The Life Cycle Carbon Footprint of Refurbished and New Buildings—A Systematic Review of Case Studies

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Abstract

CO_2 is emitted throughout the lifespan of buildings—from construction through to operation, and eventually, demolition. Life Cycle Carbon Footprint calculations (LCCF) can be employed to provide useful evaluation metrics for the analysis and comparison of their environmental impact. This paper brings together, for the first time, a systematic review of the LCCF of 251 case study buildings from 19 different countries. This review focuses on the comparison of the LCCF of refurbished and newly constructed buildings, through the synthesis of the overall outcomes of these studies, to identify whether refurbishment or replacement design alternatives achieve better performance.

The results highlight that the average embodied, operational-related and demolition-related CO_2 is responsible for 24%, 75% and 1%, respectively, of LCCF. Furthermore, this review indicates that while the type of heating and energy supply system can significantly impact overall LCCF (when normalised to $kgCO_2$/60 years/m^2 floor area), other factors, such as building floor area or number of storeys, have minimal effect. A comparison between the LCCF of refurbished and new buildings showed that while most refurbishments had lower LCCF than most new buildings, some new buildings performed better than refurbished ones. Thus, findings suggest that on the basis of current evidence, it is still not possible to conclusively determine which of the alternatives is preferred. Finally, the paper highlights the current state of buildings LCCF, in particular in terms of the analysis scope and limitations, illustrating how these terms were interpreted differently in the examined case studies, and subsequently highlighting the need for a unified protocol to be developed for building LCCF analysis.

Keywords:

Life cycle carbon footprint, Buildings refurbishment, Building reuse, Building environmental impact, Life cycle analysis

1. Introduction

List of Abbreviations	
Bath ICE	Bath Inventory of Carbon and Energy
BRE	Building Research Establishment
EC	Embodied CO_2
EOL	End of Life
EPD	Environmental Product Declaration
Engineering and Physical Sciences Research Council	EPSRC
ISO	International Organisation for Standardisation
LCA	Life Cycle Analysis
LCCF	Life Cycle Carbon Footprint calculations
LCE	Life Cycle Energy
ORCE	Operations-Related CO_2 Emissions

The built environment is responsible for 40% of global energy consumption [1]. The global construction industry is also responsible for approximately 40% of overall raw aggregate consumption and 25% of the world's wood consumption [1]–[4]. The United Kingdom (UK) is one of the world's highest CO_2-emitting countries [5]. Following the 1992 Kyoto protocol and the 2015 Paris UN Climate Change Conference, the UK Government's Climate Change Act aimed to achieve a minimum 80% reduction commitment in the UK's CO_2 emissions [6], [7].

The UK building stock includes an estimated 28 million properties. These include approximately 22 million residential and 6 million non-residential buildings, which are responsible for around 26% and 18% of the UK's total CO_2 emissions, respectively [8], [9]. While around 75% of the UK housing stock that will exist in 2050 has already been built [10], much of the effort for improving energy efficiency is focused on new buildings, which only add around 1% to the UK building stock every year [11]. Legislation and assessment tend to focus on operational stage building performance—while the building is built and used [12]. CO_2 emissions, however, also occur during other building life cycle stages such as construction, maintenance, use and demolition.

Two alternatives are often examined to analyse if the aforementioned CO_2 emissions can be achieved, namely the refurbishment of existing buildings or their demolition and replacement with new, more energy-efficient buildings. In order to understand which of the alternatives may result in the lowest (i.e. minimal) environmental impact, a comparison between the Life Cycle Carbon Footprint (LCCF) of refurbished and new buildings should be undertaken. Despite the recent increase in the number of LCCF studies, evidence supporting the benefits of either refurbishment or replacement is still considered to be uncertain and any performance advantages or either approach remain unclear [11]–[14].

This study aims to investigate the LCCF of refurbished and new buildings to determine whether the environmental impact of one design alternative outperforms that of the other.

In addressing this, the objectives of this study are:

a. To collect data of the LCCF of a series of case study buildings and, for the first time, present their results.
b. To synthesise the data and examine various factors that might contribute to the LCCF of refurbished and new buildings.
c. To compare the LCCF of new and refurbished case study buildings.

As a meta-analysis of the LCCF of case study buildings has never before been presented, a main contribution of this paper is the collection and analysis, for the first time, of the life cycle environmental impact of the built environment.

This paper is structured as follows:

Section 2 discusses the life cycle of buildings and presents the concept of life cycle analysis. The different elements of CO_2 flows in buildings and how these are taken into account in the evaluation of the life cycle performance of buildings is detailed.

Section 3 discusses existing literature examining the current 'building carbon footprint' debate, in relation to refurbishment versus replacement.

Section 4 presents the systematic literature review methodology and outlines the study scope, search technique, the case study stock and study limitations.

Section 5 includes a synthesis of review findings and presents the LCCF of the whole case study stock. Influential LCCF environmental and design-related factors are examined and a comparison between the performance of refurbished and new residential buildings in the UK is presented.

Section 6 sums up review findings and presents a set of conclusions based on the work.

2. Building Life Cycle

Although both refurbishing or replacing an existing building has the potential to significantly improve its overall life cycle impact [11], [12], [15], each option offers performance improvements at different stages. While refurbishment allows the retention of some parts of existing structures, new buildings often offer a higher potential for integrating passive and active climate-control improvements, which could potentially lead to a reduction in CO_2 emissions. A holistic life cycle approach is recommended for comparing the overall benefits of each alternative [11].

2.1. Life Cycle Analysis

To carry LCCF calculations, the Life Cycle Analysis (LCA) methodology is often used [16]. LCA is an environmental assessment and management framework that offers a holistic approach to evaluating the potential environmental impact of products and process throughout their lives [17]. LCA compares the performance of different 'system units' (a product or service, or a building in the case of the built environment). The main comparative component in an LCA is the functional unit, this a reference unit that helps quantify the performance of the product. In the built environment, a commonly used functional unit is $1m^2$ floor area. According to ISO 14040 — one of the most widely used LCA frameworks [18] — LCA studies consist of four steps (Figure 1).

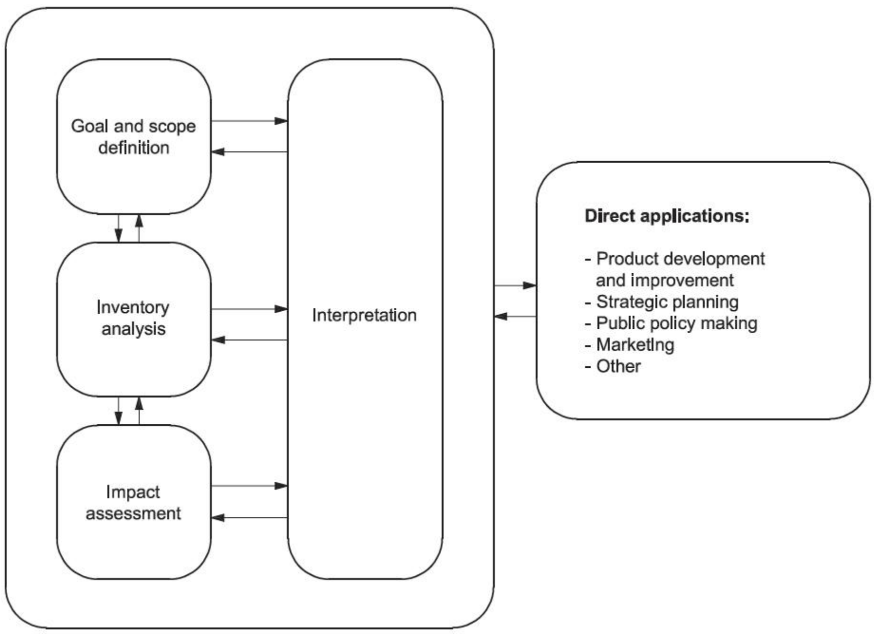

Figure 1: LCA framework (ISO 14040, 2006)

There are currently no standardised measures that address embodied CO_2 calculation methods. Yet, two approaches, referred to as 'top-down' and 'bottom-up', are often used. The top-down approach refers to pre-calculated databases of embodied energy or CO_2 values, summarising the outputs of the production processes of various generic building materials, from cradle to factory gate [19]. These include databases such as the Building Research Establishment (BRE) IMPACT, Bath Inventory of Carbon and Energy (Bath ICE), the Swiss Ecoinvent and others.

The bottom-up approach describes the embodied CO_2 calculation of individual materials, products or processes (sometimes referred to as input-output LCA). Bottom-up protocols such as the Environmental Product Declaration (EPD) or EN 15804 [20] have been established in recent years, however an accurate assessment greatly relies on the availability of these types of certificate. As there is still no binding legislation in regard to EPDs, their availability is still scarce.

2.2. CO_2 Flows in Buildings

LCCF is a measurement that accounts for all the processes that involve CO_2 inputs or outputs in buildings throughout their life cycle. According to life cycle energy analysis ([2], [16], [21]), CO_2 emissions flow in and out of building systems during the following life cycle stages (Figure 2):

- *Embodied CO_2 (EC):* the sum of CO_2 emissions due to the extraction of raw materials, transportation to and from factories, building construction, maintenance and refurbishment.
- *Operations-related CO_2 emissions (ORCE)*: CO_2 emitted in the process of maintaining comfortable environmental conditions in the building: heating, cooling, domestic hot water and lighting.
- *Demolition: End of life (EOL)*: CO_2 emissions due to the demolition of the building and transportation of waste to dump sites.

Other CO_2-related processes have gained increasing attention in recent research [22]–[24]. These are:

- *Renewables*: the generation of energy that has the potential of reducing energy use and CO_2 emissions during the operational phase of the building.
- *Recycling:* the re-use of some building components and materials and potential saving of CO_2. This might require the engagement of a novel approach towards design

(cradle-to-cradle, circular economy) that emphasises the importance of considering recycling at the earliest stages of design of a product or service [25].

According to the BRE Green Guide, the life cycle stages are assessed over an assumed building life span of 60 years [26], [27]. Since there is no procedure for incorporating future building systems or energy production technologies, when taken into consideration, their potential benefits are often calculated on a case study or 'best practice' basis.

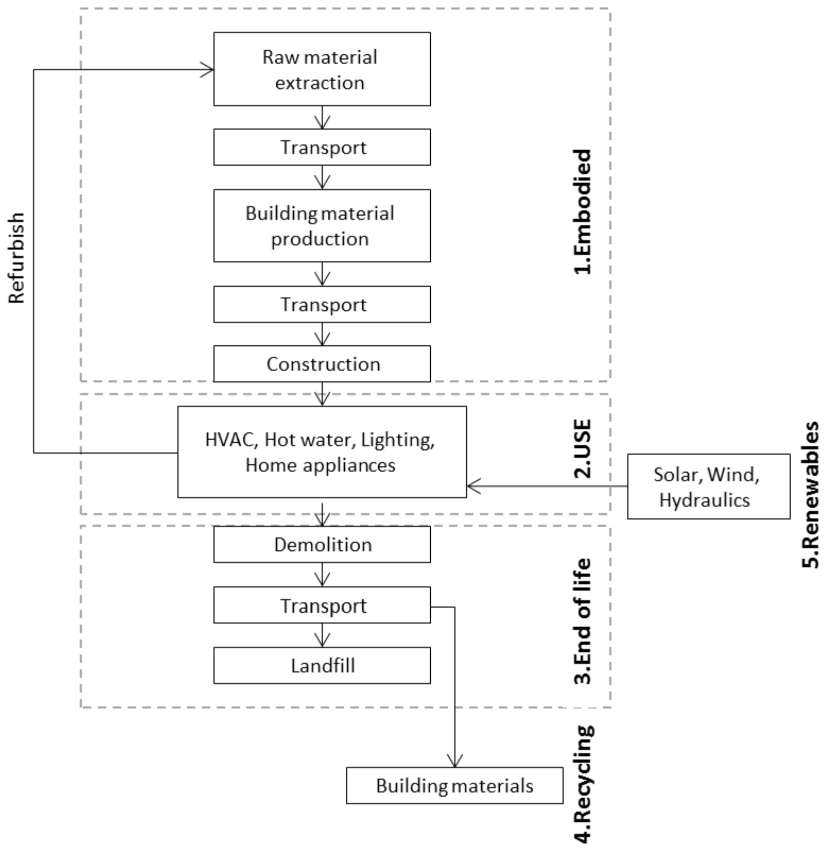

Figure 2: The system boundary of LCCF in buildings – five types of energy flows (based on [16]).

2.3. Life Cycle Performance

Although CO_2 emissions is widely considered to be the more appropriate indicator for environmental impact than energy consumption[11], most current review studies still use energy as a predominant life cycle performance indicator. This is because of the added complexities and uncertainties that lie within the calculation of CO_2 emissions compared to energy loads calculations.

While building LCCF calculations are becoming more commonly used, no database of either new or refurbished buildings that shows their overall LCCF currently exists. A few review studies, however, have attempted to summarise the Life Cycle Energy (LCE) use in buildings [16], [28]. It is important to note that while these studies were not able to quantify the CO_2 footprint benefits of refurbishment or replacement options, they represent the first significant attempt to summarise the life cycle performance of buildings.

Sartori and Hestnes [28] collated the LCE of 60 case study buildings from nine countries around the world. The authors grouped the studies into two categories based on their operational energy type: delivered energy studies (the energy that is measured at a final use level, i.e. at the building level) and primary energy studies (energy that includes losses due to processes of extraction, transformation and distribution [28]).

The embodied energy in low-energy buildings (those with an overall operational delivered energy consumption of 121kWh/m^2/y or 202 kWh/m^2/y primary energy consumption) was between 9% and 46%, while in conventional buildings it was between 2% and 38%. Interestingly, a nearly linear relationship between operational and overall life cycle energy use was presented, despite differences such as climate or construction type etc. As expected, results showed that while low-energy buildings did achieve lower LCE use values, they had a higher share of embodied energy.

A more recent study by Ramesh et al. [16] presented a detailed examination of 73 residential and office case study buildings from 13 countries. Whereas Sartori and Hestnes [28] analysed delivered-energy and primary-energy studies separately, Ramesh et al. [16] applied referenced conversion factors on delivered-energy studies to determine primary energy values for all studies. Results showed that the life cycle primary energy use of a conventional residential building was in the range of 150 to 500 kWh/m^2/y, whereas that of office buildings was between 250 and 550 kWh/m^2/y. This study also highlighted an almost linear relationship between the LCE and operational energy. Furthermore, the study found that embodied and operational energy accounted for around 10–20% and 80–90%, respectively, of building LCE use. It also showed that while operational energy demand can be reduced by using passive and active techniques, the excessive use of these measures can actually be counterproductive from a life cycle perspective due to their increased embodied energy.

While the aforementioned studies analysed the life cycle performance of buildings in terms of energy (kWh), the work presented here examines life cycle performance in terms of CO_2 emissions ($kgCO_2$).

3. To Refurbish or to Replace: Framing the Current Carbon Footprint Debate

The debate regarding the refurbishment or demolition of existing buildings has gained increasing interest in recent years. A number of studies have tried to examine the potential benefits of the two alternatives, and most have inferred that refurbishment was preferred over replacement [11]–[14], [29], [30]. Most notably, studies [29] and [30] concluded that while poorly performing existing buildings should be replaced, well-performing ones should be refurbished.

One of the earliest and most influential papers debating refurbishment versus replacement was written by Power [11], who reviewed studies by both independent and public bodies in the UK discussing this question. Power summarised arguments for and against each alternative and concluded that refurbishment should be implemented whenever possible. Despite Power's thorough investigation, the majority of arguments supporting this view were not based on quantified evidence, and only a very limited number of actual case studies were discussed. In addition, the review heavily criticised what was presented as the 'evidence for demolition' but was more accepting of the 'evidence for refurbishment' alternative.

A more recent study with similar conclusions focused on whether to refurbish or demolish social houses in the UK [13]. Although a limited number of case studies were examined, like Power, the review suggested that refurbishments can achive similar levels of energy consumption as new buildings, while avoiding the CO_2 emissions of demolition and construction. While the studies examined presented a comprehensive and thorough analysis, the balance between the potential life cycle CO_2 savings of the different approaches has, to date, not been thoroughly investigated and evidence is still unestablished [11]–[14].

Other studies have attempted to examine the potential benefits of refurbishment of existing buildings or their replacement by reviewing actual case studies. Although important and insightful, these studies often examined only one or two design alternatives, thus there are no means by which to verify that the absolute best design alternatives were actually compared. Additionally, in many cases, the different studies did not employ the same analysis methodology. Specifically, each differed in scope, CO_2 database sources or metrics (CO_2, energy or costs, in addition to social and cultural aspects which were usually qualitatively assessed through surveys of limited scope). Yet, despite these limitations, these studies are valuable as they were the first to compare the viability of building refurbishment versus replacement.

The examined studies can be categorised into three different groups, reflecting their overall conclusion (Table 1).

Table 1: To refurbish or to replace? - current debate

Study	Replacement	Refurbishment	Ambiguous
Hawkins & Mumovic [29]	X		
Rønning et al. [30]	X		
Itard & Klunder [31]		X	
Erlandsson & Levin [32]		X	
Gaspar & Santos [33]		X	
Ding [15]		X	
Empty Homes Agency [34]			X
Arup, Capital & Government [35]			X
Boardman et al. [36]			X

Replacement

An analysis of the 60-year LCCF performance of two case study university buildings in the UK [29] compared the performance of four refurbishment scenarios and one replacement alternative. The study showed that the replacement scenarios achieved the biggest LCCF reductions. Another study [30] comparing the LCCF of refurbishment and replacement of an office building in Norway reached similar conclusions.

Refurbishment

An evaluation of the life cycle performance of various refurbishment and replacement scenarios was carried out, on two post-war residential blocks in the Netherlands [31]. The analysis showed that while adding insulation to the building envelope achieved better life cycle performance than replacement in one case study and worse performance in the other, building transformation (such as joining flats together) achieved the best life cycle performance in both cases. Erlandsson and Levin [32] have examined the LCE performance of a residential complex and concluded that refurbishment had achieved the lowest LCE values. A case study examination of the refurbishment or replacement of a small family house in Portugal [33] concluded that the refurbishment performed better in terms of overall energy consumption (LCE).

Ambiguous Results

Other studies have reached ambiguous results or stated that it was not possible to conclusively determine which alternative is preferred. For example, a comparison between the 50-year LCCF of three new buildings with that of three refurbishments [34] showed that both the best and the worst performing buildings were those that were refurbished. The study also showed that the differences between the LCCF of an average new building and that of a refurbished one were negligible. Another study [35] examined three types of interventions in an existing office building and concluded that while the replacement of a poorly performing building was clearly beneficial, it was neither practical nor worthwhile in the case of a well-performing building. A similar conclusion was drawn when examining the UK building stock and the ability to reach national CO_2 reduction targets [36]. This study concluded that the worst 14% of the total stock should be replaced, while most existing buildings should be refurbished.

4. Methodology

4.1. The Search Technique

To address the aims of this paper, a systematic literature review was undertaken and a case study database was established for benchmarking. Hong et al. [37] describe two approaches for benchmarking: top-down and bottom-up. In the top-down approach a benchmark is established by performing an overview evaluation of a database (without detailing its components) and then deriving conclusions using statistical analysis. The bottom-up approach requires the aggregation of individual pieces of data into singular values, and the representation of the results of a single hypothetical building, based on these values. The method used in this report was, therefore, the top-down analysis.

The systematic literature review involved the examination of electronic databases of scientific journals available up to April 2015. These included ScienceDirect, SpringerLinks and the UCL Library journal search engine. In total, 761 relevant papers were initially found when using defined search terms. Of these, 196 articles were omitted after filtering for duplication, relevance of titles and abstract screening. Following this, the review further applied inclusion and exclusion criteria to fulfil its aims. Only studies that contained an analysis of the LCCF performance of buildings were included, and only when this information could have been extracted and normalised to units of $kgCO_2/m^2/y$ floor area (similarly to the normalisation method presented in [16] and [28]). Two parameters were defined as minimum inclusion criteria: embodied and operational CO_2 emissions (as these are the two main sources of emission). Only 43 papers contained all the relevant data and could be used. These papers examined a total of 251 case studies from 19 countries, covering residential, office, university, industrial, hotel and hospital buildings.

4.2. The Case Study Stock

To allow a cross-analysis between various design variables, this study collected data for a range of building properties. These included LCE use, the life cycle steps that had been taken into account, building floor area and number of storeys, construction type, building systems, operational energy calculation methods and more. An overview of the case studies is presented in Table 2.

It is important to note that results were presented in different ways in the reviewed papers. While some included LCCF calculations for the whole building, others calculated it per $1m^2$ of building floor area. Similarly, some studies showed results for the whole life of the building, while others only presented annual emissions. Finally, results were graphically illustrated across papers in a number of formats, including tables and graphs.

To enable a true comparison between the case studies, this study applied normalisation. In most parts of the analysis, results were normalised to an assumed $kgCO_2$/60-year life span per $1m^2$ floor area, which correlated with the BRE Green Guide [27] assumed life span for buildings. When only graphs had been presented, data were manually extracted from them. The use of this process may potentially lead to minor inaccuracies and consequent uncertainties, the impact of which will be discussed in later sections of this paper.

Whereas LCE review papers have referred to primary energy values [16], [28], most LCCF studies did not make this distinction. However, Sartori and Hestnes [28] note that embodied energy values of the most common LCA practices and databases refer to primary energy values. Furthermore, when converting operational energy values to CO_2, conversion factors take into account losses caused by the production and delivery processes, and therefore represent primary CO_2 values too [38]. For these reasons, this study assumes that full LCCF studies describe CO_2 footprint due to primary energy consumption.

Table 2: Scope of the review

Number of papers		43
Number of case studies		251
Of which	New	206
	Refurbished	45
	Residential	163
	University	34
	Office	27
	Industrial	15
	Hotel	2
	Hospital	1

Country	Number of papers
UK, Sweden	6
China	5
Finland	4
USA, Korea, Italy	3
Spain, Australia, Canada, Germany	2
Norway, Thailand, Belgium, Bahrain, Portugal, Singapore, Puerto Rico, Japan	1

Reviewed papers location (Some papers reviewed more than a single location)

4.3. Limitations and Uncertainties of the Analysed Buildings Database

When analysing the case study stock, it is important to consider limitations that might influence analysis results. Although the nature of a systematic literature review minimises these, limitations nonetheless still exist. They were therefore reviewed throughout the analysis, as described in Tables 3 and 4.

In this review, the following uncertainties can be highlighted:

- It is acknowledged that the case studies in this review differ in their location and that their operational source energy and its CO_2 emissions differ.
- Similarly, embodied CO_2 emissions of comparable buildings across the stock might vary because of different production and construction processes.
- Various databases or embodied CO_2 calculation methods were used in the studies analysed.
- A number of tools were also used for the calculation of operational energy consumption (Table 3), and for the energy/CO_2 emissions conversion factors.

Differences in the protocols used by the various studies for LCCF calculations may potentially have some impact on results. Studies included different LCA scopes and assumptions in their buildings (see Section 4.4). Despite the differences between the case studies across the database, this review is designed to provide researchers and practitioners with an initial benchmark of reasonable and sensible LCCF results.

4.4. Case Studies Scopes and Assumptions

The scopes of LCCF studies and their underlying assumptions have been identified as one potential limitation of LCCF analysis [17], [39] In analysing the scope of analysis of the case studies in the stock, this review highlights that a range of protocols and different study boundaries were used (Tables 3–6).

i. Area

When simulating the thermal performance of buildings, variations in the modelled floor area might result in performance evaluation inaccuracies. This issue is important, as the difference between gross and net area values might vary significantly. Table 5 highlights the lack of a standardised approach to the modelling of building floor areas in LCCF studies.

ii. Embodied CO_2

As described in Section 2.1, various methodologies for calculating embodied CO_2 emissions exist. Table 6 shows that the embodied CO_2 emissions of more than half of the buildings in the stock were calculated using some well-recognised local material databases (Bath-ICE, Athena and others) or designated LCA calculation tools (SimaPro, Ecoinvent). It also shows, however, that almost 30% of the buildings used independent calculation methods or relied on other academic papers to establish their embodied CO_2 values.

iii. Operational-related CO_2

The operational phase of the building makes a major contribution to its life cycle performance. Table 7 shows how the different case studies interpreted the contribution of the operational phase to their life cycle performance, the type of energy calculated (primary/end-use), and which operational-energy-consumers (space conditioning, lighting, hot water or appliances) were included.

Interestingly, only 18 papers (examining 127 buildings) explicitly noted that CO_2 emissions due to primary energy use were analysed. As expected, almost all studies (41 papers representing 239 buildings) explicitly stated that CO_2 emissions due to space heating were included in their operational-phase calculations. Additionally, although home appliances are often not taken into account in building performance analysis, around half the papers in the database (23 studies describing 119 buildings) did consider CO_2 emissions due to unregulated consumption in their analysis.

Table 3: OE calculation methods, used for the calculation of operational CO_2 emissions (of the papers who mentioned the method they used).

OE calculation method	Number of papers	Number of buildings
Dynamic simulation	19	125
Static simulation	4	22
Measured (bills / smart meters)	4	7
Estimated	3	14
Manual calculation	3	8
Mixed	1	3
	34 (out of 43 papers)	179 (out of 251 case studies)

Table 4: Number of papers that presented data about the different life cycle steps (out of a total of 43 papers and 251 buildings)

Life Cycle Stage	Numbers of papers	Number of buildings
Transport	26	117
Construction	29	145
Maintenance	30	157
End of Life	25	152
Recycling	14	63

Table 5: Building area

	Gross	Heated[1]	Net[2]	Other[3]
Papers	13	11	4	15
Buildings	79	83	25	64

[1] Included expressions such as: “Heated floor area” or “Habitable space”.

[2] Included expressions such as: “Net floor area”, “Useable area” or “Letable area”.

[3] Included expressions such as: “Building area”, “Floor area”, “Overall area” or included no description.

Table 6: Embodied CO_2 calculation

Embodied CO_2 Method / tool	Numbers of papers	Number of buildings
Local material database[1]	14	68
Independent calculation/ relying on academic papers	11	68
LCA calculation tools[2]	7	67
Mixed methods[3]	8	35
No description	2	7
EPD	1	6

[1] Databases such as Bath-ICE, Athena, PCT ITEC and others.

[2] These included tools such as Gabi, SimaPro and Eco-Invent

[3] A combination of databases, EPD and independent calculations

Table 7: Description of the operational phase across the database

	Primary energy	Space conditioning	Lighting	Water	Appliances
Papers	18	41	37	28	23
Buildings	127	239	218	165	119

5. Findings—Life Cycle Carbon Footprint in Buildings

5.1. LCCF Results

5.1.1. General Analysis

Figure 3 shows the LCCF of all case study buildings (all use types, both new and refurbished), over their original lifespans, as presented in Table 8. Almost all case studies (243 of 251 cases) calculated an LCCF of less than 8,000 $kgCO_2/m^2$ throughout the various building lifespans. The remaining eight buildings—those that achieved 8,000–16,000 $kgCO_2/m^2$—were university or commercial facilities (buildings with high operational energy profiles). Generally, buildings with high operations-related CO_2 emission profiles (university, commercial, hospital and hotel buildings) had significantly higher LCCF values than low profile ones (residential buildings). These were 4,980 $kgCO_2/m^2/y$ on average (3,820 stv), compared with 2,286 $kgCO_2/m^2/y$ (1,783 stv), respectively.

Figure 4 shows the results after normalisation to an expected 60-year life span and a breakdown according to each life cycle step (the breakdown data were available for 163 cases only). Results show that embodied CO_2 emissions account for anything between 3% and 77% of the overall LCCF (Average = 24), compared with Ramesh et al. [16] and Sartori and Hestnes [28] who found that embodied energy ranged between 10% - 20% and 2% - 46%, respectively. Operations-related CO_2 accounted for between 23% - 97% of total LCCF (75% average). Case studies that included calculations of CO_2 emissions due to demolition works (46 case studies) showed that it accounted for between 0.1% - 2.9% of the total building LCCF (Average = 1.0%).

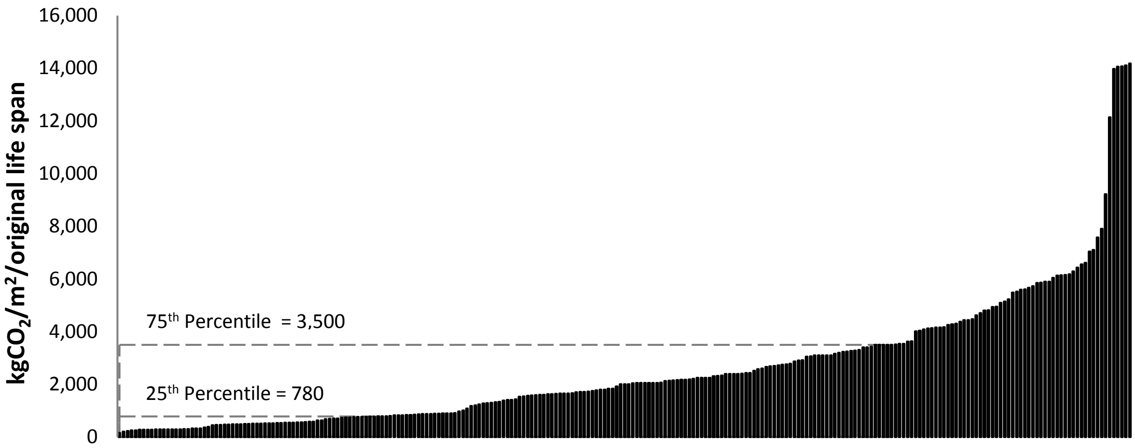

Figure 3: LCCF for all case studies, original life span.

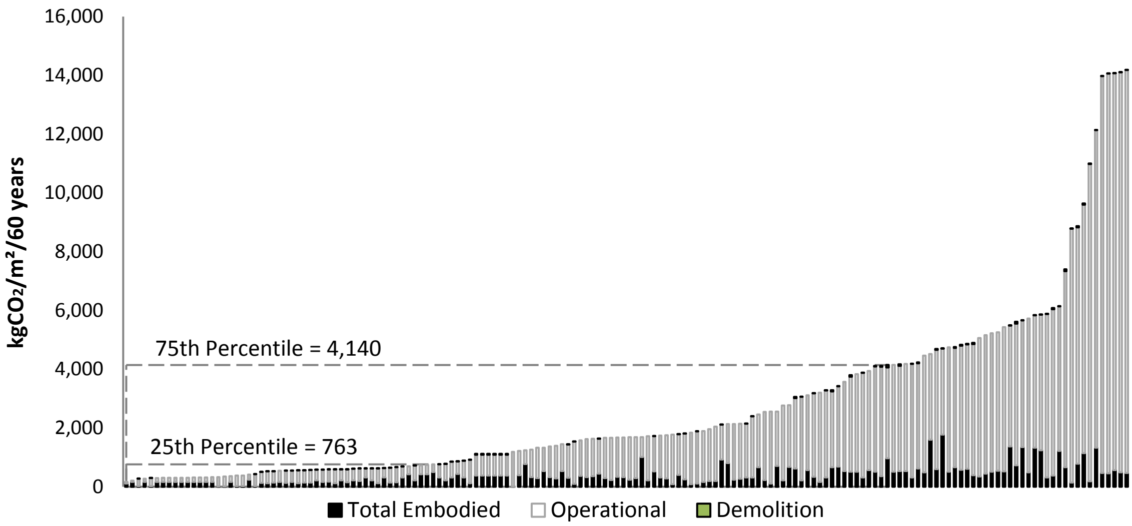

Figure 4: LCCF for all case studies, 60 years.

Figure 5 illustrates the significant relationship between operational CO_2 emissions and overall LCCF. Similar trends were found when examining new and refurbished buildings separately. This suggests that the carbon footprint of any development, regardless of whether it is a new building or a refurbishment and regardless of any other environmental (climate) or design (materials, area etc.) differences, is dominated by its operational-related CO_2 emissions.

The trend illustrated in Figure 5 closely resembles that presented in the LCE analysis by Ramesh et al. [16] and Sartori and Hestnes [28], who found similar relationships between embodied and LCE use in buildings. While this similarity might be expected, when examining case studies that presented both LCCF and LCE values (102 cases out of 251), Figure 6 indicates that there is actually a weak correlation between LCCF and LCE use (R2 = 0.24). This can be attributed to the fact that different fuel types emit different CO2 emission levels per unit of energy.

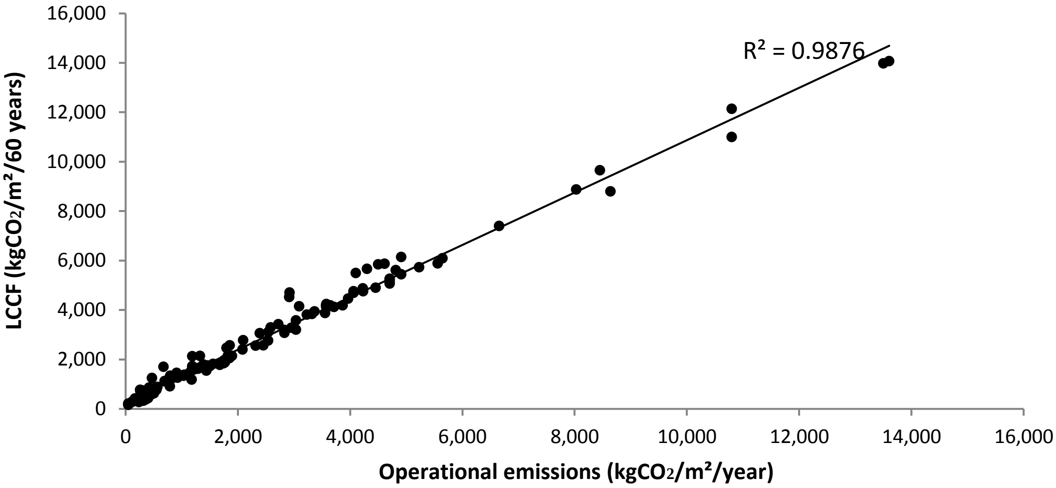

Figure 5: LCCF vs operational related CO_2 emissions (new and refurbished buildings, 60 years)

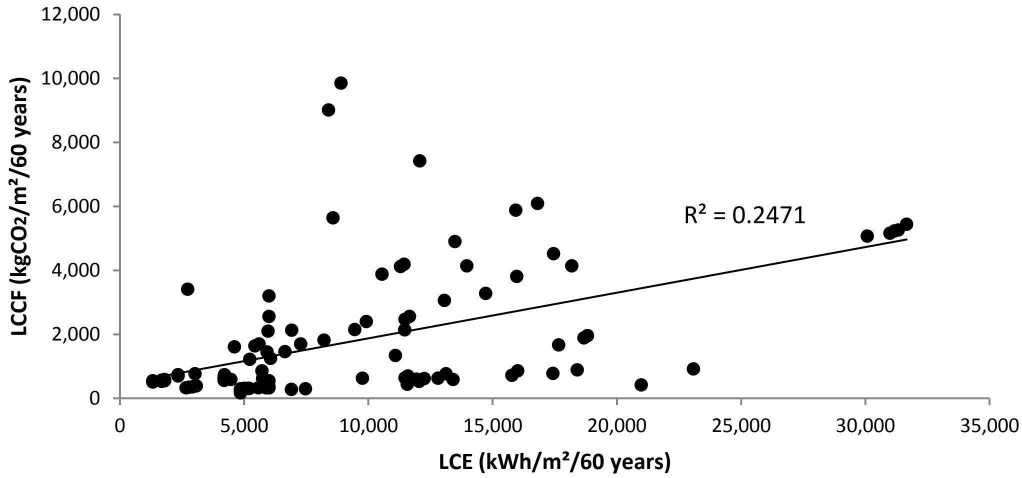

Figure 6: The relationship between LCCF and LCE

5.1.2. Influential LCCF Environmental and Design-related Factors

To better understand the relationship between LCCF and various environmental and design-related factors, this study conducted a further analysis. This highlighted the weak relationship between LCCF ($kgCO_2/m^2/60$ years) and the overall floor area of case studies ($R^2 = 0.09$) or number of stories ($R^2 = 0.05$). However, as shown in Figure 7, buildings that used district heating technology to deliver space heating—a major source of energy consumption—usually resulted in an overall low LCCF. Additionally, in examining the relationship between the building location in terms of country and climate and overall LCCF, the study matched LCCF results with climate types. This relationship can potentially be attributed to the different fuels and heating technologies used across countries, rather than to climate variation.

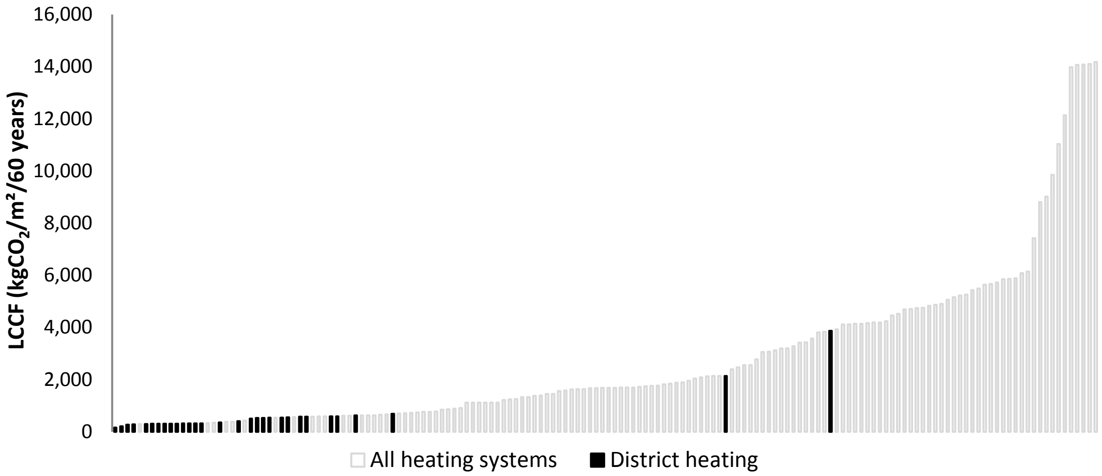

Figure 7: The impact of using district heating on LCCF.

5.2. New/Refurbished Buildings

In this section, a comparison between the LCCF of refurbished and new buildings was carried out. Although the study adopted the assumed 60-year life span from the BRE Green Guide ([26], [27]), some refurbishment LCCF studies conducted a 50-year analysis. Since it is impossible to draw out the annual emissions in these case studies and calculate their emissions for 60 years (the relevant data were not available), the results in this section have been normalised to an assumed 50-year life span.

Figure 8 presents the LCCF of refurbished buildings as compared to that of new ones, across all buildings types.

Results show that while the LCCF values of refurbished buildings are spread across the graph, with both very high and very low values, more refurbished buildings fall in the higher 50th percentiles. It is noted, however, that some refurbishments still achieved a better performance than new builds. It is also important to note that most studies did not describe the level of refurbishment that was carried out.

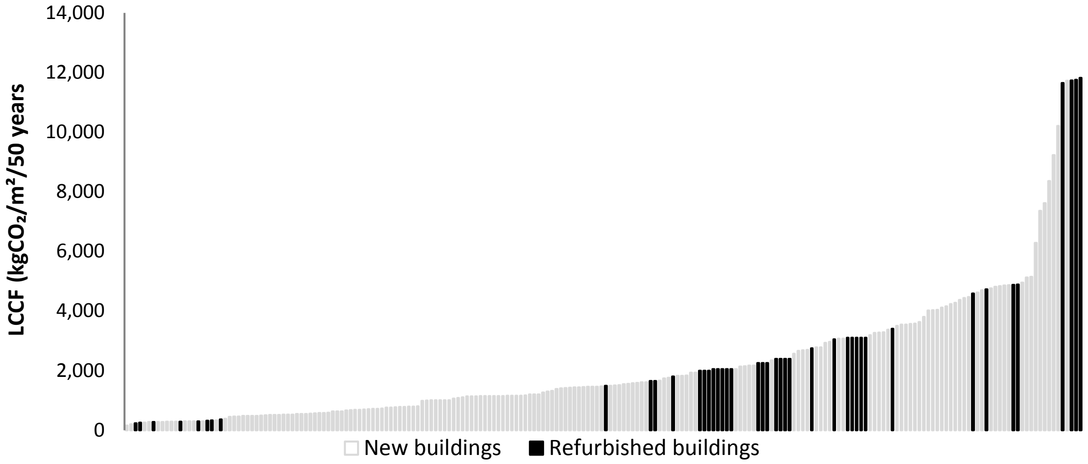

Figure 8: New/Refurbished buildings – all buildings types LCCF ($kgCO_2/m^2$) for 50 years.

To minimise the potential impact of building type and usage profile on results (university and commercial buildings, for example, are typically more operational-energy-intensive than residential buildings), a further investigation solely focused on residential buildings—the building type with the largest sample in this review.

The analysis of LCCF of residential buildings from around the world (Figure 9a) indicates that while more refurbished buildings fall in the higher 50th percentiles (26 versus 8 case studies), the lowest LCCF was achieved by refurbishments. While the average LCCF of the two groups was different, this difference was not statistically significant (average 1,162 and 2,050 $kgCO_2/m^2$/50 years, n1 = 128, n2 = 34, $P > 0.05$). It is therefore difficult to conclusively determine which option offers better performance.

The analsysis of refurbished and new residential buildings in the UK and Ireland (cases with geographic proximity and similar climates and construction materials) is illustrated in Figure 9b. Refurbished buildings seem to have a better performance than new ones, with an average LCCF of 3,500 (new) and 2,250 (refurbished) $kgCO_2/m^2$/50 years (n1 = 28, n2 = 26, $p < 0.05$). While this trend is statistically significant, some new buildings still showed a better performance than the best refurbishments. Similarly, in this case, it is difficult to determine which alternative can be considered ‘better’.

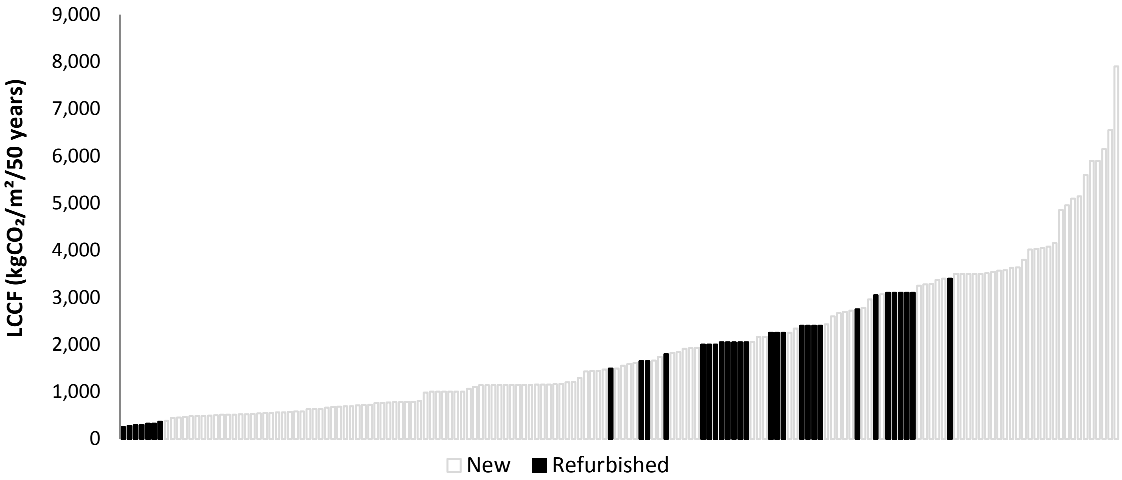

Figure 9a: New / refurbished residential buildings LCCF ($kgCO_2/m^2$), 50 years

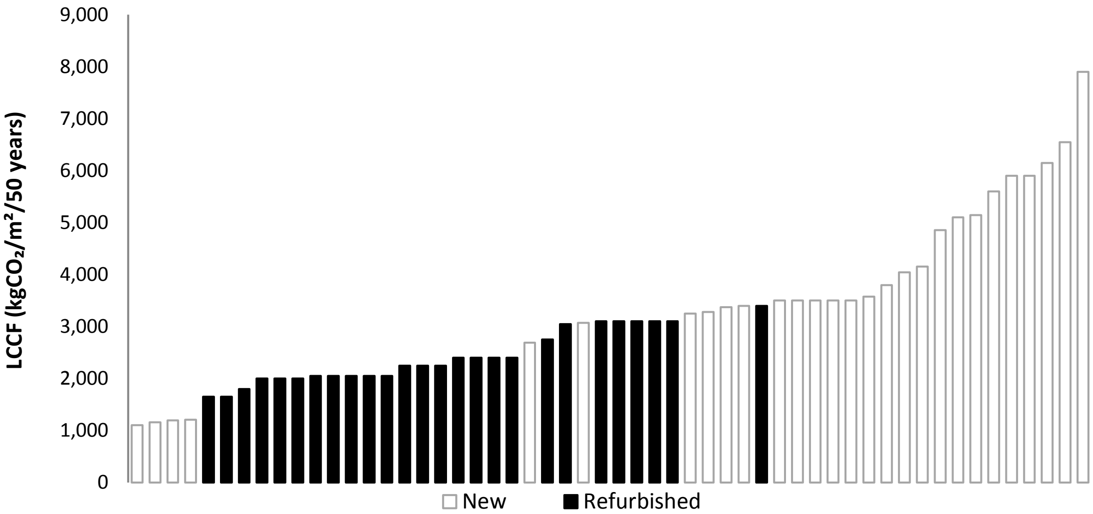

Figure 9b: UK and Ireland- new / refurbished buildings LCCF ($kgCO_2/m^2$) for 50 years

6. Conclusions

This study aimed to collect and analyse data regarding the LCCF of buildings and to compare the LCCF of new and refurbished buildings in the case studies, by performing a systematic literature review.

The review showed that most examined buildings emitted less than 8,000 $kgCO_2/m^2$ throughout an assumed 60-year lifespan and that EC accounted for around 25% of their overall LCCF. The review also found that ORCE had a significant impact on overall LCCF.

In order to compare the environmental benefits of refurbishment versus replacement, this study used a top-down analysis approach [37]. By collecting evidence from a large number of case studies, the review attempted to find evidence that might indicate which design alternative is favorable. The study suggests, however, that considering current evidence and methodologies, it is still not possible to conclusively determine which of the alternatives is preferred. When focusing on a specific building type at a specific location, while refurbished buildings on average seem to perform better than new ones, some new buildings perform even better than the best refurbishments. As illustrated in this review, there are key limitations in the ability of current research to provide a clear answer in regard to the question of 'to refurbish or to re-use?'. This outcome is one of the main findings of this review, and one that has been established by this study to inform further research.

As the reviewed case studies did not use a standardised protocol, calculation methods or boundaries, it is not clear whether the difference between the LCCF of refurbished and new buildings is due to their performance or as a result of the use of different protocols and calculation methods across the database.

It is therefore proposed that a 'bottom-up' comparative analysis be undertaken [37], where case studies are analysed within identical, carefully defined scopes and system boundaries, and LCCF is calculated similarly, where a more controlled comparison can be conducted.

Lastly, in regard to LCCF calculation, this review finds that despite the calls for establishing a unified LCCF protocol [54, 67, 70], studies still use a wide range of tools and assessment protocols to perform LCCF analysis. While most studies use dynamic thermal simulations for operations-related CO_2 emissions, the elements that compose the operational CO_2 emissions vary. An even greater variation is noted in the calculation of buildings' embodied CO_2. Building material manufactures often use different production processes for similar building materials. These might result in different amounts of CO_2 emissions. This review has shown that most studies use generic embodied CO_2 databases, which do not reflect these differences. To allow for a more accurate embodied CO_2 impact assessment, this study points out that protocols such as the EPD (Environmental Product Deceleration) or EN 15804 can help to mitigate embodied CO_2 impact assessment inaccuracies, as their production should closely describe real-life production processes of construction components.

Despite these, the database analysis presented in this review can still be considered to be of considerable value because it reflects the state of the LCCF calculation protocols used to date and systematically identifies key problems with the current methods.

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Table 8: The case study stock

	Author	Country	Case study	Original Life Span	Building Type	New/ Refurbished/ Both	Life Cycle Energy	Life Cycle Cost
[40]	Asdrubali et al.	Italy	11-13	50	Resi	N	V	
[41]	Aye et al.	Australia	181-185	25	Office	B	V	V
[42]	Blengini & Di Carlo	Italy	96-97	70	Resi	N	V	
[43]	Bonamentea et al.	Italy	57-62	20	Industrial	N	V	
[44]	Bribia et al.	Spain	4	50	Resi	N	V	
[45]	Cuéllar-Franca & Azapagic	UK	63-65	50	Resi	N		
[46]	De Larrivaa, et al.	Spain	229-233	50	Resi	R	V	
[47]	Dodoo & Gustavsson	Sweeden	81-86	50	Resi	N	V	
[48]	Dodoo et al.	Sweeden	69-80	50	Resi	N		
[49]	Dodoo et al.	Sweeden	234-239	50	Resi	B	V	
[50]	Famuyibo et al.	Ireland	190-228	50	Resi	B	V	
[51]	Fesanghary et al.	USA	1-3	25	Resi	N		V
[52]	Fieldson & Rai	UK	187-189	15	Commercial	N		
[53]	Georges et al.	Norway	172-173	60	Resi	N		
[54]	Gong et al.	China	178-180	50	Resi	N	V	
[55]	Gustavsson et al.	Sweeden	98-109	50	Resi	N	V	
[56]	Hacker et al.	UK	87-94	100	Resi	N		
[29]	Hawkins & Mumovic	UK	240-251	60	University	B		
[57]	Iddon & Firth	UK	27-30	60	Resi	N		
[58]	Kua & Wong	Singapore	47	30	Commercial	N	V	
[59]	Li et al.	China	5-10	10, 30, 50, 70, 100, 150	Resi	N		
[60]	Lützkendorfa et al.	Norway	170-171	60	Resi	N		
[61]	Ortiz et al.	Spain	95	50	Resi	N		
[62]	Radhi & Stephen	Bahrain	121	60	Resi	N		
[63]	Rai et al.	UK	48-56	25	Warehouse	N		
[64]	Rakkwamsu et al.	Thailand	174-177	25	Resi	N		
[65]	Ristimäki et al.	Finland	15-26	25, 50, 100	Resi	N		V
[66]	Rossello et al.	Spain	122-123	50	Hotel	N	V	
[39]	Rossi et al.	Belgium	66-68	50	Resi	N	V	
[67]	Rossi et al.	Belgium Portugal Sweden	156-166	50	Resi	N	V	
[68]	Russell-Smith et al.	USA Puerto Rico Germany	143-162	50	University	N	V	
[69]	Ruuska & Häkkinen	Finland	36-38	50	Resi	N		
[70]	Stephan & Crawford	Australia	186	50	Resi	N	V	
[71]	Tae et al.	Korea	39-46	Not Specified	Resi	N		V
[72]	Tae et al.	Korea	118-120	100	Resi	B	V	
[73]	Tae et al.	Korea	163-164	60	Resi	N		
[74]	Tonookaa et al.	Japan	116-117	30, 100	Resi	N		
[75]	Van Ooteghem & Xu	Canada	31-35	50	Commercial	N	V	
[76]	Wahidul K. Biswas	Australia	14	50	University	N	V	
[77]	Wallhagen et al.	Sweden	126-142	50	Office	N		
[78]	Yiwei et al.	China	167-169	35	Office	N		
[79]	You et al.	China	124-125	50	Resi	N		
[80]	Zhang & Wang	China	110-115	50	Resi	N		

Table 9: The case study stock

	Author	Total Floor area (m^2)	Number of stories	Maintenance	Transport	Construction	End Of Life	Recycle
[40]	Asdrubalia et al.	443 - 3353	3	V	V	V	V	V
[41]	Aye et al.	1,173	2	V			V	
[42]	Blengini & Di Carlo	367	2	V	V	V	V	V
[43]	Bonamentea et al.	1,000 – 20,000	1		V	V	V	
[44]	Bribia et al.	222	4					
[45]	Cuéllar-Franca & Azapagic	130, 90, 60	2	V	V	V	V	
[46]	De Larrivaa, et al.	10,934	7	V	V			
[47]	Dodoo & Gustavsson	1,190	4		V	V	V	V
[48]	Dodoo et al.	928	4		V	V	V	V
[49]	Dodoo et al.	1,190	4		V	V	V	V
[50]	Famuyibo et al.	-	-	V			V	
[51]	Fesanghary et al.	186	1	V				
[52]	Fieldson & Rai	5,000	-	V				
[53]	Georges et al.	160	2	V				
[54]	Gong et al.	5,590	-			V	V	
[55]	Gustavsson et al.	3,374	8			V	V	V
[56]	Hacker et al.	65	2					
[29]	Hawkins & Mumovic	11,900, 4,600	6	V	V	V	V	
[57]	Iddon & Firth	166	2	V				
[58]	Kuaa & Wongb	52,094	-	V	V	V	V	V
[59]	Li et al.	1,460	4		V	V	V	V
[60]	Lützkendorfa et al.	160	2	V	V	V	V	V
[61]	Ortiz et al.	160	2	V	V	V		
[62]	Radhi & Stephen	490	2	V		V		
[63]	Rai et al.	8,060	2					
[64]	Rakkwamsu et al.	164	2			V		
[65]	Ristimäki et al.	21,546	6	V		V		
[66]	Rossello et al.	-	4	V	V	V	V	
[39]	Rossi et al.	180	2		V		V	
[67]	Rossi et al.	192	2	V	V			V
[68]	Russell-Smith et al.	2,790	3	V	V	V		
[69]	Ruuskaa & Häkkinen	2,455	7	V		V	V	
[70]	Stephanabc & Crawfordc	240	-	V	V	V		
[71]	Tae et al.	8,495, 9514	25	V	V	V	V	
[72]	Tae et al.	14,424	35	V	V	V	V	
[73]	Tae et al.	3,400	20	V	V	V	V	
[74]	Tonookaa et al.	126	2	V	V	V	V	V
[75]	Van Ooteghem & Xu	586	1	V				
[76]	Wahidul K. Biswas	4,020	4		V	V		
[77]	Wallhagen et al.	3,537	4					
[78]	Yiwei et al.	22,645 - 25,455	20	V		V	V	V
[79]	You et al.	-	-	V	V	V	V	
[80]	Zhang & Wang	3,248 – 15,514	6	V	V	V	V	V

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