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Life cycle assessment and life cycle cost implications of wall assemblages designs

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ABSTRACT

This paper describes the life cycle assessment and life cycle cost analysis of a typical Australian house designs. It evaluates the effect of selected alternative wall assemblages on environmental impacts and life cycle cost over the various life stages of buildings (i.e. construction, operations, maintenance and final disposal). A case study house was used as the base case for all the alternative wall assemblage designs. This paper also reports on alternative wall assemblage designs that were produced with variations in external wall cladding, insulation type and thickness, air gap thickness and position. Each design was varied such that it achieved a chosen star rating. Five exterior wall claddings were selected, typical of the Australian building industry. These claddings were brick, autoclave aerated concrete block, fibro-cement sheet, pine saw logs and weatherboard. The results were analyzed for the whole building on a whole life cycle basis in terms of economic and environmental impact. The implications of life cycle environmental impacts and life cycle costs were evaluated and the optimum assemblage design is reported using optimization algorithm. A set of best solution is found depending on factors: the model assumptions, range of environmental and economic indicators considered, and the chosen quantitative criteria.

1. Introduction

Residential dwellings are built to last for several decades. Over such a long lifetime, a building utilizes a wide range of resources and energy intensive processes, from raw material extraction and production, to distribution, operation, maintenance and end of life disposal. Annual heating and cooling energy and maintenance have a significant ongoing economic cost and environmental impact. Construction and disposal have one-off impacts but may also be significant. Considering 3.2 million new dwellings will be constructed in Australia by 2026 [1,2], even a small reduction in economic and environmental impact would be significant across such a large number.

This study reports how different assemblage designs of the exterior walls affect the environmental impacts and costs over the various life stages of buildings. Life cycle assessment (LCA) and life cycle cost (LCC) approach are used to evaluate the life cycle environmental impact and cost effects, respectively. The chosen wall assemblage designs in the various scenarios were selected from those available in *AccuRate*, a tool commonly used for operational energy performance in the Australian building industry. Five wall assemblage designs were made with different cladding types. The different designs were costed using the Bill of Quantity and suitable costing factors. The operational energy performance of each design was evaluated using *AccuRate*. The design was varied so that the star rating varied across a range, from 3.6 to 3.9 star. The lower limit of 3.6 star designs was the rating for the actual case study house. The upper limit of 3.9 star was the maximum rating possible that could be achieved with these wall claddings. The limiting factors for all the designs were either best practice approach or minimum Building Code Australia (BCA) performance requirements.

2. Overview of LCA and LCC on buildings

2.1. LCA on residential buildings

LCA has been used in the building sector since 1990 [3]. LCA aims to evaluate the relative environmental impact of life cycle stages on

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aspects of the product life cycle included within the system boundary. A number of LCA studies have been conducted on residential buildings in Europe and North America [4–7,54–56] as well as in Australia [8–11].

Various LCA software tools have been developed in different regions: *GaBi* and *SimaPro* in Europe and *ATHENA* in the US and Canada [7]. Similarly, many life cycle inventory (LCI) databases are available (i.e. ATHENA, Eco-Invent, and AusLCI). Many LCA software packages and region specific LCI databases have been used in previous studies. Although any LCA software can be used for such analysis, the preference in recent studies is to use region specific LCI data. For example, several recent Australian LCA studies were conducted using *SimaPro* software and region specific data [8,9,11]. One UK study was conducted using *GaBi* software and region specific data [4]. Two recent North American studies were conducted using *ATHENA* software and North American region specific LCI data [5,6]. While the outcomes of these studies are valid for their region, the limitation is that they cannot be compared to studies done in other regions. Hence, the choice of LCI database is a key decision in any LCA study.

The functional units, system boundaries and assumptions vary markedly among LCA studies of residential buildings. Other variables include building typology, regulations, climate, building life span and inclusion of major or minor renovations. Hence the outcomes of any study are generally valid only for that particular region, building type and life span. The selection of impact category indicators depends on the study focus. GHG (Greenhouse gas) and CED (Cumulative Energy Demand) are most commonly used indicators. A common limitation of most studies is that they did not consider the implications of life cycle cost in their analysis.

2.2. LCC on residential buildings

LCC on buildings considers economic cost, in terms of both initial cost and future operational costs over a specified period of time [12]. For future expenses, LCC must take into account the time value of money [12–14]. It increases every year by the net inflation and interest rate. Future costs are estimated based on the current price inflated with an estimate of future inflation then discounted to present value [15,16].

Two commonly used LCC approaches are RS Means and Dodge Unit Cost Guide but they are useful only in the North American regions [17,18]. In Australia, Rawlinsons Construction Cost Guide provides cost based on local average cost data. Quantity surveyors and construction cost consultants have been using Rawlinsons Construction Cost Guide for residential projects throughout Australia since 1953 [19]. All the relevant economic factors of material, labour and demolition costs can be estimated for Australian studies using this guide.

There are several ways to estimate the future costs of building related activities. Future costs are discounted to their present value using a suitable rate over their lifetime [14,20]. This means that the discounted costs represent the total amount that has to be reserved today to finance the expenses in future [16,18].

There have been many costing studies on residential buildings, with several different goals [21–23,57]. Two studies were applied thermal modelling to investigate costs [21,57]; another study was estimated the effect on capital cost and construction techniques of increases in thermal performance [22]; and another study was also investigated the cost of 6 star rating designs [23]. The main limitation of these studies is that none considered whole building life cycle and the implications of LCA. In addition, the study outcomes depended on assumptions about the system boundaries, which were different for each study. This is shown most clearly in the varied relative contributions of the life stages for construction, operation, maintenance and disposal among the studies. This will be discussed further below.

2.3. Implications of LCA and LCC for housing design

Most studies focus on either LCA or LCC analysis of whole house or life cycle stages of assemblages design on buildings. Relatively few of them integrate LCA and LCC analysis of assemblage design. As there is a growing interest in building designs with low economic and environmental impact [18,24], this scenario will become more common. Evaluation of the effect of different wall assemblages on optimum house design is needed to capture a full picture of the environmental and economic costs of the whole building, considering both LCA and LCC.

For example, two recent North American studies reported LCA of residential building wall assemblies. However, these were not evaluated the economics of the designs [5,6]. Similarly, two recent Australian studies on building heating and cooling energy requirements calculated the LCC, but failed to consider the whole dwelling as well as whole life cycle [21,23]. This paper reports the LCA and LCC of the whole building and whole life cycle for 19 house designs with varying wall assemblies.

3. Methodology

The methodology encompasses both environmental and economic effects of material usage in residential house design. The environmental impacts were modelled using *SimaPro* software. The operational energy requirements were modelled using *AccuRate* software based on heating and cooling needs. The heating and cooling energy requirements from *AccuRate* were used as input data in *SimaPro*. AccuRate produces data in the format of MJ/m^2 per annum; this number was entered directly into the *SimaPro* model. The economic investment was calculated using an LCC approach. Linear programming (LP) was used for this optimization algorithm.

3.1. Operational energy modelling approach

AccuRate software from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was used to estimate operational energy (i.e. heating and cooling only) requirements. This popular tool is recommended by the Australian Nationwide House Energy Rating Scheme (NatHERS) as well as Building Code of Australia, and has been validated through BESTEST [21,25,26]. *AccuRate* includes an extensive database of materials that allows the user to modify building elements. It contains a selection of wall, floor and roof assemblage design options. The user can specify the materials and construction techniques, insulation levels, windows size and orientation, shading, ventilation, overshadowing, colour of indoor surfaces, geographical location, and external wall orientation [27]. In this study, for effective analysis, the various wall designs were chosen from those available in *AccuRate*.

AccuRate predicts space heating and cooling requirements in units of MJ/m^2 per annum. The results are then rated against the NatHERS star band score thresholds. The thresholds have been developed for Australian climate zones based on the Protocol for House Energy Rating Software published by Australian Building Code Board [28]. The higher the star rating, the lower the cooling or heating required for the occupants to feel comfortable.

3.2. LCA methodological approach

The ISO 14044 guidelines on LCA methodology were used in this study. A streamlined LCA approach was undertaken using PRé's *SimaPro* (version 7.3) software. *SimaPro* is particularly suitable for studies on Australian dwellings as it can be used with the Australian