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Towards an integrated approach for evaluating both the life cycle environmental and financial performance of a building: A review

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Abstract

A building is responsible for the emission of a significant amount of greenhouse gas (GHG) emissions over the various stages of its life cycle. Industry and government have been primarily focused on assessing and implementing mitigation measures related to the operational GHG emissions of buildings, leaving the emissions related to other life cycle stages, such as raw material extraction and maintenance, largely ignored. However, the uptake of assessments, such as life cycle assessment (LCA), and mitigation measures that consider buildings' emissions from a life cycle perspective has been slow due to various barriers. One such barrier that has not been as widely documented yet is the uncertainty towards the financial cost of life cycle GHG emission reduction. There has been an increase in studies that have included both the environmental and financial assessment of a building or building systems over its expected lifetime. These studies often use the economic methodology called life cycle costing (LCC), that complements the life cycle approach of LCA, to help quantify the financial impact of a project. However most of these studies either base their results on exemplary low energy buildings, not traditional buildings that dominate the built fabric. In addition there is a trend to primarily focus on residential buildings, leaving other building typologies neglected. Other aspects to notice from these studies include the fact that most present findings of the life cycle energy impact, not life cycle GHG impact. There is also a need to use more comprehensive life cycle inventory data, such as hybrid, not just process data, to provide more comprehensive results. And lastly, most studies consider at new buildings, not refurbished or existing buildings. LCA and LCC support each other from a life cycle perspective however there is still a need to further develop an approach to concurrently balance both economic and environmental performance to create a more sustainable built environment.

Peer-review under responsibility of the organizing committee iHBE 2016.

Keywords: life cycle analysis; life cycle cost; greenhouse gas; building

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Nomenclature

GHG	Greenhouse gas
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
NPV	Net Present Value
IRR	Internal Rate of Return
LCCf	Life Cycle Carbon footprint

1. Introduction

A building is responsible for the emission of a significant amount of greenhouse gas (GHG) over the various stages of its life cycle. These life cycle stage emissions can be broadly classified as operational emissions (emissions relating to the running of the building such as heating and cooling) and embodied emissions (those emissions relating to the manufacture, construction and maintenance of the building). Embodied emissions include both the initial emissions (released during extraction, manufacture, transport and construction) and recurrent emissions (released during the maintenance and repair of the building over its lifetime).

With the growing awareness towards the effect GHG emissions have on climate change [1], building environmental assessments have increased. These assessments help quantify the environmental performance of a building. The buildings' operational stage has been the main focus of these assessments and consequent mitigation strategies, leaving the other strategies largely ignored. However the embodied emissions from materials and manufacturing, transport, maintenance and disposal have been estimated to be as high as 70% for certain building typologies over their lifecycle [2]. Thus it has become paramount to assess buildings based on their life cycle performance. Life cycle assessment (LCA) has been demonstrated to provide an appropriate framework for assessing a building or a building systems environmental performance over its expected lifespan.

However there has been a slow uptake of building strategies that consider the life cycle performance of a building. Several barriers are hindering the uptake of LCA, from consistency of method, availability of comparable data and government policy. These barriers have been well documented in the literature. However one of the remaining barriers, uncertainty towards cost, has not been as widely explored. Building owners and project developers are unsure of what the cost implications might be to include both operational and embodied emission reduction strategies into their projects and design team members do not have sufficient knowledge or appropriate tools to answer their cost concerns. Building design decisions are commonly based on issues pertaining to construction cost [3] with capital cost remaining the primary criterion for building procurement decisions. Financial cost plays a large role especially when it comes to low carbon construction with the consideration of 'green' designs always prefaced with the question 'How much more will this cost?' [4].

There has been an increase in studies that have included both the environmental and financial assessment of a building or building systems over their expected lifetime. These studies often use the economic methodology called life cycle costing (LCC), that complements the life cycle approach of LCA, to help quantify the financial performance of a project. The objective of this study is to first provide a brief overview of these recent studies, secondly to determine the relevant key elements of these studies and then thirdly highlight any aspects that have been neglected in these studies that need to be developed further in future research regarding the quantification of environmental and financial performance of buildings. The structure of the paper will first include a brief introduction of the LCA and LCC methodology and then provide an overview of relevant recent studies concluding with areas for future research.

2. Background

Traditionally a life cycle assessment and a life cycle costing for a built project are carried out independently of each other, as described in the sections below.

2.1. Quantifying the environmental performance of buildings using life cycle assessment

Life Cycle Assessment (LCA) is a method commonly employed for evaluating the environmental performance of products across their entire life, including direct and supply chain effects [5]. LCA helps to analyse the relevant inputs (such as water, energy and raw materials) a product or building requires over its multiple life cycle stages in relation to its outputs (such as atmospheric emissions, waterborne and/or solid wastes). There are three main types of LCA used, namely a conventional LCA (where an individual product or system is assessed), comparative LCA (two or more products or systems are assessed and compared) or streamlined LCA (where the scope is further limited in order to only assess the energy or GHG, for example, of a product or system). In order to help consolidate and standardise the life cycle assessment approach the International Organisation for Standardisation published 'Environmental Management – Life Cycle Assessment – Principles and Framework (ISO 14040, 2006) and 'Environmental Management – Life Cycle Assessment – Requirements and Guidelines' (ISO 14044, 2006). However, recent research has highlighted some of the shortcomings of these international standards, such as ill defined system boundaries and unfairly justified inputs and outputs [6]. According to the ISO 14044 standard, there are four fundamental steps for conducting an LCA, namely: goal and scope definition (step 1); inventory analysis (step 2); impact assessment (step 3) and interpretation (step 4). The inventory analysis (step 2) can be compiled either through process analysis (a bottom-up technique); input-output analysis (a top down macroeconomic technique) or hybrid analysis (combining process and input-output analysis). Due to the fact that LCA is often seen as complex and time and resource intensive [7], there has been an increase in the number of available tools and software to aid calculation, such as SimaPro (Netherlands) and eTool (Australia), for example. It is important to be aware that due to the multiple steps and subjective nature of LCA, a large amount of uncertainty is inherent in any LCA study [8]. Sensitivity analysis is a popular technique used in life cycle assessment studies to help highlight which inputs and assumptions affect the study results most significantly.

2.2. Quantifying the financial performance of buildings using life cycle costing

Life cycle costing (LCC) provides a means to assess the costs incurred over the various life cycle stages of a building and provides a useful tool for comparing building design options. LCC analysis is defined as a 'technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs, as defined by ISO 15686 (2008)[9]. Traditional LCC is purely economic and does not take into account environmental aspects. Similar to LCA, there are a series of steps that need to be followed in order to complete a LCC. The first step is to define alternative strategies to be evaluated. The next is to identify the economic criteria (such as discount rate and analysis period). The third step is obtaining and grouping of significant costs. The last step is to perform a risk assessment, also referred to as a sensitivity analysis. Net present value (NPV), a discounted cash flow analysis technique, is often employed in LCC studies as it takes into account the time value of money (i.e. difference in value between money today and money in the future). The NPV is the sum of the discounted present values of all future cash inflows and outflows. If the NPV is positive, the project will produce a profit. If the NPV is negative, the project will come at a loss. If the NPV is zero, one will neither gain nor lose by accepting the project. Other techniques also used in LCC studies include internal rate of return (IRR) and payback analysis. Attention should be paid to these techniques as they can lead to misinterpretation if the time value of money is not accounted for, such as simple payback method, or if there are delayed investments which IRR will not always account for. LCC studies, similar to LCA, include a significant amount of uncertainty as the future is being forecast on the basis of current data and knowledge [10] [11] and it is vital to provide all assumptions and data inputs so as to aid interpretation.

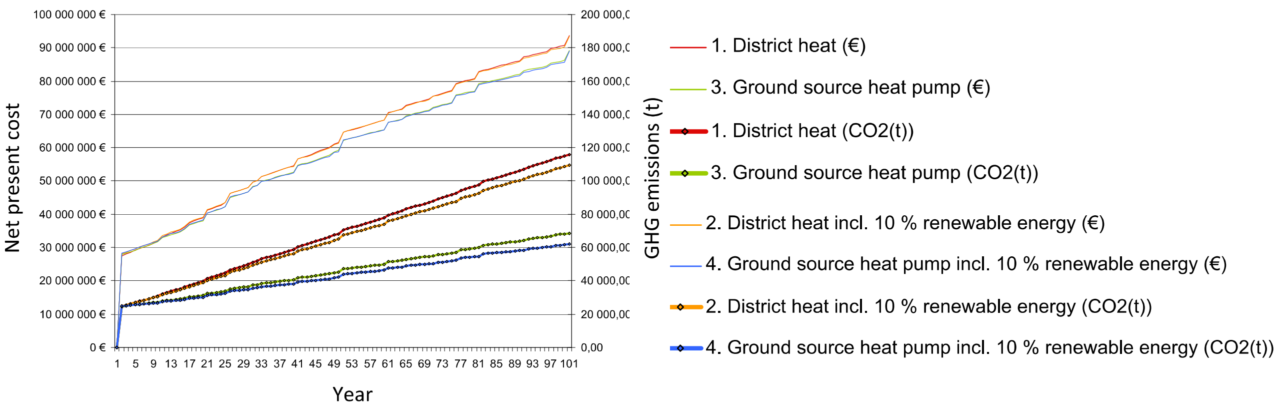
3. Recent studies that combine an assessment of both the environmental and financial life cycle performance of buildings

The previous section described the environmental assessment tool called LCA and financial assessment tool called LCC. LCC and LCA have been developed independently of each other so there is a difference in terminology, framework and calculation rules. However they both stem from the life cycle perspective and compliment each other in seeking a more holistic understanding of building performance. Often these two tools are used in isolation of each other to evaluate building projects. However there has been an increase in studies starting to include both LCA and LCC analysis in order to evaluate projects. The section below will briefly describe relevant studies that have included both LCA and LCC for building evaluation.

3.1. Recent studies

Studies that include both LCA and LCC as part of a building assessment often use the terminology, data sets and calculation methods already inherent in each. Often the calculations and analysis are performed separately first as the initial part of the assessment. The second part of the assessment then compares and evaluates the results of the LCA and LCC. These studies are more concerned with analysing the relationship of LCA and LCC and indicating how these two entities can be evaluated concurrently in order to aid the decision-making process.

A study that demonstrates how the LCA and LCC framework can be used separately at first and then the results integrated in order to provide an assessment based on both cost and environmental performance is the Finnish study completed by Ristimäki et al [12] of a new residential district energy system (which includes seven residences). LCC data was collected and calculated manually based on the NPV methodology over a 25-year period (a 50 and 100 year period was also included to test the sensitivity). The life cycle affordability of each option was calculated by including the replacement, maintenance, energy and investment cost. This was followed by a streamlined LCA assessment, which was calculated with the aid of an input-output-based software model ENVIMAT (which is based



significant effect on the results” and further analyses regarding the sensitivity of these factors will have to be carried out. The specific calculations used are unclear and would aid interpretation of results. In addition software packages each have their own data sets and internal calculations, which are often unclear to the user.

An example that demonstrates the inclusion of detailed embodied inputs and the development of a supplementary tool to aid assessment is the New Zealand based study by Mithraratne and Vale [13] where initial embodied energy and cost of building materials along with the operating energy and cost of three residential buildings were analysed. A tool developed by the University of Auckland, called the Life Cycle Analysis Model, took both these energy and costs considerations into account and found that the embodied energy was higher in the energy efficient house however operating costs were reduced thus decreasing the overall energy demand. Again the assumptions inherent in the tool need to be clear to aid interpretation of results.

Another Australasian example is the study completed by Langston and Langston [3] where 30 buildings (both residential and commercial), located in Melbourne, were analysed and resulted in a strong correlation between capital cost and embodied energy in buildings as illustrated in the Fig 2 below. This is also one of the limited examples of studies consulted that made use of a hybrid analysis, instead of process analysis alone, for their life cycle inventory.

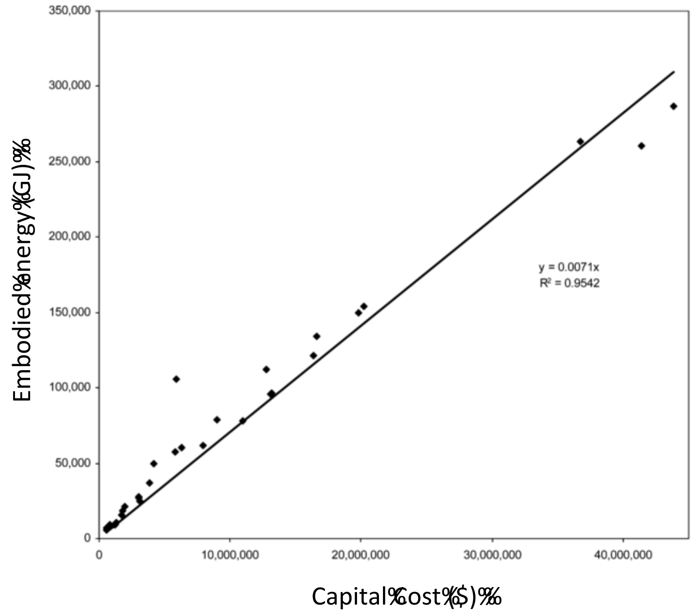


Fig. 2. Correlation between embodied energy and capital cost, [3]

Another study that found a “reasonable linear correlation between embodied energy and cost of building components” was completed by Jiao and Lloyd [14] which looked at two conventional building forms in China and one energy efficient building located in New Zealand. In order to narrow down the scope of their analysis and thus data collection, they included three selection parameters namely only selecting materials that contribute a significant mass to the overall building; have a large influence in the final budget and have a high energy intensity. Both studies are limited to only including the embodied energy (with no other life cycle energy phases considered) and only the capital cost (with no reference to other life cycle cost stages). Even though the embodied energy is taken into account, which is so often ignored within building assessments, it is vital to include the other life cycle stages such as operational, so as to ensure the resource flows within one life cycle stage does not increase flows within another life cycle stage.

Another study that also used an energy efficient building as a proxy for analysis is the LCC and energy analysis conducted for a net zero energy house in Canada by Leckner and Zmeureanu [15]. This study included passive measures (such as improving the thermal envelope) and then followed by active measures (such as solar combisystem) in an attempt to reduce the energy demand. This study considered the operating and embodied energy of the house along with the energy payback. The LCA demonstrated a decrease in life cycle energy use but the LCC demonstrated that due to the high cost of solar technologies and low cost of electricity in Montreal the financial payback was never achieved. However process data was used (due to the use Athena software[16]), which can lead to an underestimation of the embodied energy which might alter the outcome of the results [17] [18]. Caution should also be paid to using the payback method, as economic parameters such as the time value of money and discount rate are not included.

Kneifel [19] also used the NPV technique to look at both the life cycle GHG emissions and cost of a number of improvement strategies for new commercial buildings across the USA. Their study utilised 12 prototypical buildings that were used as a base line from which to perform roughly 576 simulations, with the use of thermal dynamic software Energy Plus. BEES software was used for the LCC section of the study. LCA and LCC were conducted over four different study periods, namely 1, 10, 25 and 40 years in order to demonstrate the different stakeholder interest over the life span of the building. Their study concluded that energy efficiency technologies, such as insulation, low-e windows and daylight controls, decreased energy use by 20% and often lead to a negative life cycle cost because the of the need for smaller and cheaper HVAC equipment. In addition the carbon footprint can be reduced by an average of 16%. However their study once again used process data, which as stated before can lead to underestimation of environmental flows.

A UK-based residential study completed by Schwartz and Raslan [20] split up their study into two sections. First they looked at the embodied carbon and cost and then secondly, they looked at the operational carbon and cost. They also kept the calculations separate, looking first at life cycle carbon footprint (LCCf) and then the life cycle cost (LCC). Once the values were determined, the relationship between the LCCf and LCC values was plotted on a graph (see Fig 3 below). With the use of multi-objective genetic algorithms, various building strategies, such as the brick with insulation illustrated below, were evaluated from both the economic and carbon perspective. Their study found that if a decision were only made from an energy perspective, a strategy such as large south facing windows would be deemed appropriate. But once the LCCf and LCC was combined, the strategy with, for example, the smallest windows would be selected which would save both cost and carbon over the life cycle of the building. However, they concluded that even though a selected strategy might save on carbon and financial cost, one also has to consider the user needs (such as what effect might small windows have on occupant comfort) so as to determine the most 'optimal' solution in the end.

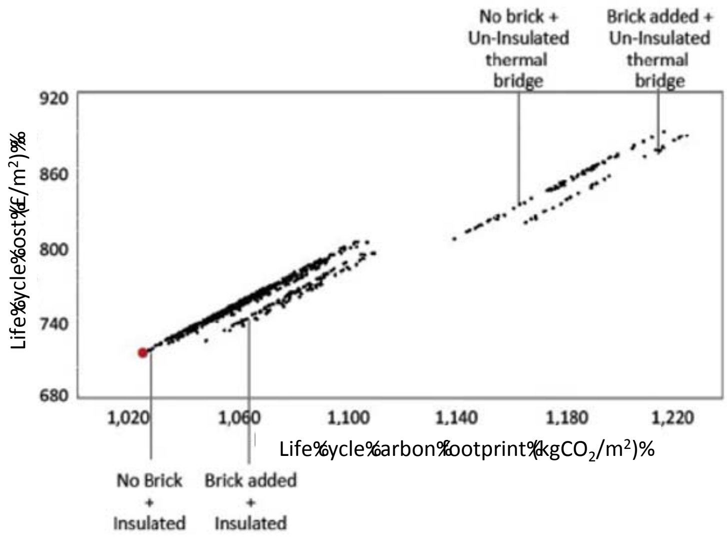


Fig. 3. Relationship between life cycle carbon footprint and life cycle cost, [20]

New buildings are often the focus of recent studies however a study that considers refurbishment is that by Bull and Gupta [21], where they looked at the energy efficient refurbishment of UK schools and the consequent life cycle effects on cost and carbon. The goal of the study was to establish which retrofit measures and combinations of measures resulted in the greatest overall reduction of LCCf and LCC. Retrofit measures included insulation (internal and external); improved window glazing; improved air-tightness and more efficient boilers. With the use of Energy Plus for operational energy calculations and Bath University data (ICE)[22], the life cycle energy was calculated. Costs were estimated from the Costmodelling software[23]. For the LCCf, the operational carbon had a bigger influence than the embodied carbon. Positive NPV values were less common, with only the condensing boiler providing a positive NPV. The worst performing NPV was the internal insulation.

Most of the studies listed above use process data for the LCI analyses. Input-output or hybrid data provide a more holistic overview of the multiple upstream processes involved with building products. Process data by comparison has quite a narrow system boundary, leading to underestimation of the embodied flows. Stephan and Stephan [24] is an example of a study that used input-output-based hybrid data for their life cycle energy and cost analysis of embodied, operational and user-transport energy for a residential building in Lebanon. They utilised a NPV calculation to supplement their LCC analysis. The use of thermal modelling was employed to evaluate the operational energy effectiveness of 22 energy reduction measures. This was then further translated into life cycle energy by combining the embodied, operational and user transport related values. Their study concluded that all operational energy reduction measures, except for photovoltaic panel, resulted in a positive NPV for the context of Lebanon.

4. Discussion

The studies discussed above demonstrate a means of using the current methods available for LCA and LCC and then using the results of both analysis techniques to inform decision-making. These studies draw upon the strengths inherent in LCA and LCC as its own independent evaluation tool but finding a way to integrate both results.

Several studies that used both LCA and LCC as part of their building evaluation made use of commercially available software. This can be noted especially for the estimation of operational energy and GHG, such as Ristimäki and Säynäjoki [12] and Kneifel [19]. For the calculation of embodied flows, some made use of software such as BEES [19] and in-house developed tools [13]. Others used manual calculation, with the use of databases for the life cycle inventory section of the study, such as Langston and Langston [3] and Leckner and Zmeureanu [15]. The decision to use computer aided software or not will depend on the nature of the study and the task at hand. Thermal dynamic modelling to produce GHG and energy estimations during the operational stage is quite a common method due to the complexity and time it would take to do this manually. Thermal dynamic modelling has also evolved and matured over the years to produce quite reliable results and is popular within industry and research. Software to estimate the embodied flows has only recently started gaining traction to help speed up the calculation process. These tools have formulas and data sets incorporated within them that get automatically selected, thus obscuring some of the assumptions inherent in each tool to the user. The discrepancies between the various tools results have also been highlighted (due to differing data sets and system boundaries, for example [25]) and will need to be further investigated. For the financial section of the studies, most used manual calculation for their LCC estimations. Manual calculations although very time, cost and data intensive, provide greater transparency as all inputs and assumptions can ideally be made clear from the start and thus provides greater user control.

What is evident from some of the studies mentioned above is that there is a trend to conduct a combined LCA and LCC analyses for buildings, such as the studies completed by Jiao et al. (2012) and Mithraratne and Vale [13]. Cabeza and Rincón [26] confirms this with their review of current LCA and LCC practices stating that this combined analysis is mostly carried out “in what is shown as ‘exemplary buildings, that is, buildings that have been designed and constructed as low energy buildings”. There are very few studies that combine both LCA and LCC for ‘traditional’ buildings, not buildings that would be classified as lower energy for example. Low energy buildings are ‘exemplary’ buildings and do not represent the majority of buildings being built,

There is also a trend in primarily focusing on residential buildings for LCA and LCC studies. While there is merit in continuing this investigation as the residential sector represents a large percentage of the overall building stock, there is a need though to increase the amount of studies looking at other building typologies. Only one of the studies found to consider both LCA and LCC looked at education [21] and none at healthcare or governmental buildings.

Other aspects to note from the studies discussed above include that most findings focus of the life cycle energy demand, not life cycle GHG emissions There is also a need to use more comprehensive inventory data, such as hybrid, not just process data, to provide more complete results. And lastly, most studies looked at new buildings instead of refurbished or existing buildings. New buildings represent quite a small percentage of the nations building stock, such as in the UK where they only represent 1-3% in any one year [27].

Kats states that "the art and science of calculating true life cycle impacts and cost of green buildings is still evolving and is generally not practiced" [28]. The economical aspects of LCC and the environmental aspects from LCA support each other from a life cycle perspective [12]. There is still a need to further integrate the practice of using both LCA and LCC so as to better evaluate the long-term performance of a proposed project.

5. Towards an integrated approach for the environmental and financial evaluation of building projects

The previous section highlighted the current state of knowledge regarding the integration of both LCA and LCC results. Several aspects were highlighted that need further improvement in order to evolve the practice of quantifying both the environmental and financial performance of buildings so as to aid decision making. These aspects, as illustrated below in Fig. 4, include greater transparency of assumptions (whether it be data inputs, calculations or software utilized); the use of traditional buildings (not just exemplary buildings); incorporation of other building typologies (not just residential); inclusion of GHG emission assessment (not just energy); the use of hybrid data (not just process data) and consideration of refurbishments (not just new buildings).

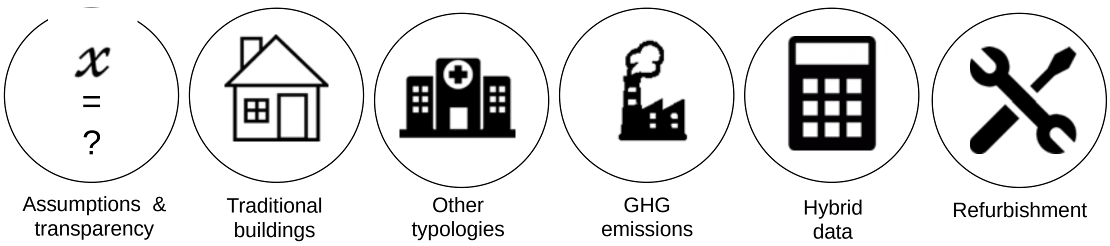


Fig. 4. Key considerations for integrated LCA and LCC evaluation of building projects

A study currently being completed as part of the Integrated Carbon Metrics Project, funded by the CRC for Low Carbon Living [29], is proposing the development of an early decision support tool that can be used to select and evaluate a building strategy based on both the buildings expected life cycle GHG and LCC performance. This research and subsequent tool will not only help address one of the main hurdles facing life cycle assessment uptake, namely uncertainty towards financial cost, but also address the current gaps facing studies that integrate LCA and LCC as illustrated above. By providing industry and building users with information regarding both the expected life cycle environmental and financial performance of the building, an appropriate building strategy can be selected that will ideally not only optimise the GHG performance of the building but also its financial performance.

6. Conclusion

This study has highlighted the importance of considering a buildings' expected performance, whether it be environmental or financial, based on its entire life cycle. Buildings span over many life cycle stages and it is vital to make sure that the mitigation measures employed to decrease a buildings GHG emissions, don't end up benefiting one life cycle stage at the expense of another. This study provided a brief introduction to the environmental assessment tool LCA and the financial quantification tool LCC. Traditionally both tools have been used in isolation of each other for building assessments; however there has been an increase in studies using both tools for the evaluation of buildings. A brief overview of these studies and discussion of some of the key elements of their respective methods and findings have been presented. This was then followed with a discussion of the shortcomings identified from these studies and areas for further improvement.. These further improvements include greater transparency of assumptions (whether it be data inputs, calculations or software utilised); the use of traditional buildings (not just exemplary buildings); incorporation of other building typologies (not just residential); inclusion of GHG emission assessment (not just energy); the use of hybrid data (not just process data) and consideration of refurbishments (not just new buildings). Research currently being undertaken as part of the CRC for Low Carbon Living aims to develop a more sophisticated approach for evaluating the performance of buildings and aid decision-making. This research will address many of the areas for improvements highlighted above and potentially lead to a greater awareness and use of life cycle decision-making in practice.

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