A framework for the integrated optimisation of the life cycle greenhouse gas emissions and cost of buildings

Monique Schmidt [a] *and Robert H Crawford* [a]*

[a] *The University of Melbourne, Parkville, VIC, 3010, Australia*

Abstract

Evaluating building design options with a focus on simultaneously minimising life cycle greenhouse gas emissions (GHG) and life cycle cost (LCC) is difficult due to a lack of comprehensive and accessible tools. An integrated approach where life cycle GHG and LCC performance can be balanced is essential in order to optimise a building's overall life cycle performance. This paper describes the development of an integrated framework designed to assist building design professionals in optimising the life cycle GHG and cost of a building. This paper demonstrates the framework's potential by applying it to glazing design options for a residential building case study. The demonstration of this framework highlights the fact that options such as triple glazing, often heralded as a solution for reducing GHG, may not lead to as great a reduction in life cycle GHG as options such as double glazing (which also comes at a lower LCC for this case study building). This paper not only highlights the need to analyse and select building design options based on both their life cycle GHG and LCC performance but also emphasises the significant amount of uncertainty attached to decision-making in these areas.

Keywords: Life cycle assessment; life cycle cost; greenhouse gas emissions; buildings

1. Introduction

There is growing concern about the effect that buildings are having on the environment [1, 2] with construction being one of the most energy intensive sectors and contributors to greenhouse gas emissions (GHG), in developed countries [3]. Over the years there has been an increase in efforts to understand the energy and GHG associated with the built environment. This increasing awareness has led to the creation of several forms of building evaluation that aim to analyse a buildings' environmental performance and suggest ways to reduce energy demand and GHG [4-6]. However, the focus has largely been on reducing the operational energy and GHG of buildings, leaving the embodied energy and GHG largely ignored [7] despite their demonstrated significance. For example, embodied GHG have been estimated to equate to between

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[*] Corresponding author:

Email: rhcr@unimelb.edu.au

Abbreviations: LCA: Life cycle assessment; LCC: Life cycle cost; LCGHGE: Life cycle greenhouse gas emissions; IEE: Initial embodied energy; REE: Recurrent embodied energy; NPV: Net Present Value

10 to 97% of the total life cycle GHG associated with a building (depending on the building location, type, material use, assessment methods and assumptions) [8]. Thus, the need to consider a building's performance from a life cycle perspective has become increasingly evident. However, building design that considers the life cycle perspective has been slow to take hold due to a number of barriers [9]. These include lack of a commonly accepted assessment method, lack of reliable data, and lack of mandatory legislation [10, 11]. Another barrier is the uncertainty towards the financial cost of life cycle environmental optimisation. Building decision-makers are unsure of the full cost implications of this optimisation and building design professionals often don't have sufficient knowledge or appropriate tools to address these concerns. Limited consideration of costs from a life cycle perspective is also a key barrier to life cycle optimisation, as financial decisions are mainly based on the initial cost of building design options, often not taking into account future maintenance and operational costs [12]. The cost-effectiveness of solutions for reducing a building's GHG has become a critical issue for building owners and one of the main drivers behind their uptake [13]. It has become vital to provide environmental and financial building analyses not only from an early-design stage, to better inform design decisions [14], but also to integrate the results in order to better understand their respective trade-offs. Several studies have aimed to integrate these two forms of assessment, typically using life cycle assessment (LCA) (either from an energy or GHG perspective) and life cycle costing (LCC), and include those such as Petrillo*, et al.* [15] and Savino*, et al.* [16]. However, several barriers still plague their successful integration. This study aims to address these barriers and proposes an improved integrated life cycle GHG and LCC framework to aid early-stage building design decision-making.

1.1. Aim and scope

The aim of this study was to develop and test a framework that integrates life cycle GHG and LCC assessment of buildings to aid early-stage building design decision-making. For this study, the environmental impact category of Global Warming Potential (GWP) has been used, which measures how much heat a GHG traps in the atmosphere and is expressed in carbon dioxide equivalent (CO_2e). The greenhouse gases considered include carbon dioxide, methane and nitrous oxide. The scope for the life cycle GHG assessment includes the initial and recurrent embodied GHG and operational GHG. The LCC system boundary includes the initial, replacement and operational costs. The end of life stages, such as demolition, disposal and recycling have not been considered in this analysis due to the limited amount of data available for these life cycle stages (Moncaster and Song, 2012) and as they have been shown to represent less than 1% of the life cycle GHG associated with a building [17, 18]. The scope of the study is illustrated in Figure 1.

<Take in Figure 1>

1.2. Structure

This paper is structured into six sections. The next section, Section 2, provides a brief overview of some of the previous studies that have aimed to integrate life cycle GHG and LCC analysis. This section concludes with the identification of the gaps and weaknesses of these previous studies and highlights how this study attempts to address them. Section 3 describes the process involved in developing the integrated life cycle GHG and LCC framework. The framework is then applied to a residential building case study in Section 4 in order to demonstrate and test its potential. This is followed by the discussion and conclusion in Section 5.

2. Previous studies attempting to integrate life cycle greenhouse gas emissions (or energy) and life cycle cost analysis

Environmental and financial assessment of buildings has been largely carried out in isolation of each other, but there has recently been increasing attempts to combine them. In most cases LCA is used to carry out the environmental assessment either from an energy and/or GHG perspective. For the financial analysis, LCC is predominantly used. Previous studies, such as Fouche and Crawford [19], have provided a detailed review of the previous attempts at integrating LCA and LCC. These can be broadly classified under two main groups. The first group use the methods and data already inherent in LCA and LCC and tend to conduct an LCA first and then an LCC and includes studies such as Leckner and Zmeureanu [20], Ristimäki*, et al.* [21], Bull*, et al.* [22] and Schwartz*, et al.* [23]. These studies tend to provide the LCA and LCC results separately with little to no integration or reference to the relationship of the results. The second group sets out to either provide a combined LCA and LCC method [24], framework [25, 26], model [16, 27-29] or tool [15, 30, 31]. Even though most of these studies suggest that they are providing a new framework or model, they actually make use of the terminology, data sets, methods and calculations already inherent in LCA and LCC analysis. However, most of these studies do not fully integrate the LCA and LCC results [27] and suffer from a range of gaps and weaknesses, as detailed in

Table 1. These gaps and weaknesses range from a lack of transparent inputs to a lack of integrated analysis of results and provide a roadmap for future development of a more sophisticated integrated framework. Table 1 describes the weaknesses that have been addressed within the framework developed in this study.

Table 1 Key gaps and weaknesses of previous attempts to integrate life cycle greenhouse gas emissions and life cycle cost analysis and how this study addresses them

Key weaknesses and gaps of previous studies (studies)	Included	How this study addresses them
Lack of transparent inputs (1,7,8,9,10,14,15,16,18)	✓	All relevant inputs have been provided.
Lack of comprehensive embodied energy/GHG assessment (2,3,4,5,6,7,12,15,16,18,19,20)	✓	Most studies make use of a process or input-output life cycle inventory (LCI) approach. Both methods have been shown to suffer from errors, resulting from truncation or aggregation of the supply chain, for example. This framework makes use of a hybrid LCI approach in order to provide more comprehensive results [32, 33].
Lack of transparent calculations (7,14,18)	✓	All relevant calculations and sources have been provided.
Lack of graphically integrated results (2,3,5,7, 9,10,12,14,15)	✓	Life cycle GHG and LCC results have been integrated into one single graph to aid user interpretation and decision-making.
Lack of weighting/scaling factors explanations (5,6,7,9,11,17,18,19)	✕	No weighting or scaling factors have been used in this framework. All results remain transparent.
Lack of/unclear recurrent embodied GHG and replacement cost inclusion (3,9,10,13,14,17)	✓	Recurrent embodied GHG and replacement/maintenance cost have been included in order to provide a more comprehensive life cycle GHG and LCC assessment.
Lack of/unclear operational GHG and operational cost inclusion (3,10,13)	✓	Operational GHG and cost have been included in order to provide a more comprehensive life cycle GHG and LCC assessment.
Lack of building scale analysis (2,3,5,17,18)	✓	The framework is applicable to building scale analysis, not just product scale.
Lack of early-stage design application (3,5)	✓	Information used within the framework is based on data typically available at an early stage in the design process in order to increase the potential to influence the design.
Lack of selection process based on user personal preferences (5,11,19)	✓	Results presented in a manner that allows the user to base their interpretation and selection of building options based on their own personal preference (i.e. either select an option that decreases life cycle GHG the most with no consideration of financial cost or select an option that decreases life cycle GHG and LCC, for example).

Sources: [1]Bierer, *et al.* [27] [2]Anastaselos, *et al.* [30] [3]Bovea and Vidal [34] [4]Bull, *et al.* [22] [5]Deng, *et al.* [25] [6]Ding [28] [7]Gu, *et al.* [24] [8]Hamdy, *et al.* [29] [9]Heijungs, *et al.* [26] [10]Hoogmartens, *et al.* [31] [11]Huppes and Ishikawa [35] [12]Kneifel [36] [13]Langston and Langston [37] [14]Leckner and Zmeureanu [20] [15]Menzies [38] [16]Mithraratne, *et al.* [39] [17]Petrillo, *et al.* [15] [18]Ristimäki, *et al.* [21] [19]Savino, *et al.* [16] [20]Schwartz, *et al.* [23]

The next section describes how this study's integrated life cycle GHG and LCC framework was developed while addressing the key gaps and weaknesses identified in Table 1.

3. Developing an integrated life cycle greenhouse gas emissions and life cycle cost framework

In order to develop an integrated framework a series of steps had to take place. The first step, of identifying the gaps and weaknesses of previous studies, has been detailed in Section 2. The next step was to identify and select appropriate life cycle GHG and LCC quantification techniques (Section 3.1), followed by identifying the key parameters associated with these techniques and the approach for visualising the integrated results (Section 3.2). Next, a brief description of the integrated visual approach is provided (Section 3.3), finishing with a description of the various steps involved in the integrated framework approach (Section 3.4).

3.1. Identification and selection of appropriate life cycle greenhouse gas emissions and life cycle cost quantification techniques

LCA is regarded as one of the most useful tools for quantifying environmental flows across the life cycle of a product [40, 41]. LCA provides a means to assess the environmental performance of a building from a life cycle perspective by analysing relevant inputs (such as energy) and outputs (such as GHG) associated with a building over its lifetime. LCA, especially streamlined LCA (which may focus on a limited range of environmental flows such as energy or GHG), has been used in many studies to quantify the expected energy demand or GHG associated with a building [22, 23, 42-44]. A streamlined LCA was thus selected as the technique for quantifying the life cycle GHG within the integrated framework.

There are four key steps involved in the application of LCA, as per ISO 14044 [45], namely goal and scope definition (step 1); inventory analysis (step 2); impact assessment (step 3) and interpretation (step 4). For the inventory analysis, where the inputs (for example energy) and outputs (for example GHG) of a product are quantified, there are three main approaches commonly used, namely process, input-output and hybrid analysis. Among these approaches, it has been demonstrated that a hybrid approach typically provides a more comprehensive analysis of a building's environmental performance than process and input-output analysis, which are typically characterised by incomplete and unreliable results, respectively (Treloar, 1997; Treloar, 2007; Crawford, 2008). Of the various hybrid approaches available, the Path Exchange hybrid approach is considered to provide the most comprehensive analysis of embodied environmental flows [46, 47]. For this reason, this approach was selected for the demonstration of the framework (Section 4). However, the framework does allow for any LCI method to be used, but this can affect the reliability of the results. As shown in Table 1, most previous attempts to combine life cycle GHG and cost analysis use a process analysis for the LCI analysis (such as Anastaselos*, et al.* [30] and Bull*, et al.* [22]), and this is a major weakness of many similar previously developed frameworks. The following equations, based on the Path Exchange hybrid approach, as developed by Treloar [33] and Crawford [48], were used to quantify the initial and recurrent embodied GHG of the case study building in Section 4.

The life cycle GHG analysis includes the initial embodied GHG (associated with extraction of raw material, product manufacture, transport and construction), recurrent embodied GHG (associated with building repair, maintenance, refurbishment and replacement), and the operational GHG (associated with the building use). Quantification techniques used for each of these are described below.

3.1.1. Initial embodied greenhouse gas emissions quantification

The initial embodied GHG (IEGHG) is based on the choice of materials, their GHG intensity and the quantity of materials used. Refer to Equation 1, adapted from Crawford*, et al.* [43] for how this is calculated using the Path Exchange hybrid approach.

Equation 1

$$IEGHG_b = \sum_{m=1}^{M}(Q_m \times GHGC_m \times W_m) + \left(TGHGBS - \sum_{m=1}^{M} TGHG_m\right) \times C_b$$

The quantity of material (Q_m) is multiplied by the hybrid embodied GHG coefficient ($GHGC_m$) (which provides the GHG intensity of a specific material). In order to take into account the amount of materials that are wasted on site a wastage coefficient (W_m) is used. These steps are carried out for each material contained within the building. All the individual material IEGHG results are summed to provide the total material-based IEGHG for the building. To complete the system boundary, the total input-output-based GHG associated with the material production processes for which process data is available ($TGHG_m$) is subtracted from the total input-output-based GHG of the building sector (TGHGBS) (which in extracted from a pure input-output model). This helps to take into account the direct GHG associated with construction of the building and the provision of related services (for example, finance and insurance). The remaining input-output value (in GJ/AUD) is then multiplied by the building cost (C_b). Due to a lack of hybrid GHG coefficients at the time of this study, hybrid embodied energy coefficients were used in the demonstration of the framework instead. The main limitation here is that non-energy GHG are excluded. Energy values were then converted to GHG terms using an emissions factor (EF).

An average EF of 60 kgCO$_2$e per GJ has been used to convert the embodied energy values to equivalent GHG, similar to other studies such as Treloar*, et al.* [44] and Crawford [48]. In reality, factors such as location and fuel mix will influence the GHG associated with a material's manufacture. For example, concrete has higher embodied GHG than wood due to its energy intensive manufacturing process. If the location of material manufacture is known, then this EF could be adjusted to reflect higher or lower emissions due to greater certainty about fuel mix, manufacturing processes or transport distances. However, this detailed level of information is not typically available at this stage of a project where the framework would be applied. Embodied GHG coefficients would solve this problem.

3.1.2. Recurrent embodied greenhouse gas emissions quantification

The recurrent embodied GHG (REGHG) are based on the material types, quantities, replacement rates and hybrid GHG coefficients. The materials within the building are considered year by year and the embodied GHG that are associated with replacement of each is calculated. Refer to Equation 2, adapted from Crawford*, et al.* [43], which is used to quantify the REGHG using the Path Exchange hybrid approach.

Equation 2

$$REGHG_b = \sum_{m=1}^{M} \left\lceil \left(\frac{BSL}{MSL_m} - 1 \right) \right\rceil \times \left[(Q_m \times GHGC_m \times W_m) + (TGHGBS - TGHG_m - NATGHG_m) \times C_m \right]$$

The building service life (BSL) is divided by the service life of the material being analysed (MSL_m) (in order to estimate how many times that material will have to be replaced over the useful life of the building) with year 1 subtracted from it (so as not to double count the embodied GHG required at year 1 as this has been included as IEGHG). This value is then rounded up to the nearest whole number (due to the fact that materials are assumed to be replaced in their entirety). This number is then multiplied by the quantity of the respective material (Q_m) and the hybrid embodied

GHG coefficient ($GHGC_m$), to estimate the embodied GHG of the materials being replaced. In order to take into account the amount of materials that are wasted on site, a wastage coefficient (W_m) is also applied. The total input-output-based GHG of the material being replaced ($TGHG_m$) is subtracted from the total input-output-based GHG of the building sector (TGHGBS). Then, in order to ensure that no material is included that is not being replaced, the sum of the GHG of all the input-output pathways (i.e. representing specific products and processes) not involved with the replacement of that material is subtracted ($NATGHG_m$). The remaining value (accounting for non-material-related GHG) is then multiplied by the cost of the material (C_m) and added to the material-related GHG. As for the IEGHG, hybrid embodied energy coefficients and an EF of 60 kgCO_2e/GJ were used in place of GHG coefficients for the demonstration of the framework (Section 4).

3.1.3. Operational greenhouse gas emissions quantification

The operational GHG associated with a building are dependent on a range of factors from the building type, envelope materials, heating and cooling system type and efficiency, number of occupants and their expected activity level, occupancy schedule, etc.. There are several methods available to quantify operational GHG, from steady state calculations to dynamic thermal simulation. Dynamic simulation is often the preferred method within industry [9] and provides a more realistic GHG demand prediction due to the fact that it can factor in elements such as thermal mass and solar radiation [49]. Refer to Stephan*, et al.* [50] for an example of steady state calculations and Haapio and Viitaniemi [4] and Attia*, et al.* [51] for a review of dynamic simulation tools. The method to be used within the framework is dependent on the user and their access to specific tools. For example, the method selected in Section 4 for the demonstration of the framework, was dynamic simulation with the help of the commercial tool Green Building Studio [52]. While most simulation tools suffer from overestimation and inherent assumptions, Green Building Studio has been demonstrated to provide results in a range of ±4% of the real building GHG data [53, 54]. However, the variation in energy consumption and associated GHG from different simulation tools have to be noted, with different tools often providing different results. Schwartz and Raslan [55] has noted a possible difference in energy consumption of ±30% between simulation tools, while Fumo [56] has noted an annual building energy consumption variation of ±7%, while monthly building loads can vary by ±40%.

3.1.4. Life cycle cost quantification

Financial cost plays a large role when it comes to building-related decision-making. The capital cost of a project remains one of the primary criterion in building procurement decisions (Jackson, 2008). However, a building goes through several life cycle stages, and focussing on just reducing costs at one stage can potentially lead to increased costs across other stages of a building's life. Life cycle cost (LCC) provides an approach that mirrors the life cycle approach of LCA. There are several LCC quantification approaches commonly used, such as Net Present Value (NPV), payback analysis and Internal Rate of Return (IRR). Even though the payback method is easy and quick to perform it is not suitable for LCC studies [39]. It ignores the project's cost of capital; ignores cash flows after the payback period and might not factor in elements such as compound interest and discounting [57]. IRR takes into consideration the time value of money and is a good technique if the aim of the assessment is to assess the relative productiveness of the capital being committed to a project but not so good at providing an absolute measure of profitability [58]. NPV is the sum of the discounted present values of all future cash inflows and outflows and is often quoted as "the most accurate and reliable decision rule (i.e. to help inform decision makers when selecting the most appropriate option being assessed) when selecting and assessing projects" [57, 58]. Net Present Cost (NPC) is another term often used in LCC studies relating to environmental issues (such as Kempton and Letendre [59], Kusakana and Vermaak [60] and Budischak*, et al.* [61]). It is similar to NPV, except that it inverts the NPV figure. The NPC approach was selected for this study due to the results being presented in a more relatable manner to users (i.e. a positive NPC will cost the user money and a negative NPC will save the user money). The NPC approach also presents a comprehensive means of estimating the value of a building-related investment over time [57, 62]. However, when using NPC to quantify the LCC of a building, it is important to be aware, as Flanagan*, et al.* [63] point out, of the assumptions, inputs and factors relating to the timescale and depreciation of the project.

The equation used to demonstrate the framework in Section 4 has been based on the NPC approach (Equation 3) and has been adapted from Stephan and Stephan (2016).

Equation 3

$$NPC_M = \sum_{y=1}^{BSL} \frac{\left(\Delta Capex_{M,y} + FS_y + MS\right) + (1+i)^y}{(1+r)^y}$$

The Net Present Cost of a building design option (NPC_M) is calculated over the building service life (BSL) and is the difference between the NPC of the building design option and the NPC of the Base Case (BC). The capital expenditure for the building design option in a specific year ($\Delta Capex_{M,y}$) is the difference between the investment for the considered building design option and the investment for the Base Case in that specific year. The fuel cost saving for that specific year (FS_y) is the difference between the fuel spending for the building design option and the fuel spending for the Base Case. The maintenance cost saving (MS) is the difference between the maintenance cost for the building design option and the maintenance cost for the Base Case. The time value of money is taken into account by multiplying the cost by the considered inflation rate (i) and dividing it by the discount rate (r).

3.2. Defining the key parameters of the integrated framework

The previous section described the various calculation methods that can be used within the framework. Each calculation requires a certain amount of data in order to perform either the life cycle GHG or LCC analysis. This data relates to a number of key parameters and are essential to the operation of the framework. These parameters are divided into two categories, namely user defined and pre-defined parameters (refer to Table 2). User defined parameters refer to those that would usually change from one project to the next. The related data will thus be project specific. Pre-defined parameters refer to those that will not change from one project to the next.

Table 2 Key parameters of the integrated framework

User defined parameters	Pre-defined parameters
Life cycle GHG: 1. Building size (m^2) 🟫🟩🟦 2. Building service life (years) 🟦🟩 3. Material type 🟫🟦🟩 4. Material quantity (m^2/m^3) 🟫🟦🟩 5. Cost of material (AUD) 🟫🟦 6. Cost of building (AUD) 🟫🟦 7. Annual electricity demand (GJ) 🟩 8. Annual gas demand (GJ) 🟩 *9.* Sum of total input-output-based GHG of all materials in building (GJ/AUD)	**Life cycle GHG:** 1. Global warming potential 🟩 2. Emission factor 🟩🟫🟦 3. Material wastage coefficient (%) 🟫🟦 4. Material GHG coefficient (GJ/unit) 🟫🟦 5. Building cost index 🟫🟦 6. Replacement rate of material (years) 🟦 7. Total input-output-based GHG of building sector (GJ/AUD) 🟫🟦 10. Total input-output-based GHG of material (GJ/AUD) 🟫🟦 11. Total GHG of all input-output pathways not associated with the installation or production process of each material (GJ/AUD) 🟦
LCC: 1. Building service life (years) 🟦🟩 2. Material type 🟫🟦 3. Material quantity (m^2/m^3) 🟫🟦 4. Cost of material (AUD) 🟫🟦 5. Replacement rate of material (years) 🟦	**LCC:** No pre-defined parameters

User defined parameters	Pre-defined parameters
6. Price of fuel (AUD/GJ) 🟩 7. Annual fuel demand (GJ) 🟩 8. Discount/Inflation rate 🟦🟩	
Life cycle phase 🟫Initial GHG/cost 🟦Recurrent GHG/cost 🟩Operational GHG/cost	

3.3. Visual integration of results

One of the critical weaknesses identified in the previous studies reviewed in Section 2, was the lack of a visualisation of integrated results either in a table, numerical or graphical form. Most previous studies present financial and environmental results separately with no indication as to how these results can be integrated and thus demonstrate their relationship to each other [22, 24, 34]. Some of the studies that managed to integrate environmental and financial data into a single graph often made use of scatter plot graphs, such as Huppes and Ishikawa [35], Langston and Langston [37], Savino*, et al.* [16] and Schwartz*, et al.* [23]. However, as reviewed by Fouche and Crawford [19] these studies tend to rely on the less comprehensive process-based LCI method and fail to take into account all life cycle stages. Section 4 provides a visual demonstration of the possible results of the integrated framework, which has been based on the scatter plot developed by Torcellini*, et al.* [64], who made use of four quadrants to plot results with the Base Case result located in the centre of the graph. This form of graph is very effective at demonstrating the relationship and trade-offs between specific variables.

3.4. Integrated framework approach

In order to carry out an integrated life cycle GHG and LCC analysis, a sequence of steps was established as part of the framework (i.e. a step-by-step guide for a potential user to follow in order to carry out an integrated analysis). These steps draw inspiration from the individual LCA [45] and LCC [65] frameworks. The step number and the task associated with each step is shown in Figure 2 and further described below.

<Take in Figure 2>

Step 1, which is similar to LCA's first step, is to define the goal and scope of assessment. Step 2, which is lacking from both existing LCA and LCC frameworks, is to establish the Base Case (or business as usual) option against which the other design options can be assessed. Step 3 is similar to LCC's first step, which is to define the alternative design options (against which the Base Case is compared). Step 4 is used to determine the economic and environmental data required for the assessment. Step 5 (similar to LCA step 3) requires the selection of an environmental impact category (for example, global warming potential (GWP)). Step 6, a step not specifically stated but implied in both LCA and LCC frameworks, requires the generation of results. Step 7, which is the critical step that is missing from most previous studies, requires the LCA and LCC results to be integrated. This step is achieved through various methods, such as an integrated visual approach (such as the quadrant based scatter plot discussed earlier) and the Marginal Abatement Cost (MAC) approach (which divides the NPV result by the amount of GHG abated). The last three steps require the user to interpret the results (similar to LCA's final step), perform a sensitivity analysis (similar to LCC's final step) and select an appropriate option.

4. Demonstration of the integrated framework

4.1. Case study

The aim of this section is to demonstrate the potential of the integrated framework by applying it to a detached residential building case study located in Melbourne, Australia. A detached building has been selected as it represents over 80% of Australia's residential building stock [66]. Figure 3 provides a plan of the 230m^2 4-bedroom building. The external brick veneer walls (with timber studs and internal plasterboard finish) have a U-Value of 0.35 W/m^{2}K, and roof (timber truss and concrete roof tiles) a U-value of 0.23 W/m^{2}K. All windows are single glazed and aluminium framed (SG_AF) (U-Value of 7.14 W/m^{2}K). Insulation is provided in the external walls and ceiling with R-values of 2 and 4, respectively. The red line indicates the extent of the wall insulation. These existing characteristics represent the Base Case.

<Take in Figure 3>

Green Building Studio [52] was used to simulate the operational energy of the case study building, utilising the Melbourne weather file extracted from Energy Plus [67]. Energy load was determined based on selected systems for lighting (6W/m^2), heating (gas ducted 3 Star unit), cooling (split system), and domestic hot water, matching the building specifications for the original building [68]. It has been assumed that there are four occupants (with a 24/7 occupancy schedule), based on recent Australian Bureau of Statistics [69] data. Heating and cooling temperature set points have been assumed to be 19°C and 24°C, respectively. Average air leakage has been assumed to be 1.5 ach^{-1} [70].

4.2. Selection and assessment of alternative design options

The function of the building, the type of materials being used and its location are often quoted as being the key contributors to a building's life cycle GHG [8, 71, 72]. During the course of the design phase a large number of decisions have to be made by the designer regarding these key items. One such decision often relates to the type of glazing [73-75]. Glazing forms an integral part of building design as it provides the user with a connection to the outdoors and provides light and heat. However, up to 40% of a building's heating energy can be lost and up to 87% of its heat gained through glazing [76]. Improved glazing options (either with lower U-Values or thermally improved frames) can help with this, however they often come at an additional financial cost, which can affect their uptake. Extra financial cost between single and double-glazing can be 50% to 100%, depending on style and manufacturer [77]. Often these more operationally energy efficient alternatives result in an increase in embodied GHG due to more materials being required. However, the embodied energy and GHG performance is often ignored in glazing assessments [78, 79]. Therefore, different glazing options have been selected to be analysed for the demonstration of the integrated framework.

The aim of the assessment was to analyse the life cycle GHG and LCC performance of different glazing options for the residential case study building. These glazing options are applied to the case study building and analysed using the integrated framework. The different glazing options along with their respective embodied energy coefficient, wastage coefficients and material service lives are provided in Table 3. The hybrid embodied energy coefficient for single glazing was obtained from Crawford [48] and adapted accordingly for double and triple glazing. Other inputs include a 6% discount rate, 3% inflation rate, 50-year BSL, cost of materials sourced from Rawlinsons [80] and cost of fuel sourced from Energy Australia [81].

Table 3 Case study glazing options considered

Glazing aspect	Type	Embodied energy coefficient (GJ/unit)[1]	Wastage coefficient	Material service life (years)

Pane material	Single glazing (SG)	1.73 GJ/m^2 432.5 GJ/m^3	1.03[1]	Dependent on frame material (see below)
	Double glazing (DG)	3.46 GJ/m^2 432.5 GJ/m^3	1.03[1]	
	Triple glazing (TG)	5.19 GJ/m^2 432.5 GJ/m^3	1.03[1]	
Frame material	Aluminum (AF)	252.6 GJ/t	1.1[1]	25[2]
	Timber (TF)	21.33 GJ/m^3	1.02[1]	40[3]

Source: [1]Crawford [48] [2]LCCS [82] [3]InterNACHI [83]

Figure 4 provides the life cycle GHG reduction from the Base Case in tCO_2e on the x-axis and the LCC on the y-axis for the glazing options considered. Only quadrants 3 and 4 are illustrated as no results fell within quadrants 1 and 2. The Base Case (SG_AF) is represented with a single black dot at the intersection of the X and Y axes. The life cycle GHG results include both the initial and recurrent embodied and the operational GHG. The LCC includes the initial, replacement and operational cost.

<Take in Figure 4>

Based on Figure 4 it is quite apparent that all options lead to a reduction in life cycle GHG (quadrant 3 and 4) with TG_TF leading to a 180 tCO_2e reduction in emissions compared to the BC. Even though all the options, except SG_TF (due to timber having lower embodied GHG than aluminium), lead to an increase in embodied GHG (due to more materials being required), the operational GHG savings pay back the embodied GHG within 50 years. Thus, based on a life cycle GHG perspective, all options would be more ideal that the BC option of SG_AF. However, only one option leads to a decrease in LCC (quadrant 3), further highlighted in Figure 5. DG_TF has a negative cost of -4.73 AUD/tCO_2e reduced, in comparison to SG_TF, which is the most expensive, costing 71.67 AUD/tCO_2e reduced. Even though TG_TF and TG_AF both lead to lower life cycle GHG due to the improved operational performance of TG, they come at a greater capital and replacement cost than DG. Based on both a life cycle GHG and LCC perspective, DG_TF appears to be the most ideal solution for this case study building, especially where cost is a key decision driver.

<Take in Figure 5>

4.3. Comparison to previous studies

The results of the glazing analysis were compared to previous studies to ensure the framework provides reliable and comparable results. Howard*, et al.* [84] also found that for a mild climate such as Melbourne, the difference between single and double-glazing, in terms of operational energy and GHG reduction, is marginal, even though some sources state a decrease of over 25% can be expected [85]. Aldawi*, et al.* [86] found a 14% reduction in total annual operational energy for their Melbourne-based dwelling when changing single to double-glazing, which is quite similar to this study's 19%. Similar to this study, Jones [87] found a 53% reduction in IEE when switching from aluminium to timber windows. In terms of cost, most studies found triple glazing to have the highest initial cost [87, 88] and double glazing more than single glazing regardless of which frame type was used [89], which is similar to this study. Bosschaert [88], using a 3% IR identical to this study, also found significant financial savings in terms of operating costs, when switching from double to triple glazing (however the DR is not provided). A Jordanian study by Jaber and Ajib [90] also found a LCC decrease when switching from single to double-glazing. However, the IR used (8.9%) is significantly higher than that used in this study, which could alter the findings. It is important to bear in mind that comparing LCC results across studies is quite a controversial exercise as the results are highly dependent on a multitude of inputs and assumptions, for DR, MSL, IR etc.. Life cycle studies suffer inherently from a significant amount of uncertainty [72] as it is impossible to know for certain how many of these key factors will change over time. The sensitivity of the results to this uncertainty is explored further in Section 4.4.

4.4. Sensitivity analysis

In order to test how sensitive the integrated framework is to the various uncertainties associated with its individual elements, a sensitivity analysis was conducted. This not only evaluates the potential reliability of results but also assesses the influence of factors known to cause variation in both life cycle GHG and LCC analyses. Table 4 summarises the sensitivity parameters tested. These sensitivity parameters are based on the parameters most frequently included in environmental and economic life cycle studies and include discount rate (DR), inflation rate (IR), building service life (BSL), price of goods (POG), material service life (MSL) and variability regarding embodied and operational GHG results. For example, the operational GHG results within the framework's demonstration include a ±20% range, similar to Petersen [91] and Crawford [92]. Refer to Table 4 for sources regarding these parameters. The effect of any other source of uncertainty on the variation in results can also be easily tested within the framework, such as transport distance, GHG conversion factor or embodied GHG coefficient.

Table 4 Sensitivity parameters tested for case study glazing results

Sensitivity parameter	**Variation**	**Detail**
DR and IR [1,2,3,4,5,6,7]	Low DR, Low IR	3% DR and 2% IR
	High DR, High IR	10% DR and 3% IR
BSL [1,2,3,5,10]	Low BSL	20 years
	High BSL	100 years
MSL [3,11]	Min MSL	Aluminum 15 years[13]; Timber 20 years[14]
	Max MSL	Aluminum 40 years[15]; Timber 65 years[11]
POG [3,7,11]	POG increase	POG +/- 10% to POG +/- 40%
	POG decrease	
GHG variability [8,9,10,12]	Min GHG	-20% OGHG; -40% EGHG
	Max GHG	+20% OGHG; +40% EGHG

Abbreviations: DR: Discount rate, IR: Inflation rate, BSL: Building service life, MSL: Material service life, GHG: Greenhouse gas emissions, EGHG: Embodied greenhouse gas emissions, OGHG: Operational greenhouse gas emissions, Min: Minimum, Max: Maximum, POG: Price of goods

Sources:

[1]Stephan and Stephan [93] [2]Leckner and Zmeureanu [20] [3]Flanagan*, et al.* [63] [4]Langston [58]
[5]Mithraratne*, et al.* [39] [6]Ristimäki*, et al.* [21] [6] Morrissey and Horne [94] [7]Islam*, et al.* [95]
[8]Crawford [92] [9]Juodis*, et al.* [96] [10]Crawford [48] [11]Rauf and Crawford [17][12]Petersen [91],
[13]Seiders*, et al.* [97] [14]Ransley and Tyrrell [98] [15]Ding [99]

The results of the sensitivity analysis are illustrated in Figure 6. In order to maintain consistency in the visualisation of results, the four-quadrant graph was used again with the range of possible results provided with a shaded colour coded prism. The BC is shown at the intersection of the X and Y axes as a black dot. Sensitivity results for DR and BSL are shown for all glazing options. What is interesting to note is that the LCC results are significantly influenced by the MSL (i.e. if an option gets replaced more often it will lead to a greater LCC, compared to an option with a longer MSL which requires less frequent replacement). Another key finding is the significant influence of the DR, as can be seen with the TG_AF and DG_TF options. The lowest LCC is achieved when the DR is set to 3% (in comparison to 6% for the BC). As for the life cycle GHG, the results are heavily influenced by the BSL. A lower BSL of 20 years results in most options achieving the lowest life cycle GHG reduction, as the building does not have enough time to pay back its embodied GHG through operational GHG savings. In comparison, the longer 100 year BSL achieves the greatest life cycle GHG reduction for all options as the building has a much longer time to benefit from the operational GHG savings.

<Take in Figure 6>

Based on this sensitivity analysis, it is quite difficult to tell which option will most consistently lead to the greatest decrease in life cycle GHG and LCC, thus emphasising the significant amount of uncertainty still plaguing life cycle studies. However, based on the results, TG_AF and SG_TF most consistently lead to a greater increase in LCC in comparison to the other options. TG_TF and DG_TF will lead to a decrease in both life cycle GHG and LCC, if the average or maximum MSL is assumed and a 50-year or longer BSL is assumed. While the framework has been designed to consider the potential variation in results due to these various inherent uncertainties, it is up to the user to judge how the level of confidence in the results will affect their decision-making.

5. Discussion and Conclusion

Studies such as that by Bierer*, et al.* [27] confirm that there is an undisputed need to couple LCA and LCC in order to increase their uptake within the construction industry. This study sets about addressing this need and has provided a framework that integrates LCA (in the simplified form of a life cycle GHG analysis) and LCC. It is the first integrated approach, in the form of a framework, that aims to address some of the most critical gaps and weaknesses associated with previous attempts at developing an integrated environmental and financial assessment for buildings. The framework also provides a more comprehensive form of LCA and LCC analysis with the use of the Path Exchange hybrid approach for embodied GHG calculations and the NPC approach for LCC calculations. This helps to address the limitations of studies such as Anastaselos*, et al.* [30] and Bull*, et al.* [22] who made use of less comprehensive LCA methods, such as process analysis. This study's framework also includes a broad range of life cycle stages, unlike Petrillo*, et al.* [15] and Langston and Langston [37]. The developed framework provides a suggested approach (as demonstrated in

Section 4) that can be used by design professionals to inform decision-making. It provides the calculations (and the relevant data inputs) required to carry out this integrated assessment (Section 3 and 4), which is a major aspect lacking from previous studies such as Gu*, et al.* [24] and Hoogmartens*, et al.* [31]. It also provides a suggested visual format for integrating the results, one of the key weaknesses identified in previous studies such as Bierer*, et al.* [27] and Heijungs*, et al.* [26].

This study not only developed an integrated LCA and LCC framework but also demonstrated its potential by applying it to a case study building. This is another one of the key gaps in previous studies where a framework or method would often be suggested but not tested on a real case study, such as in Huppes and Ishikawa [35].

5.1. Limitations and further research

This study has developed a novel and comprehensive integrated LCA and LCC framework and has demonstrated its potential by applying it to a case study building. However, there is a range of limitations to be aware of when interpreting the results from the application of the framework, particularly for the case used within this study. Firstly, the demonstration of the framework has only been applied to a single element (glazing) of one building. The results are only applicable to this particular case. However, case study research has been deemed appropriate for the preliminary stages of an investigation [100], which complements the nature of this study. As the aim of the study was to develop an integrated framework and not to provide an exhaustive analysis of all possible building design options, the limited case study and options considered serve their purpose in aiding the development of the framework and demonstrating its potential. In order to make the results of this study more statistically relevant more case studies of different buildings and design options would need to be analysed.

Secondly, several other aspects must be considered when interpreting the results of this analysis. For example, Green Building Studio [52] was used to predict the annual energy consumption of the case study building. Different simulation tools often yield different results due to assumptions and calculations inherent in the tool [101, 102]. However, some studies, such as Adams [103] have stated that Green Building Studio is suitable for early stage design analyses, which complements the nature of this study’s enquiry. In practice, the choice of operational energy simulation tool may alter the overall findings of an analysis using this framework.

Thirdly, there are several assumptions made in applying the framework, such as the fact that it is assumed that the energy consumption, price of goods and energy price for the case study building will remain the same throughout the life of the building. This might change in real life if the building users, equipment, usage patterns etc. change. Embodied GHG coefficients are also assumed to remain constant over time. However, due to the difficulty and uncertainty in predicting future GHG implications (such as factors affecting fuel mix; emission factors or advances in technology etc.) and user energy consumption, the complexity has been simplified in order to focus on the development of the framework. Future iterations of the framework could be easily designed to enable variation to these and other factors over time. Several assumptions regarding the building characteristics have also been made, including those related to the temperature set points, number of occupants, and heating and cooling schedules, for example. These assumptions can be replaced with more accurate data if more detailed building information becomes available.

Fourthly, life cycle GHG studies suffer from a large degree of uncertainty, demonstrated by the ±40% and ±20% variability ranges for embodied and operational GHG results that are often used [92]. In order to decrease this uncertainty several aspects that continue to plague life cycle studies will have to be addressed in future research, such as data availability and assessment approaches [48, 104].

The next step in the evolution of the integrated framework is applying it to a broader range of buildings and building elements (such as insulation, for example) in order to demonstrate its flexibility and applicability, and further test its reliability.

5.2. Conclusion

This study has emphasised the fact that there is a critical need to integrate environmental and financial information during the early-stage building design decision-making processes. The trade-offs between the two can then be better understood and factored into the design process. By looking at building design options from a life cycle perspective, selections based traditionally on the operational performance or the capital cost alone can be made from a more holistic point of view. This can potentially lead to a better long-term outcome for building owners, users and the environment. This study addressed the gaps and weaknesses associated with previous attempts at integrating environmental and financial building assessment, by developing an integrated LCA and LCC framework to further aid the building design decision-making process. The framework was applied to a case study building in order to demonstrate its potential to elucidate the environmental and economic trade-offs prevalent in design decisions. These trade-offs became apparent for options such as double-glazing with timber framing, where a user could select this option knowing that it will most likely lead to a life cycle GHG reduction and financial savings. This demonstrates how this integrated framework, based on early-stage design data, could be used to aid decision-making. By providing building decision-makers with both the environmental and financial data at an early design stage, design decisions can be better informed and this lead to greater confidence that environmental benefits are being achieved. While in its current form, the application of the framework is a very manual and labour and time intensive process, further work is underway to streamline it. This involves an integration with emerging approaches for automated LCA [46] and early-stage building design decision-making tools [105]. This will assist in broadening its uptake by building design professionals.

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