floor designs, the high star skillion flat roofing and mixed floor houses were the attractive trades-off.

1. Introduction

Building design encompasses assemblages of materials in its wall, roofing and floor, which vary widely from one country to another. The majority of Australia's residential buildings built since 1996 conform to the building code of Australia (BCA) guidelines to achieve some minimum performance requirements irrespective of climate and building approval processes [1]. The building approval processes are imbedded in Australian standards and local by-laws. There are several common structural typology, cladding and assemblage techniques available for wall, roofing and floor designs for the Australian building industry in the literature. This study specifically focuses on roofing and floor designs. Roofing option in the literature includes flat or pitched roofing within hip, gable and skillion types [2–4]. A pitched roof with flat ceiling is one of the most popular in Australia and elsewhere. Tiles and metals are common options for rooftop material. Timber is the most common for structural frames in Australia. The ceiling linings are plasterboard, fixed directly to the underside of timber ceiling joists. Suspended timber floor and concrete slab on ground are the two common types of floor designs. Popular floor tops are tiles, carpet, bared timber, carpeted over timber and carpeted over tiles [5]. Plywood and particleboard are common for floor deck. The installation of timber flooring over a concrete slab is also common in newly built houses in Australia [6].

In order to have different thermal performances (i.e. star rating) there are several assemblages available in roofing and floor designs. Building code Australia outlines the assemblage techniques based on arrangements of cladding and insulation along with their position, thickness and air gap [1]. For example, there should be a minimum air gap between floorboard and insulation in floor designs. In suspended timber floor, reflective insulation material is fixed on the under-side of joists, while in concrete slab on ground design, the insulation is pinned to the under-side of the slab [7]. For roofing design, insulation is attached under the battens or draped over the battens. Insulations are also attached above the ceiling linings, placed either over the joists, or between the joists.

Abbreviations: BCA, building code of Australia; BOQ, Bill of Quantity; COP, coefficient of performance; CED, cumulative energy demand; GHG, greenhouse gas; LCEI & LCC, life cycle environmental impacts and cost; RFL, reflective foil laminates; GMR, gable metal roof; GTR, gable tile roof; SFR, skillion flat roof; SFR, skillion pitch roof; CFH, carpeted floor house; CTH, ceramic tiles floor house; TFH, timber floor house; MFH, mixed floor house.

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Some builders in Australia also use additional reflective insulation (reflective foil laminates – RFL) over bulk insulation [5].

The cladding and insulation materials production involve with energy intensive processes like, harvesting/mining to transportation. Each process produces a range of wastes and environmental impacts. Maintenance and disposal have also impacts and may be significant. Buildings are built to last for several decades, which use heating and cooling energy based on variation of climate and thermal characteristics of materials and its assemblages. All these materials and activities also incur cost. A small reduction of environmental impact and cost would be significant because 3.2 million new dwellings will be constructed in Australia by 2026 [8]. Hence, the life cycle assessment (LCA) and life cycle costing analysis are established approaches to evaluate the life cycle environmental impact (LCEI) and life cycle cost (LCC), respectively. The four LCEI indicators are: greenhouse gas (GHG) emission, cumulative energy demand (CED), water use, and solid waste generation. The reasons to choose these categories as these are the prime interests in the Australian context as explained in [66].

Extensive literature review shows that LCA and LCC studies on buildings focus on either whole building or part of building considering whole life cycle (i.e. construction, operation, maintenance, and disposal) or part of life cycle. For example, two recent North American studies [9,10] reported LCA only for residential buildings by varying wall materials and assemblages. Two Australian studies [11,12] evaluated the LCC and LCEI considering operational phase only (e.g. heating and cooling energy). Some studies [9,10,13–19] on buildings focused on LCA only without evaluating LCC, while other studies [20–22] considered LCC without evaluating LCA. Relatively fewer studies [23–26] integrated both LCA and LCC in their analysis. First author's three recent studies [27,28,61] integrated both LCA and LCC for other goals. However, there are no published studies that have taken LCA and LCC together along with star rating to identify optimum roofing and floor designs. Here star rating of the buildings are varied by changing the cladding and insulation materials, and its assemblages. Each roofing or floor design is varied in such a way that the building achieves a chosen star rating from 3.6 to 4.4 star.

This study mainly reports how different assemblages of roofing and floor designs affect the LCEI and LCC over the various life stages of the buildings. A case study house in Brisbane is used as a Base House, and modified with 8 alternative roofing (e.g. roof and ceiling) and 4 floor designs, typical of the Australian building industry. Specifically, the Base House (3.6 star) was modified using a constrained experimental design, i.e. one variable either from roofing or floor was varied at a time. When the design of roofing was modified, the floor and other components were as in the Base House. The chosen roofing and floor assemblage designs were selected from *AccuRate*, a tool commonly used for star rating in the Australian building industry. The regulating factors for all the modified designs followed the best practice approach complied with building code Australia (BCA) guidelines. The detailed characteristics and results on LCEI and LCC for the 12 modified houses and Base House are presented later. The results with varied materials, assemblages and resulting star rating are analyzed using whole building on a whole of life cycle basis. Then, a number of trades-off on the houses modified with roofing and floor designs are identified based on LCEI & LCC indicators.

2. Contemporary LCA and cost studies on buildings

2.1. Comparison on LCA studies

The salient features of LCA results from some previous studies are shown in Table 1. It shows the variations in their system description, assumption and boundary undertaken along with GHG, CED, water use and solid waste contributions for different life cycle phases. A high degree of dissimilarities particularly for GHG and CED results are apparent among Australian, European and North American studies. These differences may be attributed to the variation in system boundaries and assumptions.

The findings of the study [13] are not similar to the study [19]. The differences may be attributed to differences in system assumptions (such as maintenance and carbon sequestration on disposal). Hence, the study [19] did not report any GHG emission for material replacement in maintenance. The study also excluded demolition due to the scarcity of reliable data on demolition process. The study [19] included only transportation impact for the operation of a landfill site, but study [13] included maintenance, transportation and landfill as well as reuse and recycling impact for disposal.

The study [15,16] found that the operation phase contributed about 90% of GHG emissions throughout its design life. These studies gave an average ratio of construction to operation phase GHG emissions 1:5.5–1:22.5. Three other studies [10,29,30] also found similar outcomes, estimated that the operation phase accounts for around 94, 93 and 91%, respectively of the total energy consumption throughout its design life (i.e. 50 years). The studies [13,19] have a range of ratios of construction to operation 1:1–1:2. This large difference is not surprising, but is attributed to the differences in system boundaries and assumptions (Table 1); the difference in lifetime, inclusion of impact of water heating, lighting, house hold appliances as well as the efficiency (i.e. COP) of the heating/cooling devices would vary the relative contribution of operational phase. Hence, the energy consumption in operational phase would make a big difference, and so construction would be proportionally smaller.

For GHG among European and North American studies, the variation for life cycle phases was not very high, except the study by Szalay [31]. Szalay evaluated the maintenance impact separately while other studies combined operation and maintenance (i.e. operation/use) together. Hence, the other differences may be attributed to the variation in system description, assumption and system boundary.

The findings for the water use appear in two recent Australian studies [13,15]. The authors had found an interpretation challenge how the actual water was quantified. The study [13] found construction and maintenance phase dominate the total water usage, around 72% and 36%, respectively, while operation and disposal have less water use. It is to note that the operation phase only includes water use due to heating and cooling only. The water use in operation phase does not include inmate consumption.

Only one study [13] reported solid waste generation in each life phases in Table 1. The author reported that disposal phase contributed the majority (up to 67%) of solid waste generation. Solid waste generations were also reported in two other study [10,32] (not listed in Table 1), but fail to specify the impact contributions in each life cycle phases. All the above three studies, the authors specifically focussed on the effect of solid waste generation by varying floor, framing and wall design. The study [13] looked at the difference between elevated timber floor and concrete slab construction, and found 20–30% difference of the effect of solid waste. The study [10] found 5% variation of the effect of solid waste generation between the concrete block and insulated concrete wall designs. The study [32] found 9% difference of the effects of solid waste generation between the steel and wood frame residential house. This variation may be attributed for the assumptions of disposal. For example, study [13] considered both reuse/recycling as well as landfill for waste disposal, while study [32] summarized the weight of all waste materials.