Carbon Dioxide Emissions of Office Buildings in Scotland:

Life-Cycle Assessment of New-Build Offices

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Abstract

In the context of the global trend towards reducing the carbon footprint of buildings, the design team must make decisions, which have major consequences on the carbon footprint. This should be during the early stages of the building design process, as changes made later on can be costly. Although Life-Cycle Assessment (LCA) is the ‘gold standard’ method to evaluate the design from 'cradle to grave'.

The lack of detail available on the concept design makes LCA very difficult if not impossible. Unfortunately, this is the very stage at which decisions are made that have a most significant influence on the life cycle. In order to support designers, a database of LCA case studies data is needed, accessible to designers and decision makers, and giving guidance on specific areas of significant impact, on which they can concentrate to reduce the building’s total impact. The work in this thesis sets out to address this need.

This thesis presents life-cycle case studies of two new-build offices in Scotland that could be used as guidance during the concept stage of the design process. This is achieved by modelling the carbon emissions of different life-cycle stages, and different building materials and components used in building activities. The hypothesis that the current trend of office building in Scotland produces buildings which are relatively lower in their emissions than those reported in the literature is tested by a full life-cycle assessment of two new-build offices in Edinburgh. Scenario and sensitivity analysis is used to assess the future of office buildings in Scotland.

The carbon dioxide emissions of the two case study buildings, when normalised according to floor area, are similar and lie towards the lower end of the range of worldwide data reported in the literature. Sensitivity analysis shows that the life cycle results are affected by changes in design parameters, and are highly sensitive to the assumptions about the future made at the design stage, such as

future changes in electricity generation over time, refurbishment and recycling. Large savings in carbon dioxide emissions can result from small changes at the design stage, such as glazing ratios and the provision of parking. Some of these are fields for future research and development.

Dedication

بسم الله الرّحمن الرّحيم

I dedicate this piece of work to:

The Syrian People

Fight the battle for someone who proves they're worth the victory, fight the war for someone who proves they're worth dying for.

My Family

To my father: Dr. Ahmad Khasreen, and my mother: Rafat Khasreen.

You deserve all respect, honour and love.

“And your Lord has decreed that you worship none but Him. And that you be dutiful to your parents. If one of them or both of them attain old age in your life, say not to them a word of disrespect, nor shout at them but address them in terms of honour” Isra 23

To my wife: Iman Alsumsam, my son: Homam, and my daughter Mariam

Life is difficult without you.

To my sisters and brothers:

Giyath, Amany, Firas, Anas, Zelal, and the cheeky Raiya (lolo).

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Glossary of Abbreviations

AP	Acidification Potential
AR	Air Emissions
BMCC	Building Materials and Components Combinations
DA	Depletion of a Biotic Resource;
EC	Eco-toxicity
En	Energy Consumption
EP	Eutrophication Potential
GHG	Green House Gases
GWP	Global Warming Potential
HT	Human Toxicity
LCA	Life Cycle Assessment
LCEA	Life Cycle Energy Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Depletion Potential
RS	Resources Consumption
W	Waste Creation
WC	Water Consumption
WPC	Whole Process Construction

Publications

1. KHASREEN, M., BANFILL, P. F. & MENZIES, G. (2009) Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. Sustainability, 1, 674-701.

2. KHASREEN, M. & BANFILL, P. F. (2010) Carbon Dioxide Emissions of a Typical Office Building in Scotland. IN AKINTOYE, A., GOULDING, J., RAHIMIAN, F. P., BRINDLEY, D. & EMMITT, S. (Eds.) International Detail Design in Architecture. 9 ed. Preston, University of Central Lancashire.

3. KHASREEN, M. & BANFILL, P. F. (2013) Carbon Dioxide Emissions of new-build offices in Scotland. To be submitted to Building and Energy Journal.

Chapter 1 - Introduction

1.1. Introduction

The World Commission on Environment and Development at their final meeting stated that: "We remain convinced that it is possible to build a future that is prosperous, just, and secure. The possibility depends on all countries adopting the objective of sustainable development as the overriding goal and test of national policy and international co-operation" (World Commission Development, 1987).

Of the many environmental impacts of development, the one with the highest profile currently is global warming, which demands changes from government, industry and public. Concerns about the local and global environment situation are rising all over the world. Global warming is the consequence of long term build-up of greenhouse gases (CO_2, CH_4, N_2O, etc.) in the higher layer of atmosphere. The emission of these gases is the result of intensive environmentally harmful human activities such as the burning of fossil fuels, deforestation and land use changes (Buchanan and Honey, 1994). This is generally accepted to be the reason that average global temperatures have increased by 0.74°C in the last 100 years. Global temperatures are set to rise by a further 1.1°C in a low emissions scenario, and by 2.4°C in a high emissions scenario, by the end of the century (Houghton et al., 2001). It is necessary to reduce Green House Gases (GHG) emissions by 50 per cent or more in order to stabilise global concentrations by 2100 (Houghton et al., 2001). The Tyndall Centre has suggested that a 70 per cent reduction in CO_2 emissions will be required by 2030 to prevent temperature rising by more than 1°C (Bows et al., 2006). UK emissions of greenhouse gases fell by nearly 14.6 per cent between the 1990 base year and 2004, but have risen by about 1 per cent since 2002, most recently because of increased oil and gas consumption. The UK has a legally binding target under the Kyoto[1] protocol to reduce its emissions of the basket[2] of six major greenhouse gases (TSO, 2006), and has announced its intention to put itself on a path towards a reduction in CO_2 emissions of 80 per cent by about 2050 (TSO, 2003).

Perhaps because GHG emissions can be more readily quantified than other impacts, they have attracted most attention from researchers and policy makers but GHG emissions are just one of a range of parameters that should be considered in assessing environmental impacts. Others are ozone depletion, water consumption, toxicity, eutrophication of lakes and rivers, and resource depletion, and the aim of this thesis is to review Life Cycle Assessment (LCA) as a means of evaluating the environmental impact of buildings, and use LCA to count the carbon dioxide emissions of new-build offices in Scotland.

It is well known that the biggest contributor to greenhouse gas emissions is the built environment, accounting for up to 50 per cent of global carbon dioxide emissions (Raynsford, 1999). Building construction industry consumes 40 per cent of the materials entering the global economy generating 40-50 per cent of the global output of greenhouse gases and the agents of acid rain (CIWMB, 2000). In the European Union and the United States, the construction and building sector has been estimated to be responsible for roughly 40 per cent of the overall environmental burdens (Junnila et al., 2006).

The embodied environmental impact generated by the building during its whole life cycle can be of the same order of magnitude as those generated during the utilisation stage (Citherlet, 2001). Embodied energy and "carbon capital cost" of buildings is increasingly considered to be significant within the whole life cycle consumption, as very intensive efforts of researchers and developers have been spent to reduce the impacts within the utilisation phase, which is considered to be

[1] The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change.
[2] The basket comprises the six main gases with a direct greenhouse effect: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

the main contributor to the environmental impacts of buildings. However, the embodied energy and carbon capital cost reduction is gaining the attraction of researchers to reduce the overall impacts as much as possible. A host of new methods, interventions, building specifications, and materials has been employed to reduce the utilisation phase energy consumption and environmental impacts. The relationship between the embodied carbon of new environmentally friendly buildings applying these new techniques and interventions and usage phase carbon reductions is still a big question.

The research within this thesis used LCA as a tool to count the whole life cycle carbon dioxide emissions of new-build office buildings in Scotland to add to the growing national and international literature of buildings life-cycle assessment studies. It investigated and identified the materials, components, and processes which have most significant environmental impact, and recommended changes which can be considered in future building activities. This is the first time that such a study on Scottish office buildings has been reported.

After this introduction, Chapter 2 reviews the literature on office buildings, while chapter 3 reviews the field of life-cycle assessment, as applied to buildings. Chapter 4 describes the research methods that were applied to the case study buildings which are detailed in chapter 5. The results, presented in chapter 6, are discussed in chapter 7, leading to conclusions in chapter 8.

Globally and nationally, commercial buildings contribute significantly to resource consumption, as well as to other environmental impacts, such as air emissions and solid waste generation.

These and other global environmental and human-health related concerns have motivated an increasing number of designers, developers and building users to pursue more environmentally sustainable design and construction strategies.

However, compared to other "products" buildings are more difficult to evaluate for the following reasons. They are large in scale, complex in materials and function and temporally dynamic due to limited service life of building components and changing user requirements. Their production processes are much less standardized than most manufactured goods because of the unique character of each building. There is limited quantitative information about the environmental impacts of the production and manufacturing of construction materials, or the actual process of construction and demolition.

All of these factors make environmental assessments of the building industry challenging. While there is substantial knowledge about energy- and water-saving strategies for building operations, there is far less information on the upstream (extraction, manufacturing, transportation) and downstream (deconstruction, disposal) impacts of buildings.

This research within this thesis employed Life-Cycle Assessment (LCA) methodologies to calculate and estimate the carbon dioxide emissions of new-build office buildings in Scotland.

1.2. Hypothesis and Research Questions

1.2.1. Hypothesis

There are two hypotheses behind this research:

"Embodied carbon emissions are becoming more significant to total life-cycle carbon emissions"

"Carbon dioxide emissions per square metre of new-build offices in Scotland over their whole life-cycle are less than the currently used benchmarks"

1.2.2. Research Questions

- How much are the carbon emissions of a new-build office building in Scotland?
    - This question includes two other questions:
    - How much are the embodied carbon emissions of a new-build office building in Scotland?
    - How much are the carbon emissions of the usage phase of a new-build office in Scotland?
- Are the results higher or lower than the benchmarks derived from the literature?

1.3. Environmental Burdens

As noted already, concerns for the environment have been growing over the decades since the publication of Rachel Carson's Silent Spring in 1962 (Miller, 1990), and focus on global warming. Nevertheless, there are other significant environmental burdens, which can be summarised as follows:

Ozone depletion: *"refers to the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar UV-B radiation to reach the earth's surface, with potentially harmful impacts on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials"* (Fava, 1993).

Acidification: "*Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). Examples include fish mortality in Scandinavian lakes, forest decline and the crumbling of building materials. The major acidifying pollutants are SO_2, NO_x, and NH_x Areas of protection are the natural environment, the man-made environment, human health and natural resources"* (Fava, 1993).

Eutrophication *"is the ecosystem response to the addition of artificial or natural substances, such as nitrates and phosphates, through fertilizers or sewage, to an aquatic system. Eutrophication covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P)"* (Fava, 1993).

Energy consumption: "*refers to the energy used by an activity. For example, the world energy consumption refers to the total energy used by all of human civilization"* (Fava, 1993).

Depletion of abiotic resource: "*encompasses both the use of non-renewable and renewable abiotic resources (e.g. wind, flowing of water, etc.).*

Human toxicity: "*is a calculated index that reflects the potential harm of a unit of chemical released into the environment. It is based on both the inherent toxicity of a compound and its potential dose. It is used to weight emissions inventoried as part of a life-cycle assessment"* (Fava, 1993).

Eco-toxicity: "*This impact category covers the impacts of toxic substances on aquatic, terrestrial and sediment ecosystems. The area of protection is the natural environment (and natural resources). This impact has sub-categories, like: Freshwater aquatic, marine aquatic and terrestrial eco-toxicity"* (Fava, 1993).

1.4. The Built Environment Role

Environmentally harmful activities differ from industry to another, but it is well known that the biggest contributor to greenhouse gas emissions is the built environment accounting for up to 50 per cent of global carbon dioxide emissions (Raynsford, 1999). In addition, the embodied environmental impacts generated by the building during its whole life cycle, can be of the same order of magnitude as those generated during the utilisation stage (Citherlet, 2001).

Building construction industry consumes 40 per cent of the materials entering the global economy generating 40-50 per cent of the global output of greenhouse gases and the agents of acid rain (CIWMB, 2000).

The construction sector is responsible for a high percentage of the environmental impacts produced by the developed countries (UNEP, 2003). In the European Union, the construction and building sector is responsible for roughly 40 per cent of the overall environmental burden (UNEP, 2003). Homes alone in the United Kingdom (their occupation and construction) are responsible for the consumption of 40 per cent of the primary energy in the country (Defra, 2004). Petersdorff and Boermans (2004) stated that if the rest of the building stock is considered, the impact of buildings will rise, because 30 per cent of the building stock is not residential. The construction industry is a highly active sector all over the world (UNEP, 2003), and ISO stated that it is the largest industrial employer, accounting for 7 per cent of total employment, and 28 per cent of industrial employment. It is responsible for a high rate of energy consumption, environmental impacts and resources depletion (ISO, 2006a).

In the European Union and the United States, the construction and building sector has been estimated to be responsible for roughly 40 per cent of the overall environmental burden (Junnila et al., 2006). Most European governments have introduced new policy instruments such as the European Community's energy performance directive for buildings in order to reduce the negative impacts from the building sector (Bee et. al, 2002).

1.5. Office Buildings Role

Companies are also concerned about the environmental issues related to buildings, there are more than 49,000 companies in the world that have been certified to the ISO 14001 environmental management system (EMS), of which 23,142 are European (ISO, 2001). In the UK there are 2917 companies certified to the ISO 14001 (EMS) (ISO, 2001). These companies have an explicit requirement to consider the environmental performance of their purchases and suppliers, including buildings and building materials (Hendrickson and Horvath, 2000). It is critical to get the appropriate knowledge and tools to control the environmental aspects to manage the building-related environmental issues, in order to minimize or eliminate the environmental impacts.

Some descriptive work on office buildings has been done, but there is limited research published on complete LCA of office building (Ortiz et al., 2009), although office buildings are significant sources of energy use and emissions, but there is a lack of quantitative comprehensive studies including all the phases of office buildings life-cycle (Junnila et al., 2006). Researchers suggested that a detailed focus on the embodied energy of every material or building component alone without looking on their relative significance is an ineffective approach.

1.6. Why Life-Cycle Assessment for Buildings/Construction?

Life cycle assessment in the construction industry is less developed than other industries today, however involving and developing the life-cycle assessment methods in the building sector is increasing. Building industry, governments, designers and researchers of buildings are affected by the trend of sustainable production and eco-green strategies. The importance of obtaining environment-related product information by LCA is broadly recognised, and LCA is one of the tools to help achieve sustainable building practices.

Applying LCA in the building sector has become a distinct working area within LCA practice. This is not only due to the complexity of buildings but also because of the following factors, which combine to make this sector unique in comparison to other complex products. Buildings and constructions have extremely long lifetimes, often more than 50 years. It is difficult to predict the life cycle 'from cradle-to-grave'.

During this life span, the building or construction may undergo many changes in its form and function. These changes can be as significant, or even more significant, than the original construction. The ease with which changes can be made and the opportunity to minimise the environmental effects of changes are partly functions of the original design. Many of the environmental impacts of a building occur during its use. Proper design and material selection are critical to minimise those in-use environmental loads. There are many stakeholders in the building industry. The designer, who makes the decisions about the final building or construction or its required performance, does not produce the components, nor does he or she build the building. Traditionally, each building or construction is unique and is designed as such. There is very little standardisation in whole building design. New choices have to be made for each specific situation.

The comparability of LCAs of distinct products and the way these LCAs are applied to design and construct environmentally sound Building is a main point of attention in LCA practice. Several initiatives for harmonisation and standardisation of methodological developments and LCA practice in the building industry have taken place at a national level, but in general much scope remains for wider involvement and co-operation.

1.7. Research Methods

In this realist research, to answer the questions *"how"* and *"why"* a case study method was used, especially because the research investigates an open system over which the investigator has limited or no control (Yin, 2009). This choice was supported by multiple sources of evidence (drawings and specifications of a building, company documents, environmental statistics, interviews and observation) had to be used to collect the data needed. The chosen method also supports the goal of the study to gain in-depth knowledge of the cases; it helped to understand *how* and *why* certain life-cycle phases and elements contribute more to the environmental impact than others. Chapter 4 gives detailed explanation of the methods used.

1.8. Originality of the Research

As mentioned earlier in this chapter, there are few published examples of complete studies held to find out the environmental impacts during the whole life cycle of office buildings, however there are some studies held in Europe and the USA; mainly by (Junnila, 2004) in Finland, (Junnila et al., 2006), and (Scheuer et al., 2003). The research presented in this thesis is an attempt to fill this gap in our knowledge, specifically:

- There is no published study which held a complete life cycle assessment of a "new-build" office building in Scotland.

- There are no published comparisons of new-build office buildings to find out their carbon emissions current state if related to other cases in the literature.

- Often life cycle assessment results and databases are incomparable. Using the same data sets and following the same approach under the same goal and scope of the study of multiple cases allows the study practitioner to hold many useful comparisons.

1.9. Conclusion

Life-cycle assessment of the environmental impact of office buildings in Scotland has not been done before, and this offers the possibility of answering important research questions.

Chapter 2 - Office Buildings

2.1. Introduction

When considering office buildings we are talking about buildings in which people spend most of their working times. Offices occupy a great variety of structures, from low-rise to high-rise. Office layouts have evolved with changes in technology. In the 1960s the typical office building was composed of private offices, but modern office layouts are more flexible and open.

There is large literature related to the most suitable layout (Marmot and Eley, 2000) which is mainly connected with the type of the company, and the requirement of its work. Comfort of office workers is also researched and many studies highlighted the parameters of comfort within office buildings (Huizenga et al., 2006), but detailing this is beyond the scope of the research objectives in this thesis. Other researchers studied office buildings in terms of energy consumption, and environmental impact, and defined the related parameters. This chapter discusses offices, describes the parameters which affect carbon emissions from office buildings, and reviews the relevant literature.

This chapter reviews and shows a body of knowledge on features of office designs needed to minimize the energy and carbon footprint of new-build office buildings.

2.2. History of Office Building

Office buildings as a separate type first appeared approximately 100 years ago. Before that there was a lack of demand for offices and lack of technology to construct more than low rise buildings. In the late nineteenth century, cities began to grow and companies with large numbers of workers appeared. Then the demand for office as a separate land-use started to push for building offices. The nation's population increased significantly between 1870 and 1920, but demand for office space increased five times (ULI, 1982).

Using masonry walls, builders faced several problems. The height of the building affected the thickness of the walls, which was in direct proportion to its height. Architects believed that a twelve-inch wall could support the first storey, but that four inches had to be added for each additional story. Therefore, very thick walls at the ground level were necessary for multi-storey building. The tallest masonry building, the sixteen-story office building in Chicago, had six-foot thick walls at its base. Additionally, new technologies were needed to prevent foundations from settling under such heavy buildings and to provide a safe method of transporting people and materials up and down many levels.

The structural problem was solved by introducing new technologies such as the steel frame. The invention of the steam hammer for pile driving and the use of caissons to anchor a building's foundation to bedrock solved the second problem. And, the perfection of the elevator, invented by Elisha Otis in 1853, solved the third. These came together in 1880s Chicago.

Other inventions made working and living in multi-storeyed buildings comfortable. Steam was used to heat the buildings. The invention of the electric light bulb and the creation of electricity generation and distribution systems provided for the illumination of buildings. The invention of the water closet and water supply and drainage systems permitted people to remain at their desks all day. At this same time, primitive methods of air conditioning were being tested.

Technology influenced the development of office buildings in other ways. Modern communication, using first Samuel Morse's telegraph in the 1860s and then Alexander Graham Bell's telephone in the late 1870s further increased office worker productivity. Internet and other types of networks increased the number of office workers as so many new types of office work appeared and large number of related companies dominated the work market. Accordingly, all these invented technologies increased the demand for office buildings.

The downtown area was a hub for most city activities; within this area you can visit post offices, banks, law firms, commodities and securities markets, repair shops, employment agencies, clubs, restaurants, taverns, and everything else one might need. It was convenient to construct office buildings in the downtown area, which allowed the employers to locate near transit lines, close to all facilities possibly needed for their company.

The downtown became a kind of information hub. Every worker can find information easily near to his work place; as a result companies located in this area grew and became larger in comparison with other companies. This increased the demand for downtown office space. The result was a boom of multitenant office construction in most large cities.

World War II had a negative impact on office buildings, as during that era office building development was limited. However, by the early 195Os, new office buildings were again under construction, and downtown continued as the primary office space location. A variety of cladding materials were used, including stainless steel, pressed aluminium, glass, and precast concrete. The improvement of central air conditioning encouraged the development of increased floor sizes and lower ceilings. High-speed, operator-less elevators encouraged taller buildings. Fluorescent lighting reduced power consumption and permitted higher light levels. Oil- and gas-fired boilers replaced many coal boilers.

The system of highways played a two edged role by allowing employees who lived in the suburbs to easily reach to the downtown. But as decay and disrepair began to overtake the downtown areas of many cities, suburban communities encouraged office developers to build in outlying areas. Many tenants were attracted by the proximity to the residences of employees and by the lower rents. Clusters of office buildings were developed along with the growth of cities.

During this period, floor plates and building sizes continued to increase, and the energy crisis created a new generation of buildings designed to conserve energy.

Personal computers, FAX machines, photocopiers, satellites, internet and fibre optic cables lowered communication costs and increased the speed of information flow. In many markets, office construction occurred mainly in the suburbs, as proximity was no longer necessary for information exchange. Many new office buildings were wired for advanced technology applications. Heating and air conditioning were integrated in new computer-controlled, energy-conserving systems.

While new office buildings were being constructed, the large steps in office technology were working to reduce the need for more space. Technology increased worker productivity and permitted some tenants to think about staff and space reduction. This trend persists today and is partially responsible for some buildings operating at less than full occupancy. In addition, there is a trend to work from home when possible, not only to reduce the transportation environmental impact but also to improve workers' work-life balance; this as well may affect the demand for new office buildings in future.

2.3. Office Building Research

Office space research until late sixties was dominated by the technological development of building structures. Until then height was restricted by the load bearing masonry walls. New technologies and materials for constructing high-raise buildings and creating the comfortable spaces for workers were under development. As office building development began to mature, research expanded to other areas of interest.

Spatial, social and technical research of office buildings is still being developed , and researchers are active in important areas like thermal comfort in offices, behaviour of office user, layout development, natural and artificial light in offices, office buildings structural systems, energy profiles, and environmental impact of offices. Those key study areas are being developed by researchers from all around the world. However, the amount of research is small compared to the importance of office buildings as the work place of most people. While it is beyond the scope of the research in this thesis to review all office building research, this paragraph gives some examples and studies of LCA of offices will be detailed in next chapter.

2.4. The Non-Domestic Building Stock

This section gives an impression of the scale of the office building stock in Scotland, from which its contribution to environmental impact can be assessed. The building stock could be classified according to ownership into the public and private sector. The public sector buildings include all government offices, educational institutions and defence buildings. The private sector buildings comprise commercial offices, shops, factories, warehouses, hotels, catering establishments, communication buildings, etc. Some other buildings could be classified as shared ownership buildings; those are owned by public and private sector, (health buildings, etc.).

According to their use, buildings could be classified as domestic and non-domestic buildings. Domestic buildings include all buildings used for residential purposes (dwellings, houses, flats, etc.). Non-domestic buildings are all other purposes buildings, these are quite varied. Figure 1 shows numbers of domestic and non-domestic buildings in Scotland, and their floor area according to (SAA, 2011).

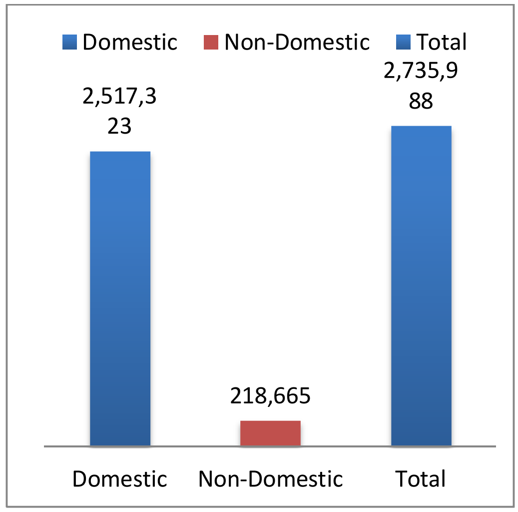

Figure 1 - Building stock in Scotland

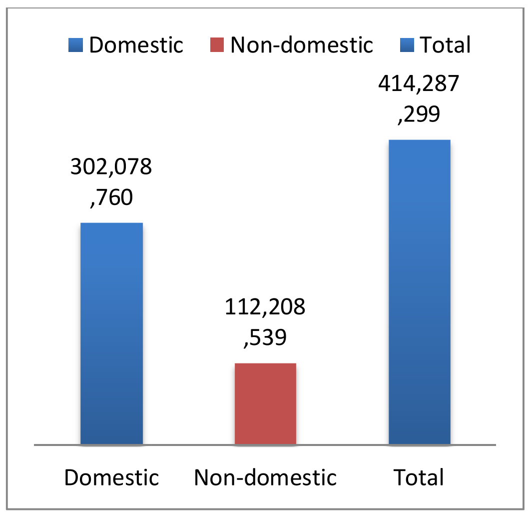

Figure 2 - Building stock area in Scotland

Figure 1 and Figure 2 show that by number the non-domestic building stock is approximately 8 per cent of the total building stock, however, by floor space the ratio of non-domestic buildings is approximately 27 per cent. This is because the average area of non-domestics is more than in the case of domestic buildings.

The UK non-domestic building stock can be explored by using data sets from the Valuation Office Agency (VOA). The VOA holds data, such as floor space and rateable value statistics, on every property in England and Wales which is subject to commercial rates. The data are organised by "hereditaments" which are defined, according to the Office of the Deputy Prime Minister document (ODPM, 2006), as property on which rates may be charged. In practice, a hereditament may be a room or part of the floor in the building, a whole building or a group of buildings. Some are not buildings at all and consist only of land, for example, open-air car parks, storage land, and various kinds of sports grounds. Hereditaments are grouped into bulk classes. The bulk class properties are those for which floor space and other descriptive information is consistently available. There are five bulk classes defined:

- Retail premises,
- Offices,
- Factories,
- Warehouses, and
- Other premises.

The offices bulk class is composed of hereditaments which serve mainly commercial activities such as purpose-built office buildings, offices over shops, light storage facilities and light industrial activities. This class also includes larger banks, building societies and post offices which contain substantial office space.

The document produced by the Department for Communities and Local Government in collaboration with the VOA provides a summary of hereditament, floor space and rateable value statistics for non-domestic property in England and Wales as at 1st of April 2008 (Wyatt, 2008). Figure 3 shows the number of hereditaments in each bulk class. It can be seen that the retail bulk class has the highest number of hereditaments, nearly 550,000 units which is 30.5 per cent of the total number of hereditaments whilst there are slightly more than 350,000 office properties equal to 19.5 per cent of the total number of hereditaments in England and Wales.

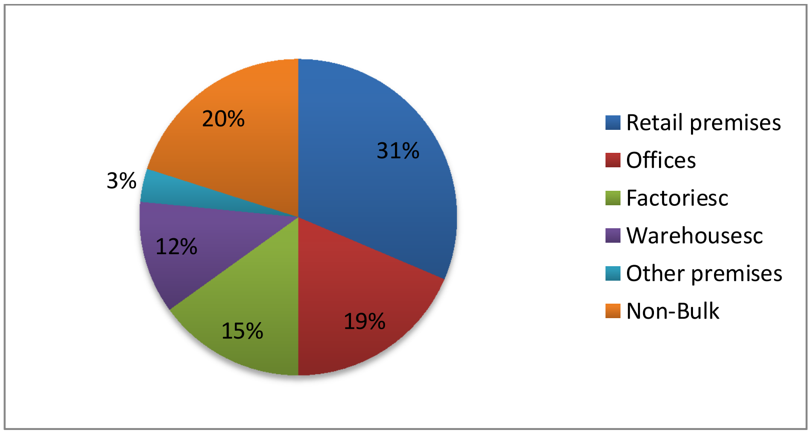

Figure 3 - Commercial and industrial hereditaments: England and Wales by (Numbers)

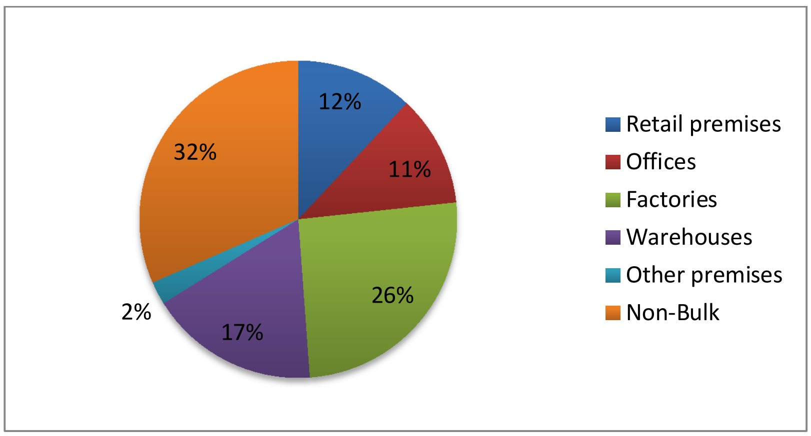

Figure 4 - Commercial and industrial hereditaments: England and Wales by (m^2)

In Scotland, there are 37194 offices according to Scottish Assessors Association (SAA, 2011) making 18 per cent of the non-domestic building stock (total 207,231). However, by floor area the ratio becomes approximately 9 per cent as presented in Figure 5 and Figure 6. This is because the average floor area for office units in Scotland (258 m^2) is less than the average non-domestic building area of (540 m^2). The numbers in these statistics reflect all types and sizes of buildings, (i.e. single unit could be a small corner shop or a large building), but the required data to find out the total floor area of office buildings in Scotland is not accessible, unlike the case of England and Wales. The average floor area of offices according to this data is 258 m^2. The total area of offices in Scotland according to Building Standard Division (BSD, 2011) is 9,619,532 m^2.

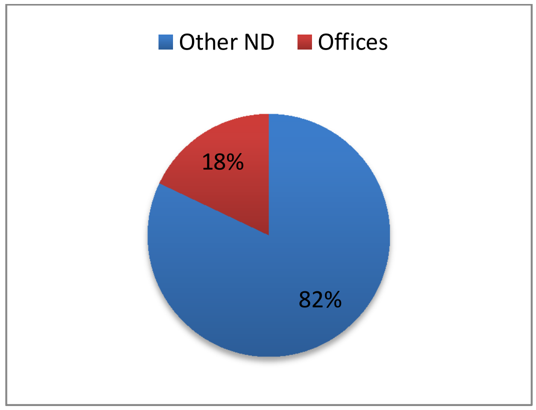

Figure 5 - Non-domestic buildings, Scotland

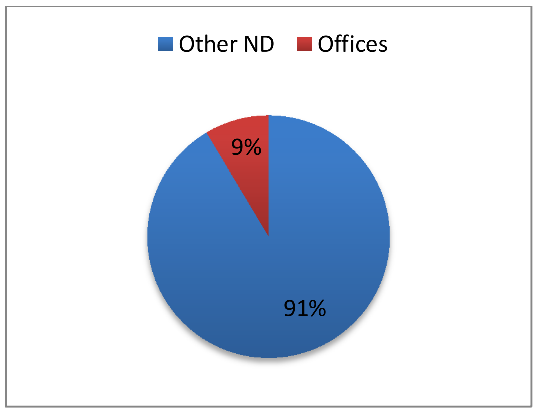

Figure 6 – Non-domestic buildings' area, Scotland

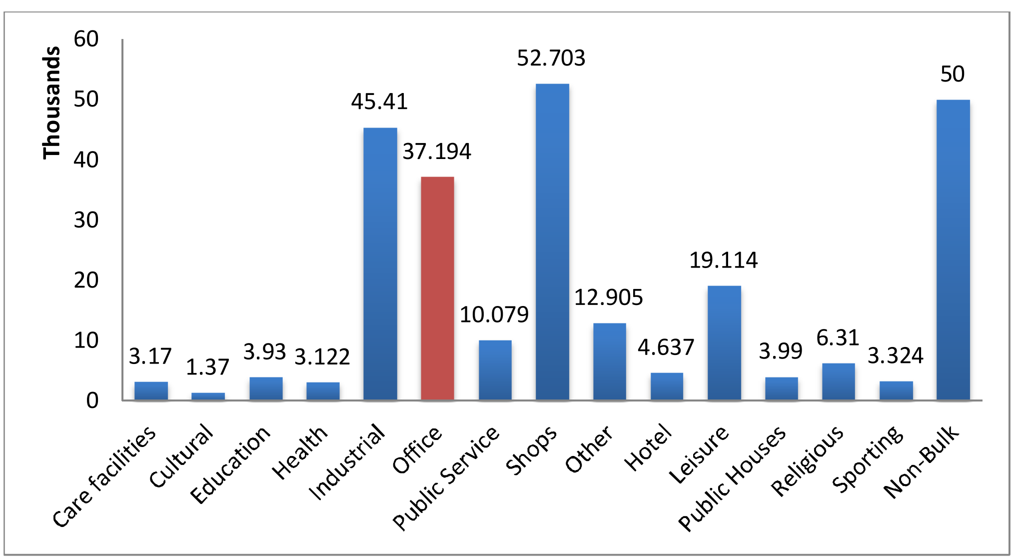

Figure 7 - Commercial and industrial hereditaments: Scotland by (Number) (BSD, 2011)

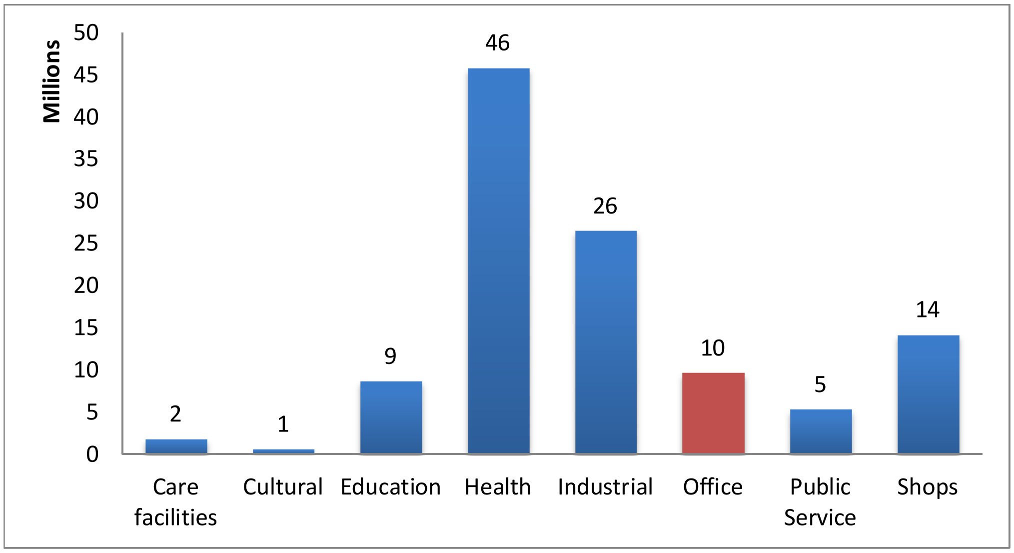

Figure 8 - Selected non-domestic categories area: Scotland, by m^2 (SAA, 2011)

This research is focused on office buildings only. The office building can be defined as a place in which business, clerical, or professional activities are conducted. The VOA subdivided the office bulk class into two classes called "commercial" offices and non-commercial "other" offices. The commercial offices group is composed mainly of purpose built office buildings and various types of non-domestic buildings converted to offices, offices over shops and computer centres. Central government offices are also included in this category. The "other" office category includes mainly local government offices, surgeries and clinics, and police stations.

Besides the share of office buildings in the non-domestic building stock and the ratio between commercial and "other" offices, it is interesting to see the age profile of the office building stock. The Office of the Deputy Prime Minister published the document *"Age of Commercial and Industrial Stock: Local Authority Level 2004"* (ODPM, 2005) which provides analysis of the age of non-domestic properties as at April 2005. The document is also based on the data sourced from the VOA. Figure 9 shows the age distribution of office properties in England and Wales. Just over half of office hereditaments were built before 1940 while properties completed between 1990 and 2003 account for 12 per cent of the total stock. However, figure 10 shows that total office floor space area is much more evenly distributed between the different age ranges. Just below 28 per cent of all offices were built before 1940 while a 20 per cent were constructed between 1990 and 2003. By comparing Figure 9 and Figure 10, it can be concluded that newer properties tend to have a larger floor space on average. In addition, it can be observed that a certain number of properties are of unknown age. There is no year built information for about 1.7 per cent of office hereditaments which accounts for around 5.8 per cent of the total floor space.

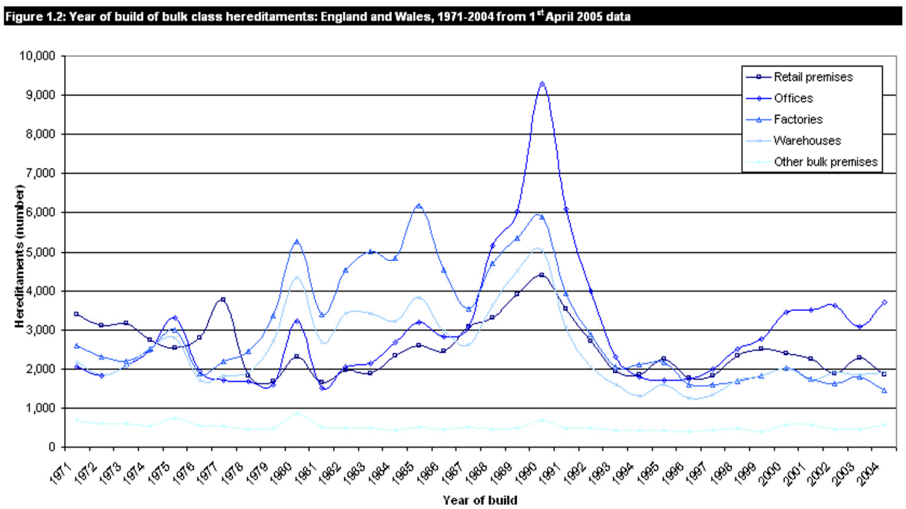

Figure 9 - Number of non-domestic buildings according to year of build

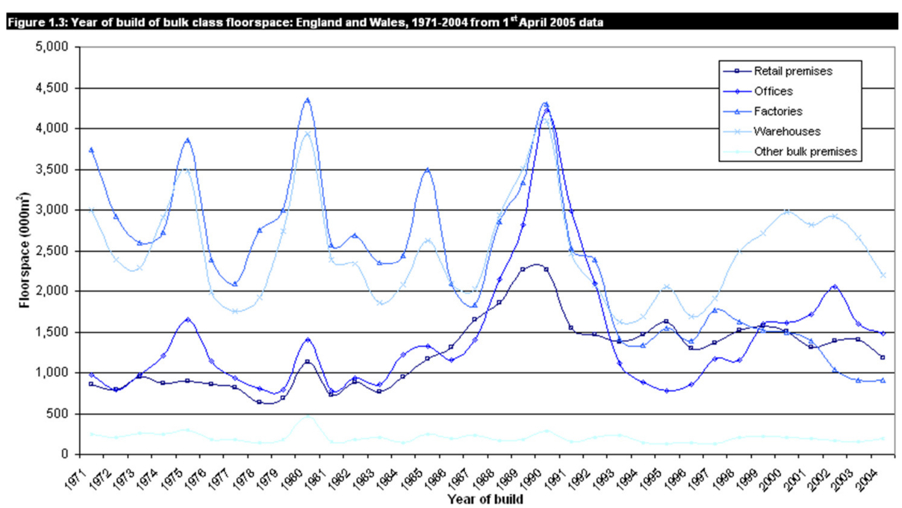

Figure 10 - Area of non-domestic buildings according to year of build

Against this background of stock of non-domestic buildings, the UK government has set an ambition for new non-domestic buildings to be zero carbon from 2019, with earlier dates for schools (2016) and other public sector buildings (2018); Non-domestic buildings account for approximately 16.5 per cent of the UK's total carbon emissions. Some parts of industry have already taken steps to help improve energy efficiency through initiatives such as 'green leases' and LES-TER[1], and many non-domestic buildings are being developed using sustainability tools such as BREEAM. However, it is important that we take steps to reduce these emissions further. In March 2008 the Government announced an ambition that all new non-domestic buildings would be zero carbon from 2019.

This ambition sits against the backdrop of the policy context, such as the UK's commitment to an 80 per cent reduction in greenhouse gas emissions by 2050, the development of the Renewable Energy Strategy (RES) and the development of European-wide requirements on the energy performance of all types of buildings. In addition, there are a number of other policies designed to reduce emissions for non-domestic buildings, for example:

- the European Emissions Trading Scheme EU ETS which covers more than 11,000 factories, power stations, and other installations with a net heat excess of 20 MW in 30 countries, all 27 EU member states plus Iceland, Norway, and Liechtenstein. The installations regulated by the EU ETS are collectively responsible for close to half of the EU's emissions of CO2 and 40 per cent of its total greenhouse gas emissions (EU ETS, 2012). Installations must monitor and report their CO2 emissions, because every year they must return leftover emission allowances to the government.

- the Climate Change Levy which taxes the use of energy in industry, commerce and the public sector to encourage energy efficiency and Climate Change Agreements which allow energy intensive business users

[1] landlord's energy statement and tenant's energy review

to receive an 80 per cent discount from the Climate Change Levy, in return for meeting energy efficiency or carbon saving targets.

- the Carbon Reduction Commitment Scheme (CRC), which was introduced in 2010, provided incentives for large commercial and public sector organisations whose electricity use is above 6,000 MWh (around 10 per cent of the UK emissions) to take energy efficiency measures.

- alongside the need for an Energy Performance Certificate to be produced for all new buildings, large public buildings must now also have Display Energy Certificates which enable everyone to see how energy efficient our public buildings are, and so create an incentive to ensure that buildings are first built, and then used, in the most energy efficient way possible; and

- advanced or 'smart metering' for business premises could help consumers reduce their energy use by providing them with more information on their consumption than is currently available. The Government has announced its intention to proceed with the provision of advanced metering for large businesses and sought views on its application to small and medium enterprises, smaller sites of larger businesses and the public sector. In the longer term, setting clear targets for achieving zero carbon could help enhance the take-up of advanced metering.

$kgCO_2/m^2/pa$	Heating	Cooling	Auxiliary	Lighting	Domestic hot water	Equipment	All end uses
Commercial Offices	20	6	4	20	3	26	78
Communications and Transport	16	12	5	22	4	28	87
Education	10	0	2	15	6	15	48
Government	20	6	4	20	3	26	78
Health	17	0	12	27	9	62	127
Hotel	12	0	4	14	27	13	70
Retail	11	49	8	68	0	13	150
Sports and Leisure	0	30	15	22	31	14	112
Warehouses	17	0	0	4	0	5	26
Other services	13	10	7	27	9	31	97
Industrial	1	0	15	52	0	0	69
Average all sectors	12	8	7	28	5	16	76

Table 1 - Average emission rates for buildings which meet 2006 building regulations

The average carbon emission for non-domestic buildings as presented in Table 1 is 76 kg CO_2/m^2/year. Accordingly, the total emissions of Scottish non-domestic Buildings is approximately 8.5 million tonne CO_2/year of which offices are responsible for 9 per cent.

The UK Green Building Council (UK GBC) produced a report for the Department in December 2007 which modelled some costs for low carbon buildings. It showed that different types of non-domestic buildings will face different levels of costs to install energy efficiency measures and renewable energy solutions. For example, an office block would typically have high levels of heating, lighting and ventilation, as well as a high level of energy use from equipment. However, there would be scope to improve the energy efficiency of the building fabric and building services and possibly opportunities to export heat to nearby buildings.

In August 2007, Scottish ministers appointed an expert panel chaired by Lynne Sullivan to advise on a Low Carbon Buildings Standards Strategy for Scotland.

The Sullivan Report was published in December 2007 setting out a wide range of recommendations for new and existing buildings to deliver reduced emissions from Scotland's building stock. 56 recommendations within the Sullivan Report were considered in the Climate Change (Scotland) Act 2009. In February 2009, Scottish Ministers announced revised energy standards for new homes and non-domestic buildings. Following public consultation, revised energy building standards came into force on 1 October 2010, reducing carbon dioxide CO_2 emissions from new buildings by 30 per cent compared to the 2007 building standards. This is in contrast to the Sullivan recommendation of a 50 per cent reduction to new non-domestic buildings which was revised due to the current economic downturn whilst looking to ensure the long term climate change targets are met.

The Scottish Government has undertaken to review energy standards on a 3 yearly cycle and the review for 2013 based on the Sullivan recommendation commenced in autumn 2010. "*The 2013 change in energy standards for non-domestic buildings should deliver carbon dioxide savings of 75 per cent more than 2007 standards*".

All this discussion confirms the importance of the offices sector of the non-domestic building stock. It has the potential to deliver considerable savings in carbon emissions.

2.5. Office Building Built Forms:

As carbon emissions of a building are dominated by energy consumption over its life time, special attention has to be paid to a classification of built forms, because building geometry has a significant impact on building energy demand. A detailed study of building geometries resulted in the identification of several principal built forms. The study was based on data from a series of local surveys carried out in four English towns in which the non-domestic building stocks might be considered characteristic of the national stock: Manchester, Swindon

(Wiltshire), Tamworth (Staffordshire) and Bury St Edmunds (Suffolk). These four towns were selected for their range of population size, widely spread geographically across the country, a great variety of building types, and the fact that none is dominated by a single industry (Brown et al., 2000).

In each case, a sector of the town was chosen and all non-domestic buildings in that area were surveyed. The surveys were part of a project to develop a national Non-Domestic Building Stock (NDBS) database which main purpose was to provide a better statistical picture of the non-domestic stock, and of uses of energy in non-domestic buildings (Steadman et al., 2000a, Steadman et al., 2000b). In total, some 3,350 addresses were covered by survey with the total area of floor space just under 4 million m^2 (gross external area). Each building was inspected externally and a large number of building characteristics were recorded. The recorded data included: building estimated age, overall building form (including roof type and number of storeys), and details of fabrics and constructions visible from the outside such as structural type, glazing type, and external wall and roof finishing.

The classification of built forms was made according to two basic criteria: whether or not a space is predominantly day lit or artificially lit and a space layout (Steadman et al., 2000a). The authors observed that rooms take typical ranges of size depending on their functions and created three subcategories: cellular spaces, open plan spaces, and halls. Cellular space arrangement is typical for strings of individual offices in commercial buildings, bedrooms in hotels, classrooms in schools, etc. Such rooms are more or less comparable in size, equipped and furnished in similar ways, serve quite standardised purposes, and accommodate roughly equal number of occupants.

Open plan spaces and halls are similar in both size and shapes, and both are unobstructed by walls. The difference between them is in the occupants' activity. Halls are large single specialised spaces occupied by single coordinated activity such as lecture theatres, conference and meeting rooms, assembly halls, churches and chapels, cinemas, etc. On the other hand, the occupants of the open plan spaces are engaged in many different activities. In most cases, this type of space accommodates office activities, but the same description can be applied to many large shops or warehouses. By combining these two basic criteria, Steadman et al. (2000a) proposed the six basic built forms:

- Day lit cellular,
- Artificially lit cellular,
- Day lit hall,
- Artificially lit hall,
- Day lit open plan, and
- Artificially lit open plan.

The day lit cellular group includes most office accommodation, except open plan offices, and majority of the space in hotels. The artificially lit cellular built form is quite rare and occurs mainly in spaces such as basements. Large spaces such as churches, which are generally day lit from the side, or courtyards, which most of them are day lit from the top, are typical examples of the day lit halls. Cinemas, theatres or television studios fall into the artificially lit halls category. Typical examples of the day lit open plan category are spaces which are top lit, for example single-story buildings or top floors, or side lit spaces with maximum depth which allows an acceptable level of day lighting. The artificially lit open plan category includes all types of large spaces with none or very limited day lighting such as large open plan offices, majority of shops, and some of warehouses.

Beyond this, Steadman et al. (2000a) adopted several strategies to simplify the representation of complex built form. All minor details of form are ignored, such as building attachments, balconies, small bay windows, etc. Buildings of complicated form are disaggregated into smaller component parts, and, where is suitable, these separate built form components are assigned to different classification categories. Some building forms are subcategorised according to numbers of storeys to make a distinction between forms in which vertical communication can be obtained by staircase only (forms up to four storeys) and forms for which lifts are necessary (forms with five storeys and more). Schematic drawings of the principal built forms are given in Figure 11. The side lit strip built forms are illustrated with constant depth and straight lengths. However, actual buildings might consist of multiple strips, varying depth and can even have curved plan. Artificially lit built forms are represented in Figure 11 with simple rectangular plans, although they have no limitations on the building depth and could have many various plan shapes.

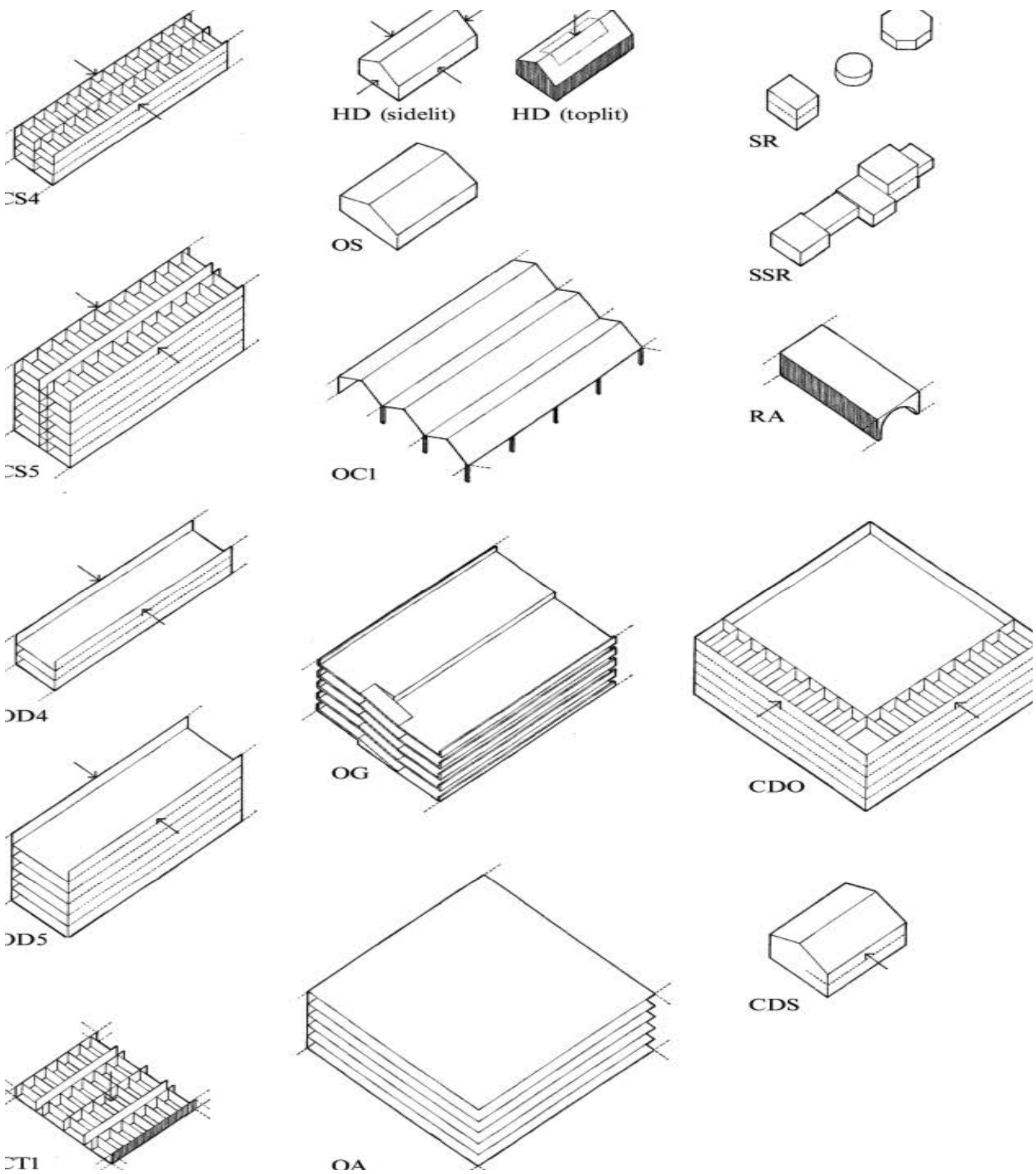

Figure 11 - Office buildings' built forms

Where CS4: Cellular day lit strip (1 to 4 storeys), OC1: Open plan continuous single-storey space, CS5: Cellular day lit strip (5 storeys & above), OG: Open plan car parking or trucking deck, OD4: Open plan day lit strip (1 to 4 storeys), OA: Open plan multi-storey artificially lit, OD5: Open plan day lit strip (5 & above), SR: Single-room form, CT1: Cellular top lit single storey, SSR: String of single-room forms, HD: Day lit hall, side lit, top lit or both, CDO: Day lit cellular strip around some or all edges of artificially lit or top lit open plan space, and RA: Railway arch.

All floor space from the surveyed addresses in the four towns was categorised according to this classification. Steadman et al. (2000a) gives the total gross area of floor space devoted to each type of principal form listed in the classification. However, only built form categories which are suitable to accommodate office activity, beside other activities, are presented in Table 2 individually.

Other built form categories are grouped either into "other principal forms" if they belong to the principal built form category or into parasitic forms. Parasitic form is any form which accounts for significant amount of floor space, especially if that floor space is heated or otherwise serviced, and cannot be added to any of six basic categories of space. Typical examples of parasitic forms are atrium, basement, large balcony, circulation bridge, attached circulation tower, small single-story extension, occupied pitched roof or attic, roof-level plant room, etc.

Table 2 shows that the side lit cellular up to four storeys tall (CS4) is the most common built type with nearly 34 per cent of the floor area. Five per cent is the share of the side lit cellular more than four storeys tall (CS5) built type. The side lit cellular built form category dominates the non-domestic building stock with roughly 40 per cent of the total gross floor area. Second largest individual built form category is the composite side lit cellular around artificially lit open-plan (Emmerich et al., 2007) which occupies approximately 20 per cent of the total floor area.

The majority of the corresponding activities in these two categories are offices, shops and hotels. Open-plan artificially lit multi-storey space (OA), which accounts for 5.5 per cent of the total, is used for warehouses, factories, offices and shops. The side lit open-plan up to four storeys (OD4) and the side lit open-plan with five storeys or more (OD5) use together nearly 3 per cent of the floor area and accommodate mainly offices.

Type	**Floor area (m^2)**	**Percentage**
CS4	1 343 247	33.9
CS5	207 516	5.2
CS4 + CS5	1 550 763	39.1
OD4	36 615	0.9
OD5	79 632	2
OD4 + OD5	116 247	2.9
CDO	771 402	19.5
OA	216 322	5.5
Other principal forms	871 808	22.1
Parasitic forms	432 631	10.9
Total	**3 959 173**	**100**

Table 2 - Total gross floor areas in principal form types of buildings **(Steadman et al., 2000a)**

Recognising that the building stock can be categorized in this way, buildings are complex structures and many more parameters, besides shape and floor layout, affect energy consumption. Parameters can be grouped into two categories. The first category includes building construction parameters such as insulation levels, glazing percentages, infiltration, etc. The second category is related to environmental conditions and building activity and includes lighting, appliances and occupancy density. The research within this thesis studied the chances of carbon reduction by modifying some of the first category parameters, specifically, building envelope parameters.

2.6. Building Envelope Parameters

Most important components of building envelope are external walls, roof, foundation and fenestration. A fenestration is any area on the exterior building envelope which allows day light penetration and includes windows, glass doors, and skylights.

By acting as a thermal barrier, a building envelope plays an important role in regulating interior conditions, as well as in determining a building's energy use. A building's energy use can be affected by a building envelope in many ways and one of the key factors in reducing energy needs is to minimize heat transfer through a building envelope. As a result, special attention during building design is always paid to the insulation of roof and walls, appropriate selection of glazing and framing for windows, air tightness of the building fabrics, suitable shading strategy, etc.

2.6.1. Insulation

It is a fact that increasing the level of insulation will remarkably decrease the level of heating energy consumption. This was practically tested and proved throughout many comparisons between buildings with different levels of isolations. For instance, Aksoy and Inalli (2006) compared buildings without insulation at all with 50 mm insulation material buildings. They found out the insulated buildings will approximately save 35 per cent of heating energy regardless of the building shape and orientation. Thus, different studies dealt with the optimization of the insulation thickness as a function of different energy sources and life-cycle costs. In the city of Denzili in Turkey, the optimum insulation thickness of the external wall was calculated by Dombayci et al. (2006) for the five different energy-sources (coal, natural gas, LPG, fuel oil and electricity) and two different insulation materials (expanded polystyrene and rock wool). It was found that, by using the optimum insulation thickness, heating energy consumption decreased by 46.6 per cent (Dombaycı, 2007).

A similar experience was conducted by Bolattürk (2006). In order to get more reliable results, he included sixteen different cities from different four climate zones. Eventually, he found out that the thickness required for optimum isolation would be between 20 to 170 mm, and the saving in energy would be between 22 to 79 per cent, depending on the city and the type of fuel used, with a payback period between 1.3 to 4.5 years. He also found out that cities in the same climate zone should be studied separately to calculate the optimum insulation and that the climate zone cannot be studied as a whole because he could detect different results for different cities in the same climate zone.

The analysis of the heating and cooling loads influence on energy consumption is of no less importance in the process of determining the optimum insulation. Bolattürk (2008), for example, argues that optimization of insulation thickness as a function of cooling loads is more appropriate for energy savings in warm zones. Also, to quantify the impact of insulation of various parts of building envelopes on building energy consumption, Kim and Moon (2009) did a series of parametric simulations by using two different climate weather files, cold and hot. They found that after a certain point, any further reduction in the U-values will result in a negligible saving in energy. In addition, they found that, in cold climates, insulation will help reducing heating energy consumption in the winter whereas there is no benefit for saving cooling energy in summer. Consequently, only minimum insulation is needed in hot climate because, according to them, any additional insulation has no impact on reducing heating or cooling energy consumption.

Chvatal and Corvacho (2009) did a more comprehensive study in terms of evaluating the impact of insulation level on building total energy consumption and on number of hours when indoor temperature causes discomfort. In their study, they included the analysis of other factors that can reduce overheating such as shading and ventilation strategies. In office buildings, the discomfort level rose with increments in insulation, mainly due to high internal gains, although more shading and a proper ventilation strategy may reduce it. Besides the discomfort issue, they also reported that the increase of insulation results in higher total energy consumption as more energy will be used for air conditioning. Thus, depending on their study, the overall recommendation was to avoid using highly insulated buildings if they accommodate office activities with high internal gains.

Almost the very same conclusion can be found in the Report on carbon reductions in new non-domestic buildings (Emmanuel & Baker, 2012). An important issue is that Lowering U-values resulted in increasing the CO_2 emissions as the improvement in insulation levels kept the heat in, and created higher cooling requirements. Masoso and Grobler (2008) also showed what might look like widely accepted rules such as “better insulation will save energy” are not universally applicable; in their simulation, they found that when the cooling set point is above a certain value, depending on the average temperature during the cooling season, more insulation causes cooling load to rise rather than decrease.

2.6.2. Thermal Mass

The materials used in the structure of the building will significantly affect the thermal mass of the building and the ability to absorb and store heat. For instance, the thermal mass will be increased by the usage of dense elements in the fabrics of building, such as bricks, stone and concrete. It is argued that walls, floors and ceilings made of such dense materials will interact with the internal environment which has several positive effects on the indoor conditions and energy consumption (Braham et al., 2001). During a winter period, on sunny days, solar heat gains are absorbed by thermal mass to be released later slowly. In fact, two advantages can be identified from this; overheating will be avoided during the high solar radiation periods of the day. Moreover, the heat released during the late afternoon and early evenings will reduce the heating load. In summer, heat stored in the thermal mass reduces peak cooling loads which could result in the use of a smaller HVAC plant. The ability to store and shift the loads also increases a thermal comfort by minimizing indoor temperature variations in both summer and winter.

It can be said that the thermal mass of the building can play an important role in energy saving in both heating and cooling. Aste et al. (2009) did parametric analysis on the influence of the external wall thermal inertia on the energy performance of well insulated buildings. Construction elements in the external wall were varied by keeping the same U-value and it was found that up to 10 per cent reduction in heating energy consumption can be achieved in buildings with a high thermal mass. When it comes to cooling energy, it was found that the reduction could reach around 20 per cent.

These results were also supported by other studies; the above mentioned 20 per cent saving in the energy consumption for cooling was also reported by Balaras (1996) who did a review of a lot of studies that investigated the relationship between thermal mass and indoor air temperature, and the effect of thermal mass and night ventilation on cooling demand. Moreover, he concluded that using night time ventilation or pre-cooling during off-peak hours could result in even higher reduction in the energy consumption of HVAC systems, especially in buildings that are unoccupied during the night such as office buildings and schools. An overview of research studies dealing with the night time ventilation and the mechanical pre-cooling was provided by Braun (2003). He reported that there is a significant savings potential for use of building thermal mass. However, it was suggested that the savings potential is very sensitive to many factors such as utility rates, type of equipment, occupancy schedule, building construction, climate conditions, and control strategy.

The extent of the positive effect of thermal mass is highly influenced by location of insulation layer in an external wall and insulation thickness (Asan, 1998). Kossecka and Kosny (2002) analysed the effect of insulation location on heating and cooling load in a continuously operated building with a high thermal mass. Their study showed that differences in total energy demand between least-efficient wall configuration, which is a wall with insulation placed close to the internal surface, and the most effective configuration with externally placed insulation layer might exceed 11 per cent depending on climate.

It was noted that further improvement can be done by using two separate layers of insulation instead of one. According to Asan (2000), the almost optimum solution is to place half of the insulation in the mid-centre plane of the wall and another half in the outer surface of the wall. He also argues that insulation in general should not be used but in outer surfaces of walls. This is also supported by other researchers such as Ozel and Pihtili (2007) who reached similar conclusions and extended the analysis by splitting insulation into three layers. In that case, they argue that the best result was achieved by placing three equal thickness insulation layers on the indoor surface, on the outdoor surface, and in the middle of wall.

A benefit of thermal mass that is perhaps less well known in the UK is its ability to help reduce fuel consumption during the heating season when used in passive solar design. This approach to design seeks to maximize the benefit of solar gain in winter using the thermal mass to absorb gains from south facing windows, along with heat produced by cooking, lighting, people and appliances. This is then slowly released overnight as the temperature drops, helping to keep the building warm and reducing the need for supplementary heating.

Thermal mass can be provided by all of a building's structural elements, including walls, frame and floors. Even furniture can to a limited extent provide some reduction in heat gains. However, concrete slabs provide the bulk of thermal mass. Heavier materials tend to be better in terms of providing thermal mass benefits, specifically those which are exposed to sunlight and internal gains directly and located in the inner side of the building. Exposed concrete surfaces, masonry walls, and ceramic tiled areas which face the sunlight could be of huge benefit. Generally, the more thermal mass the better. A brick or masonry cavity wall on a concrete slab offers the highest comfort benefits and energy savings.

However, the cost and embodied carbon of heavyweight materials can outweigh the value of energy savings, thus a careful choice of materials and thickness should be considered by the designers.

2.6.3. Glazing

The size and orientation of glazing are parameters which have a significant impact on building thermal behaviour. Increased glazing area results in higher gain from solar radiation, which can be beneficial during a heating period but during a summer period affects cooling demand and can lead to overheating. In addition, conductivity gains/losses of the whole envelope are also increased due to the difference in U-values between glazing and external wall to the detriment of the glazing. On the other hand, perimeter areas benefit from the higher percentage of glazing in terms of daylight. However, large amount of daylight, which enters a space through highly glazed areas, often reduce the quality of visual comfort due to glare problems (Woolley, 2003).

All these issues have been studied in detail and results have been widely published. The effect of window position and size on the energy demand for heating, cooling and electricity was studied by Bokel in (2007) and the study concluded that an optimal window size is around 30 per cent of the façade area and preferable position of the window should be a top half of the façade. The study also reported that a trend in cooling demand follows the increment in window size, while in the case of heating demand there is an optimum minimum around 50 per cent of window size. Window size for glazing areas up to 50 per cent highly affects lighting load while for the larger window sizes the advantage of larger area is negligible (Bokel, 2007).

Poirazis et al. (2008) investigated the impact of glazing area on the energy consumption of an office building with 30 per cent, 60 per cent and 100 per cent window to external wall area. The study showed that the total end use energy consumption increased by 23 per cent for the 60 per cent glazed building and 47 per cent for the 100 per cent glazed building in comparison with energy end use of 30 per cent glazed building. These results were obtained by using clear glazing in all three cases. The study also analysed the consequences of implementing glazing units with lower thermal transmittance and total solar transmittance and found that the total energy end use can be reduced. This measure resulted in "only" 15 per cent higher total energy end use of 100 per cent glazed buildings when compared to the 30 per cent glazed building with clear glazing (Poirazis, 2008).

Influence of orientation should be studied when the plan is flexible enough to change building orientation. In city centre developments this parameter is not changeable in most cases. However, influence of orientation is significant in the case when facades are different in terms of window-to-wall ratio, or building has one dominant façade.

The effect of window size on day lighting, peak heating/cooling loads, and overall energy consumption was investigated by Tzempelikos and Athienitis (2005). Their study used a single perimeter office space with one exterior wall as a base case and came to conclusion that the effect of orientation on heating load is small. The difference between a south façade and north façade did not exceed 13 per cent, which was explained as a result of small solar effects for heating design day. However, the influence on cooling load is significant and the difference between east/west and south facing façade is approximately 17 per cent, while in the case of north orientation the cooling load for a south-facing façade is two or three times higher. On the other hand, if facades are identical, the orientation does not have much effect on the energy use on a building level (Poirazis et al., 2008). Aksoy and Inalli (2006) studied different positions of variously shaped test models. They used positions from 0° to 90° with 10° step between each position. The study found that the difference between the minimum and maximum yearly heating energy consumption is about 5 per cent.

2.6.4. Solar Gains

Because solar heat gains and internal heat gains are both essential components of office building cooling loads, a number of measures to reduce these heat gain sources can be implemented.

The solar heat gains can be reduced by employing different shading systems whether installed externally or internally. Shading instalments can take a variety of shapes depending on the place of installation; they can be horizontal, vertical, or combination of both. In addition, shading elements can be movable or fixed. The efficiency of this type of shading depends on the type of shading and its placement relative to openings. As for internal shading devices, such as Venetian blinds or curtains, these are said to have a less effect than their external counterparts in controlling the solar gain. However, these interior devices can contribute to visual comfort in the work place through glare control. For instance, blinds, in addition to other shading systems can be used between glass panels in double or triple glazed windows.

Although they do not have a significant effect in reducing the beneficial solar heat gain received in winter time, overhangs, if precisely sized, can lead to significant cooling energy reductions. In this contest, an interesting model was presented by Raeissi and Taheri (1998). This model deals with the effect of windows overhangs on the building energy consumption. They found that upon using the optimum dimensions, the overhangs can decrease the cooling load up to 12.6 per cent with an increase in the heating load of only 0.6 per cent. The outputs were validated by measured data. The results of this model were given for specific climate and latitude. However, the effect of overhangs on overall cooling/heating energy consumption varies with different climate conditions and geographical position as well as window characteristics such as size and properties of glazing. On the other hand, similar study examined the influence of external shading on energy consumption. In 2009, Manzan and Pinto optimized a shade outside an office building with aim of reducing the energy consumption used for heating, cooling and lighting. Four external shading variables (height above window, depth, angle and distance from wall) were calculated for several glazing systems (standard glass, high performance glass, window with/without reveals). Each configuration required different optimum external shading geometry providing savings in primary energy consumption between 5 per cent and 17 per cent.

One powerful means of reducing the solar heat gains is through the proper design and the employment of certain glazing elements that have low values of solar heat gain coefficient (SHGC). This can be achieved by using glazing either with high reflective capabilities or with high heat absorption characteristics.

Many studies compared the different glazing types in terms of their influence on energy consumption; Cordoba et al. (1998) did a comparison of the influence of various glazing types on the office building energy consumption in Madrid. Glazing, which was used in comparison, was composed of clear inner glass and outer heat absorbing tinted glass with total solar heat gain coefficient of 0.48. They replaced the reference glazing with a reflective outer glass and solar heat gain coefficient of 0.26, they found that there will be a reduction of 10 per cent in the yearly energy consumption. Stegou-Sagia et al. (2007) did a similar study in which they compared the energy consumption of a 20 per cent glazed office building with clear glazing units with the same building equipped with grey tinted glazing units. Just like one would expect, there was a reduction of the energy consumption of 10 percent in the case of Athens and 6.5 per cent in the case of Thessalonica.

2.6.5. Infiltration

Infiltration is the uncontrolled flow of outdoor air into a building through cracks and other unintentional openings and mainly depends on wind direction and pressure, temperature differences between outdoor and indoor air, construction type and quality, and occupant use of exterior doors and operable windows.

Infiltration is also known as air leakage into a building or building air tightness. Uncontrolled air infiltration causes heat loss in winter and heat gain in summer, which results in higher energy consumption.

Emmerich and Persily (1998) studied the effect of infiltration on energy use in commercial buildings. The study estimated the energy impact of infiltration in office buildings by analysing a set of 25 buildings developed to represent the U.S office building stock. According to their study, 13 per cent of the heating load and 3 per cent of the cooling load are related to infiltration. Higher level of insulation in newer buildings makes the ratio of infiltration impact even higher about 25 per cent of the heating load and 4 per cent of the cooling load. The overall conclusions of this study was that the total annual energy impact of infiltration in U.S. office buildings is 15 per cent of the total heating energy and 4 per cent of the total cooling energy.

The airtightness of a building envelope can be given as a measure of air flow rate through the building envelope in $m^3/s\ m^2$ at a specified pressure difference. Alternatively, it can be provided as a predicted overall rate of infiltration by depending on the number of Air Changes per Hour (ACH). Only when the geometry of the building is known, these two measures can be linked. Measured air flow rate is usually given at indoor-outdoor pressure difference of 50 Pa in the United Kingdom, or at 75 Pa in the U.S.

When it comes to real airtightness levels in buildings the data available is, in fact, limited. One of the studies that assembled and evaluated measured envelope airtightness was done by Persily (1998). The study, based on a review of published literature data for 139 buildings, reported insignificant airtightness value for all buildings of 27.1 $m^3/h\ m^2$ at 75 Pa, but the range and standard deviation were large. The previous analysis was updated by including data from over 100 additional buildings in another study held by Emmerich and Persily in (2005). The overall average airtightness of 28.4 $m^3/h\ m^2$ at 75 Pa was very close to the value reported by Persily in 1998.

A recent study done by Emmerich et al. (2007) excluded buildings older than 1960, industrial buildings, and extremely leaky buildings, and divided the data into north and south subsets for the North American buildings only. This scenario led them to an average airtightness at 75 Pa of 23.76 $m^3/h\ m^2$ for north subset and 42.48 $m^3/h\ m^2$ for south subset. Another study done by VanBronkhorst et al. (1995) included 25 buildings that represent the U.S office building stock and attempted to summarize infiltration rates. A wind speed of 4.5 m/s was used to generate Infiltration rates based on factors like the age and height of the building and the average annual temperature difference. There was a minimum reported infiltration of 0.16 ACH, while the leakiest building had infiltration rate of 1.0 ACH.

Another study by Sharples et al. (2005) tested a warehouse in the UK with nearly 58,000 m^2 floor area for airtightness. There was a measured air permeability of 2.25 $m^3/h\ m^2$. This is substantially lower than what is required by the regulations. The study also compared results with similar studies that measured air permeability of very large buildings. Eventually, the study found that, upon employing the standard techniques, a value of 10 $m^3/h\ m^2$ can be reached, which is the target value that is specified by current UK building regulations.

2.7. Activity Related Parameters

The minimum values which satisfy indoor thermal comfort and air quality are defined by various national and international standards. This is because buildings are made to provide good indoor conditions for the comfort of occupants along with other purposes. Occupants' health, productivity and comfort are very connected with the indoor conditions. This is particularly in office buildings, as poor indoor conditions lead to decreased productivity and increase illness-caused absence. This could be avoided by adequate spending on improving and maintaining the most satisfactory indoor environment. Seppänen and Fisk (2006) reviewed the literature on the effect of indoor environment on health and productivity and found that there is a strong relationship between: ventilation rates and short-term sick leave, ventilation rates and work productivity, perceived air quality and productivity, temperature and productivity, and temperature and sick building syndrome symptoms. It is obvious that special attention has to be paid to an indoor thermal comfort and an indoor air quality.

In addition to indoor conditions, internal heat gains are another important parameter which has significant impact on energy consumption both directly, through lighting and equipment loads, and indirectly by affecting heating and cooling loads. They can be the dominant reason why in the temperate climates, such as in the UK, cooling systems in office buildings exist (Jenkins, 2009). The main sources of internal heat gains are:

- Occupants,
- Office electrical equipment, and
- Artificial lighting.

Benchmark values for internal heat gains are mainly based on measured data collected in numerous surveys of different building types and activities. When measured data is not available, the common way of obtaining values for internal heat gains is to use empirical values, based on experience, which are considered good practice in the industry (CIBSE, 2006).

Internal heat gains, in particular from artificial lighting can be reduced by implementing daylight control. Many results related to energy savings due to daylight control has been presented in literature. Lam and Li (1998) proposed a simple method for estimating energy savings of electric lighting and cooling. In their case study, which was based on generic office building in Hong Kong, daylight could maintain sufficient level of indoor illuminance for about 40 per cent to 60 per cent of the time, which resulted in 50 per cent reduction in artificial lights electricity consumption and additional 11 per cent electricity savings for cooling by assuming the coefficient of performance (COP) of 3 for the chiller plant. The same authors did field measurements for several fully air-conditioned cellular offices facing opposite orientation with and without daylight control (Li and Lam, 2001). Measurements confirmed that energy savings in electricity for artificial lighting could be up to 50 per cent for the perimeter offices. Li et al. (2006), in the similar study, found that the percentage of saving is slightly lower for an open plan office space and amounts to around 33 per cent.

Roisin et al. (2008) evaluated the performance of different daylight control systems for three locations in Europe and the four main orientations. The parametric study showed that the potential saving could vary from 45 per cent to 61 per cent. The former value was obtained for the north-facing office room in Stockholm, while latter was calculated for the south-oriented office room in Athens. Bodart and De Herde (2002) analysed the impact of daylight energy savings on the total energy consumption in office buildings by varying façade configuration, orientation and internal walls reflection coefficients. They found that daylight control could reduce the total primary energy consumption (energy for heating, cooling, humidification, dehumidification and artificial lighting) for around 40 per cent for a typical office building and up to 50 per cent for a building with high performance glazing. At the same time, the artificial lighting electricity savings were between 50 per cent and 80 per cent. Similar level of reductions was reported by Knight (1999) who measured between 44 per cent and 76 per cent of daylight-linked savings depending on the type of a daylight control. Lee and Selkowitz (2006) also reported significant savings in artificial lighting electricity consumption, up to 60 per cent, based on nine-month monitored field study of the New York Times Headquarters.

2.8. Conclusion

The research reviewed in this chapter shows that there is a body of knowledge on features of office designs needed to minimize the energy and carbon footprint of office buildings. This has informed the design of the current generation of new-build offices. The next chapter considers the environmental impact of the building fabric by reviewing studies which aimed at the impact of building materials and components combinations. It reviews life-cycle assessment studies of residential and non-residential buildings including offices, and reviews and try to address and highlight gaps in the literature to justify the objectives of this research.

Chapter 3 - Life Cycle Assessment of Buildings

3.1. Introduction

This chapter presents a review of literature that relates to the research objectives introduced in Chapter 2. This review starts by examining literature that addressed life-cycle studies of offices and goes on to discuss literature that investigated the carbon emissions and other environmental impact of building materials and components, as this is a key to the future design process for delivering low impact office buildings. The review includes: detailed explanation of life-cycle assessment; Materials and component combination LCAs; residential buildings LCAs; and office building LCA literature. The aim of this review is to identify gaps in current knowledge and highlight the objectives that could usefully and feasibly be met by this research.

3.2. What is Life Cycle Assessment?

There are many methods available for assessing the environmental impacts of materials and components within the building sector. While adequate to an extent for a particular purpose, they have disadvantages mainly, incompleteness, and lack of details. Life Cycle Assessment (LCA) is one of various environmental management tools (Eco-labelling, Environmental Performance Method, Folksam Environmental Guide, Environmental Declaration Sheets for Building Products, and The Natural Step) currently available for justifying environmental concerns (Jonsson, 2000). LCA is a methodology for evaluating the environmental loads of processes and products during their whole life-cycle (Sonnemann et al., 2003). The assessment includes the entire life-cycle of a product, process, or system encompassing the extraction and processing of raw materials; manufacturing, transportation and distribution; use, reuse, maintenance, recycling and final disposal (Consoli et al., 1993). LCA has become a widely used methodology, because of its integrated way of treating the framework, impact assessment and data quality (Klöpffer, 2006).

LCA is defined in (ISO, 2006b) as:

"A technique for assessing the environmental aspects and potential impacts associated with a product, by:

- Compiling an inventory of relevant inputs and outputs of a product system;
- Evaluating the potential environmental impacts associated with those inputs and outputs;
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

A research study by Curran (1996) stated that LCA is the most suitable method for a holistic assessment; it is a systematic approach to life-cycle. Employed to its full, life cycle assessment examines environmental inputs and outputs related to a product or service life cycle from cradle to grave, i.e. from raw material extraction, through manufacture, the usage phase, reprocessing where needed to final disposal. The LCA methodology is based on ISO 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the life-cycle inventory, assessing the impact and finally interpreting the results (ISO, 2006b).

LCA is often employed as an analytical decision support tool (Fava et al., 1993). Historically it has found popular use comparing established ways of making and processing materials, for example comparing recycling with incineration as a waste management option (Selmes, 2005). Therefore LCA is increasingly being seen as a tool for the delivery of more eco-efficient life cycles.

3.3. History of Life Cycle Assessment

The usage of life-cycle assessment has started in the 1960s as an environmental management tool in different ways and under a variety of names, and the current name of this tool is life-cycle assessment (Selmes, 2005). There is a confusing similarity between some of the terms that reflect different depths and type of study like (life-cycle cost analysis, eco-balance, etc.), and this is especially when reading the literature of the early l990s. The term life-cycle assessment has since been adopted to reflect environmental life cycle studies.

It has been suggested that the origin of life cycle thinking can be attributed to the US defence industry (LaGrega et al., 1994). It has been used to consider the operational and maintenance costs of systems. This has become a costing technique known as ‘Life Cycle Accounting’ or ‘Life Cycle Costing’. The first appearance of life-cycle assessment in its current environmental understanding was in a study held by Coca-Cola, to quantify the environmental effects of packaging from cradle to grave (Hunt and Franklin, 1996). The emphasis at that time was primarily on solid waste reduction, rather than environmental emissions or energy use.

The UK’s first experience of the life cycle perspective was published as a handbook of industrial energy analysis, which provided a methodology for energy analysis from a life cycle perspective (Boustead and Hancock, 1979). During that era many life-cycle studies had appeared followed by significant increase of public interest in the subject (Hunt and Franklin, 1996).

The Society of Environmental Toxicology and Chemistry (SETAC) held two LCA workshops during 1992. The first was on life-cycle impact assessment (Fava et al., 1993) and the second concentrated on data quality. The North American and European SETAC LCA advisory groups met in Portugal 1993, and produced Guidelines for Life-cycle Assessment: A ‘Code of Practice’ (Consoli et al., 1993), sometimes referred to as the ‘LCA Bible” (Jensen, 1996). Apart from

SETAC work, some LCA guidelines which appeared during the 1990s include the publication of the Dutch guidelines on LCA (Heijungs et al., 1992). Authors from Sweden, Finland, Denmark and Norway published Nordic Guidelines on Life-cycle Assessment (Lindfors and Ministers, 1995). The UN Environment Program published the “Life-cycle Assessment: What Is and How to Do it”, and “The European Environment Agency’s Life-cycle Assessment: A Guide to Approaches, Experiences and Information Sources” (Selmes, 2005).

There were many initiatives to standardize the methodology of life-cycle assessment; the Canadian Standards Association released the world’s first national LCA guideline Z-760 Environmental Life-cycle Assessment in 1994, to provide in-depth information on LCA methodology (Bardy and Paynter, 1995). But the most recognized standards were the ones published by the (ISO, 2009).

- ISO 14040 Environmental management, LCA, Principles and framework (1997).
- ISO 14041 Environmental management, LCA, Goal definition and inventory analysis (1998).
- ISO 14042 Environmental management, LCA, Life-cycle impact assessment (2000).
- ISO 14043 Environmental management, LCA, Life-cycle interpretation (2000).

3.4. Life Cycle Assessment Methodology:

ISO 14040 defined four main phases of life-cycle assessment study, each affecting the other phases in some way, see Figure 12.

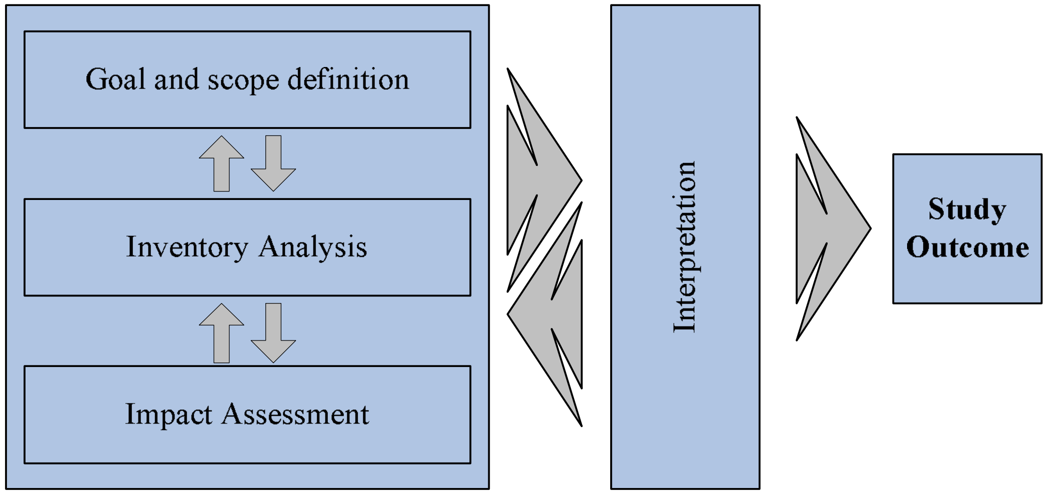

Figure 12 – Life-cycle assessment framework (ISO, 2006d)

When LCA is applied to a building, the product studied is the building itself, and the assessment will be defined according to a certain level and contain all the materials processes. This level could be called "whole process of building" (WPC) and there are many tools available to work at this level e.g. BREEAM, (Suzuki and Oka, 1998). If the LCA is concerned with a part of the building, building component or material, the level could be called "building material and component combination" (BMCC), and in this case it is very important to recognize the component impact equivalent according to the functional unit of the building or component.

LCA should be part of the design process as a decision making support tool, to be used by the designers of the building in parallel with other criteria like cost, and functional requirements. The architect/designer has to balance these three criteria to achieve the optimum performance of the building. Brainstorming during LCA in the early stages of the design will help find alternatives to the current proposals which better achieve this balance. It is necessary to consider the functions of the studied construction itself, as the environmental impacts of civil constructions are different from those of buildings, which are dominated by energy consumption.

It has been estimated that the use phase in conventional buildings represents approximately 80 per cent to 90 per cent of the life-cycle energy use, while 10 per cent to 20 per cent is consumed by the material extraction and production and less than 1 per cent through end-of-life treatments (Sartori and Hestnes, 2007). By the development of energy-efficient buildings and the use of less-polluting energy sources, the contribution of the material production and end-of-life phases is expected to increase in the future.

Lastly it is important to note that the building's location and orientation will have considerable impacts on its energy consumption, and therefore on the overall environmental impacts, even if the same BMCCs and construction techniques were used. For example, the benefits from the use of passive solar energy or natural ventilation will need to be incorporated in the assessment.

3.4.1. Goal and Scope Definition:

The first step of life-cycle assessment, this is a critical step to identify the purpose of the study, and determine the questions to be answered. It can affect the results of the LCA (Selmes, 2005). Within this step the study holder forms the objectives, limitations and constraints of the study, and sets many important assumptions: mainly identifications of system boundaries, such as the full life time of a product or one phase of production; functional unit e. g. m^2 floor area; data quality; and other limits. These should all be specified at this stage.

The goal definition and scoping exercise ultimately defines the direction of the study and the benchmarks, with which the study will later be appraised in the interpretation stage. Within the life-cycle of any product there might be some areas of limited interest, these could be omitted within this phase, but even describing the elements of whole life-cycle in general fashion will prevent missed opportunities for improvement (Selmes, 2005).

The goal and scope of a study may change according to many considerations within the study e.g. data unavailability, impact insignificance, etc. According to ISO 14040, the goal of any LCA states the intended application, the reasons for carrying out the study and the intended audience. This includes the product system to be studied, its functions, the functional unit, the system boundaries, allocation procedures, impact categories selected, methodologies of impact assessment, data requirements, assumptions, limitations, initial data quality requirements, and the type of critical review and report required for the study (ISO, 2006b). The functional unit determination in this phase is critical as it is a reference to which all the inputs and outputs are related, and in the case of buildings there are many functional units which could be considered (m^2, m^3, number of occupants, etc.).

The general goal of holding an LCA on the level of buildings is to minimize the environmental burdens over the whole life-cycle (Fava et al., 1993). Whether designer or researcher, the life-cycle practitioner will have direct effect on the type of audience. In the case of designers the audience may be clients, but in the case of researchers the audience may be policy-makers, developers and investors. Buildings are always described as complex products, complexity which lays in the process of production. Due to the complexity of the construction industry and the long life span of buildings, and because the scenarios within a building life span are not very clear, all subsequent phases of LCA will affect and modifies the goal and scope definition phase in some way, so it will need review and modification within and after each phase.

LCA studies in the literature differ in terms of their goal and scope definition, and it is sometimes clear that their goals have changed according to unexpected problems raised during the LCA studies. Scheuer et al. employed an LCA to find the environmental burdens of a university building in Michigan (Scheuer et al., 2003). They set the study boundaries to include only the building itself (structure, envelope, interior and backfill), and set the life span to 75 years, which is very long compared to most other studies, which assume 50 years. The study neglected the insignificant contributions, e. g. impacts from facilities used for production, and omitted the factors which are not related to building design, e. g. furniture, movable partitions, street and side walk modifications, etc. Lack of data had its influence on the scope of the study due to data unavailability; the study holder was forced to omit materials used during the construction process, and small replacement materials. For this case the materials omitted did not affect the results significantly, but in other cases, unavailability of national and realistic data might drive the study in the wrong direction, or change its goal and scope (Scheuer et al., 2003).

Junnila and Harvath (2003) assumed the study boundaries to be from raw materials acquisition through production and use to disposal. The main purpose of the study was to find the environmental impacts of a specific well described high-end office building in Finland, and used a national up-to-date manufacturer's data, verified by an independent third party. Lack of data affected the study, forcing the omission of heavy metal emissions from transportation and use of construction equipment. The life span was assumed to be 50 years as in many other LCA studies applied to buildings. The study was limited to calculating the impact categories identified as most important in Finland, but again lack of data had its influence on the study forcing omission of ozone depletion and biodiversity, although they were mentioned as most important within the Finnish impact categories list (Junnila and Harvath, 2003).

Within the goal and scope definition phase, Asif et al. addressed eight different materials (timber, glass, concrete, aluminium, ceramic tiles, plaster board, slate and damp course), which they considered as significant in the studied Scottish house (Asif et al., 2007). The study identified five main materials, which are most important in terms of their embodied energy. The studied house had a specified description and layout, and the study allocated the embodied energy distribution according to the studied materials, and calculated one impact category - global warming potential (Asif et al., 2007).

In many other examples of LCA studies presented later, it is clear that one of the main reasons hindering comparison is differences in goal and scope definition. Within the goal and scope definition, a well-established description of the case study building is necessary. The description should include as much detail as possible starting with the function and the geographical location of the building, and passing through other technical features. The system boundaries should be clearly set, whether the study will consider the whole building life-cycle, or one phase of it; the whole building, or one system; and the environmental impact categories to be studied should be determined. Within this step, the LCA practitioner should also consider the functional unit, methodologies of impact assessment, data requirements, assumptions, limitations, initial data quality requirements, type of critical review and type of the report required for the study (ISO, 2006b).

In the case of whole building LCAs, the functional unit could be one of many (m^2, m^2 internal space, m^3, each, number of occupants, etc.). The ease of comparing the outcome of the study to other studies is a very important factor in determining the functional unit (Weidema et al., 2004). There have been many attempts to standardize the functional unit for buildings e. g. (Consoli et al., 1993), but there are no results available yet. Within the literature the most commonly used functional unit in life-cycle assessment of buildings is square meter floor area, however in specific cases this unit had been changed, for instance some studies considered the square meter of living floor area in the case of dwellings, some others used the tonne of material as the unit when the study is related to a material environmental burden. It is important to note that all the environmental impacts calculated within one LCA study must refer to the chosen functional unit.

3.4.2. Inventory and Inventory Analysis:

The second step of the LCA is inventory analysis. It contains the “data collection and calculation procedures” (ISO, 2006b), and is of key importance since this data will be the basis for the study. This step is the most time intensive phase of life cycle assessment especially in the case of buildings as complex products (the production process is complicated), the data collection includes all data related to input-output of energy, and mass flow in terms of quantities and emissions to air, water and land (Ortiz et al., 2009).

Inventory is also tied to the scoping exercise since data collection and other issues may lead to refinement or redefinition of the system boundaries. Lack of data may result in changing the scope and/or objectives of the study, so data completeness is very important. ISO defines several levels in the inventory phase starting by data collection from available high quality resources; passing through data calculation, which involves validation of data collected, relating data to unit processes and relating calculated data to functional unit, down to allocation procedures when dealing with systems involving multiple products and recycling systems. The wider the system boundaries, the less the need for allocation, and in some cases there is no need for allocation, especially when there are no multiple products, and when the system boundaries are very wide (e. g. from cradle to grave) (Selmes, 2005). Choosing the most appropriate data is critical as the quality of data sources is very important to assure the correctness of the results, and in some cases the data will drive the study and determine its quality level or even its success or failure. Data nationality is an important factor to be considered when choosing the data sources, see Table 3.

The quality of a life-cycle assessment is directly related to the quality of inventory data, its correctness and its concordance with the goal of the study. The source of data might be one or more of direct measurements, laboratory measurements, governmental and industrial documents, trade reports and databases, national databases, environmental inventories, consultancies, academic sources, and engineering judgments (EPA, 2006). The source of data plays a role in its reliability, accompanied by acquisition methods and verification procedures used.

Another important factor to be considered is the completeness of data, which relates to its statistical properties, and shows how representative the sample is, and whether the sample includes a sufficient amount of data. Three other indicators relate to the correlation between the data and the data quality goals, namely temporal correlation, geographical correlation, and technological correlation (Weidema et al., 2004). Data quality indicators should be used to improve the data collection strategy, allowing the study holder to highlight the main data problems in the study, and help overcome data problems. Table 3 gives criteria for assessing the quality of data for LCA.

Indicator score	**1 Excellent**	**2**	**3**	**4**	**5 Unreliable**
Reliability	Verified data based on measurement	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years different from year of study	Less than six years different	Less than 10 years different	Less than 15 years different	Age of data unknown or more than 15 years different from year of study
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table 3 - Data quality assessment matrix (Weidema et al., 2004)

The data collection includes all data related to input-output of energy, and mass flow in terms of quantities and emissions to air, water and land (Ortiz et al., 2009). The life-cycle of a building consists of many phases. The number of phases differs according to the goal of the study, and it could be three or more, but the sum of the proposed phases must result in the whole life-cycle of the building in all cases. For example, some studies use three phases starting by the pre-construction phase, which includes all the processes from materials extraction up to the start of building occupation, followed by usage phase, and ending with demolition phase, but each of these phases could be divided into many sub-phases according to the goal and scope of the study.

The life-cycle inventory phase (LCI) generally uses databases of building materials and component combinations. The availability and accuracy of data should always be clearly described within the goal and scope definition phase. This concerns the materials, components, and scenarios already finished, but building construction includes past, current and future activities and scenarios. All of them, and any assumptions related to them should be clearly mentioned (Fava et al., 1993).

What is generally included within an LCA of buildings is the embodied energy of materials and building component combinations, the transport of materials and building components to site, the use of the building (as energy use), the waste of materials (sometimes), water consumption (sometimes), maintenance and replacement, demolition of the building, and transport of waste to the treatment site. What is generally not included is the transport of equipment to site, the construction phase at the site of the building, and construction waste (Kotaji et al., 2003). The goal of the study is the main driver to determine what is and what is not included, and data availability has a direct effect on this as well, and it consequently can change the goal of the study. Whether included or not, any process or item within the life-cycle assessment must be set clearly in the scope of the study, because any process included in the life-cycle of a building requires data to be included in the data inventory, whether collected, measured or estimated. The data should quantify the input and output of the building, and should be described well and thoroughly referenced.

Life-cycle inventories, until recently, were incomplete and many problems hindered the production of an internationally accepted protocol to be used in

LCA analyses. Currently available databases fit four categories: Public database developments, academic, commercial, and industrial (Menzies et al., 2007). It is most important to be aware that these data differ from one source to another in many ways: mainly boundary definitions, energy supply assumptions, energy source assumptions, product specifications, manufacturing differences, and complications in economic activities (Menzies et al., 2007). For example, Sinclair (1986) found a variation in the embodied energy of a brick of between 5 and 50 MJ. Geographical factors have the greatest effect, and underlie most of the variations mentioned earlier in this paragraph; accordingly it is important for each country to have its own data according to its construction industry resources and traditions. LCI involves collecting data for each unit process regarding all relevant inputs and outputs of energy and mass flow, as well as data on emissions to air, water and land. It includes calculating both the material and the energy input and output of a building system. The limitations associated with LCI have a subsequent impact on the reliability of the overall LCA findings. A higher level of completeness and reliability in LCI is needed to permit a more accurate and precise assessment of life-cycle environmental loadings from the manufacture of a particular product.

There are many methods to calculate the LCI across a range of disciplines, but many obstacles are still unresolved. A lack of transparency between data centres (data or data origins and references are not accessible) makes it difficult to compare the results. There are some national and international databases that might be accepted in some cases, but in detailed local studies these databases should not be used as the international ones differ, and the national ones generally discuss the simple basic construction materials (Menzies et al., 2007). However, these could be identified as a background source of data. National inventory data depends on information and processes of local production scenarios rather than considering the possibility of using international materials and counting the transportation of such materials as an important factor which increase the results significantly. Within United Kingdom construction industry, it is common that high percentage of building materials and components are imported from other countries. Locality of data should be used only when components are produced locally, and Data of the country of origin should be used and transportation impact should be added.

Researchers suggest that three approaches could be used to overcome data problems, namely process analysis, input/output analysis and hybrid analysis. The traditional method is process analysis, involving analysis of direct and indirect energy inputs to each product process. It usually begins with the final product and works backwards to the point of raw material extraction. In many cases the process of production might be difficult to understand, and problems will arise in the calculation phase, because of this lack of understanding. So this method is impracticable on its own (Trusty, 2004). Process analysis results are found to be considerably lower than the findings of other methodologies (Lenzen and Treloar, 2002). Input/output analysis can overcome the problems of process analysis. It is based on input/output tables, where the inputs may include energy and natural resources, and the outputs may include CO_2 and other gases emissions. Both methods are widely used, but each of them has its own advantages and disadvantages. Process analysis can be significantly incomplete, due to the complexity of the requirements for goods and services (Lave et al., 1995). While the accuracy of process analysis method can be higher, it is only relevant to the particular system considered, and can be subject to considerable variability (Crawford, 2008).

Input/output analysis uses national average data of each sector of the economy, and is considered to be more comprehensive than process analysis (Lave et al., 1995). It has a complete system boundary, but is generally used as a black box, with little understanding of the values being assumed in the model for each process. This method could give valuable estimates of the embodied energy but it is not as accurate as process analysis. Hybrid analysis is a combination of both methods and results in better quality data inventories. It minimizes the limitations of the other methods, and there are several types of hybrid analysis:-input/output based hybrid analysis, process based hybrid analysis, tiered hybrid method and integrated hybrid analysis. Each works in a different way to deal with the deficiencies of traditional methods (the incompleteness of process analysis, and the low level of accuracy in the case of input/output analysis).

Database	**Country**	**Function**	**Type**	**Level**	**Software**	**Website**
Athena	Canada	Database + Tool	Academic	whole building design decision	Eco Calculator	www.athenaSMI.ca
Bath data	UK	Database	Academic	product comparison	No	people.bath.ac.uk/cj219/
BEE	Finland	Tool	Academic	whole building design decision	BEE 1.0	--------------------------
BEES	USA	Tool	Commercial	whole building design decision	BEES	www.bfrl.nist.gov/oae/software/bees.html
BRE [1]	UK	Database + Tool	Public	whole building assessment	No	www.bre.co.uk
Boustead	UK	Database + Tool	Academic	product comparison	Yes	www.boustead-consulting.co.uk
DBRI[2] Database	Denmark	Database	Public		No	www.en.sbi.dk
Ecoinvent	SL	Database	Commercial	product comparison	No	www.pre.nl/ecoinvent
ECO-it	NL	Tool	Commercial	whole building design decision	ECO-it	www.pre.nl
ECO methods	France	Tool	Commercial	whole building design decision	Under develop	www.ecomethods.com
Eco-Quantum	NL	Tool	Academic	whole building design decision	Eco-Quantum	www.ecoquantum.nl
Envest	UK	Tool	Commercial	whole building design decision	Envest	envestv2.bre.co.uk
Gabi	Germany	Database + Tool	Commercial	product comparison	Gabi 4	www.gabi-software.com

Table 4 - Databases and tools of LCA of WCP and BMCC (Continued next page)

[1] Building Research Establishment
[2] Danish Building Research Institute

Database	**Country**	**Function**	**Type**	**Level**	**Software**	**Website**
IO-database	Denmark	Database	Academic	product comparison	No	---------------------
IVAM	NL	Database	Commercial	product comparison	No	www.ivam.uva.nl
KCL-ECO	Finland	Tool	Commercial	product comparison	KCL-ECO 4.1	www.kcl.fi/eco
LCAiT	Sweden	Tool	Commercial	product comparison	LCAiT	www.ekologik.cit.chalmers.se
LISA	Australia	Tool	Public	whole building design decision	LISA	www.lisa.au.com
Optimize	Canada	Database + tool	---------	whole building design decision	Yes	----------------------
PEMS	UK	Tool	Public	product comparison	Web	----------------------
SEDA	Australia	Tool	Public	whole building assessment	SEDA	----------------------
Simapro	NL	Database + Tool	Commercial	product comparison	Simapro 7	www.pre.nl
Spin	Sweden	Database	Public	product Comparison	No	http://195.215.251.229/Dotnetnuke/
TEAM	France	Database + Tool	Commercial	product comparison	TEAM 3.0	www.ecobilan.com
Umberto	Germany	Database + Tool	Commercial	product comparison	Umberto	www.umberto.de
US LCI data	USA	Database	Public	product comparison	No	www.nrel.gov/lci

Continued **Table 4** - Databases and tools of LCA of WCP and BMCC

Some of the datasets listed in Table 4 are complete, or there are extensive efforts of people working on completing them. Due to the wide range of materials in the construction industry, and the variety of construction techniques, none of these tools and data sets are able to model or compute the environmental impacts of a whole building or construction, including all the life-cycle phases and production processes in detail (Scheuer et al., 2003).

The databases and tools listed vary according to study goal, users, application, data, and geographical location (Ortiz et al., 2009). Databases differ from one country or region to another according to many factors, including energy sources, supply assumptions, product specifications, manufacturing differences and complications in the economic activities (Menzies et al., 2007). Each of these factors can produce significant variations in the environmental impact assessment, for instance, (whether delivered or end use) energy supply assumptions can cause significant differences in the embodied energy calculations, as different countries have different energy sources. For example, France depends strongly on nuclear power, while the UK depends more on gas and electricity, and this fundamental difference in the energy sources affects the environmental impacts of production.

The key steps to produce a life-cycle inventory are to: develop a flow diagram of the process being evaluated, develop a data collection plan, collect the data, and evaluate and report the results. The diagram of the process should be as detailed as possible to get a high level of accuracy, which means spending more time to get this level of detail in this step, which is already time and effort intensive. Of course the more detailed the diagram is, the more accurate the results are. Figure 13 is an example of a process flow diagram, and Figure 14 gives a medium level of detail.

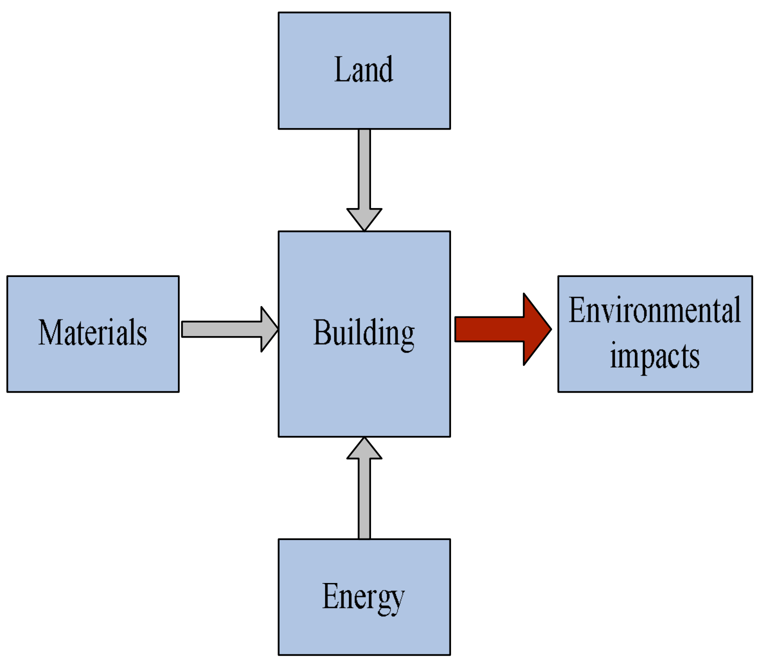

Figure 13 - A very simple flow diagram of building.

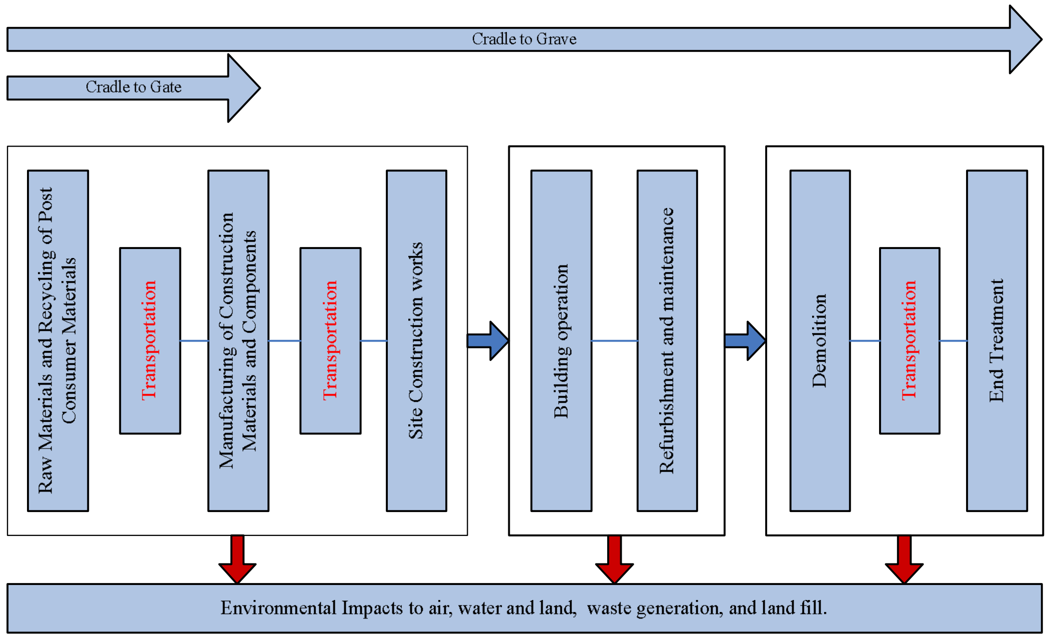

Figure 14 - Medium detailed flow diagram of a building/construction

After drawing the detailed production diagram, the next step will be setting a data collection policy, and it will be useful to start by dividing the flow into sub flows, to be able to understand the inputs and outputs of each sub phase of the process. Defining data quality goals and setting benchmarks will take place before data collection, to test whether the data meets the goal requirements. Data sources and types should be explained well within this step, and then at the end of this step data spread sheets should be produced (EPA, 2006). After that, the data collection step will start followed by evaluation and validation of data, according to the benchmarks already set (ISO, 2006d). The next step will be relating data to the functional unit of the building, which is different from the functional unit of BMCCs. For example, the functional unit of the concrete might be a ton of material, while the functional unit of the building might be m^2 of floor area, so to relate the quantity of concrete used within the building to the functional unit used the sum of concrete used is divided by the area of the building, see Figure 15.

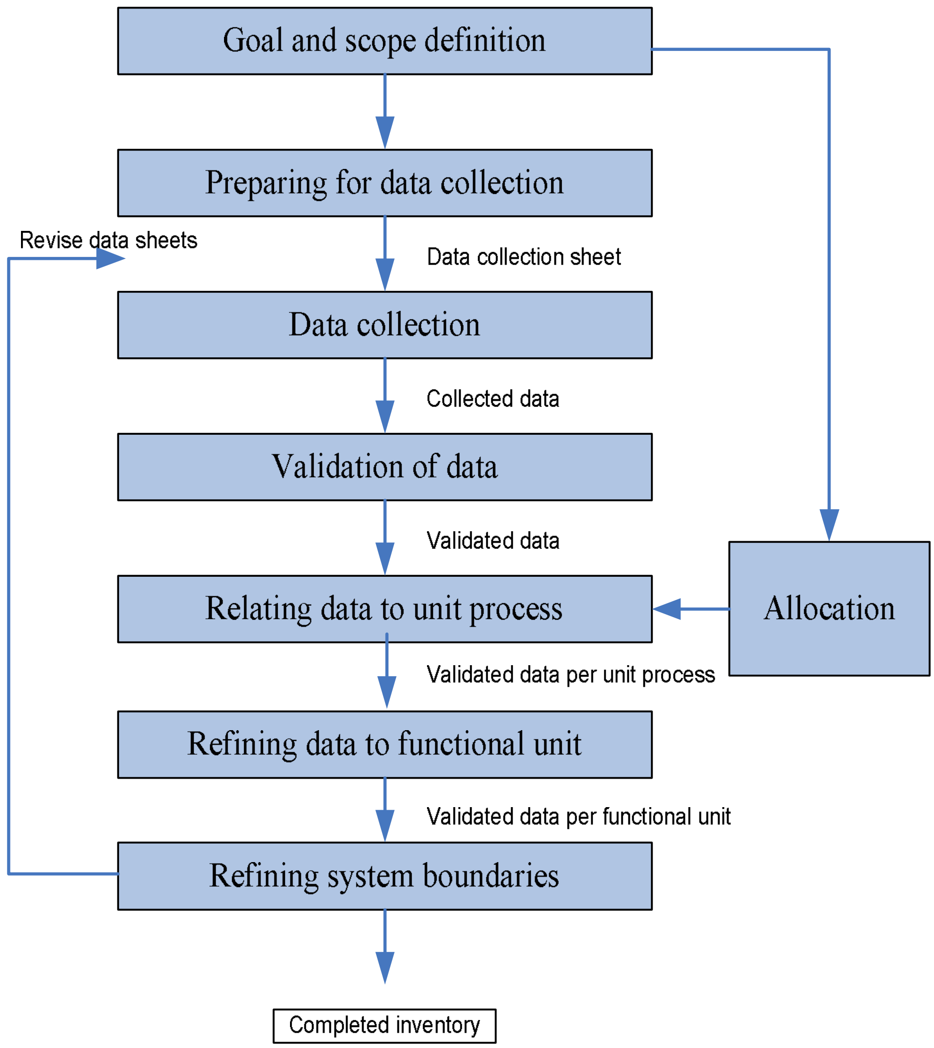

Figure 15 - Simplified procedures for inventory analysis (ISO, 2006d).

In the case of studying the whole life-cycle of a building using process analysis, there is no need for allocation procedures, which means distributing the impacts and relating them to the unit process.

The allocation procedures are dependent on and directly related to the goal of the study. For example, if the goal of the study is to compare building systems in terms of their environmental impacts, the allocation procedures will be different from comparing the impacts of construction phases. The last step in the data inventory analysis is refining the system boundaries. This step includes verification of data collected using benchmarks, so the initial system boundaries may be revised, and then the results of the refining process and the sensitivity analysis shall be documented. Sensitivity analysis may result in exclusion of life-cycle stages or unit processes shown to have no significance, exclusion of inputs and outputs which are not significant to the results of the study, or inclusion of new unit processes inputs and outputs that are shown to be significant in the sensitivity analysis (ISO, 2006d).

3.4.3. Impact Assessment:

ISO 14042 is the international standard for life-cycle impact assessment (LCIA); it defines the impact assessment as aiming to: "Examine the product system from an environmental point of view using impact categories and category indicators connected with the LCI results. The LCIA also provides information for the life-cycle interpretation phase (ISO, 2006c)."

The impact assessment framework is a multi-step process, starting by selecting and defining impact categories, which are relevant to the buildings [such as, global warming, acidification, toxicity, etc., as listed in Table 5 which is an extended version of the table of published LCAs applied within the building sector in Europe & USA within the last 15 years, produced by (Ortiz et al.) in 2007. This is followed by a classification step, which assigns LCI results to the impact categories, e.g. classifying carbon dioxide emissions as causing global warming, and modelling the impacts within impact categories using conversion factors, e. g. modelling the potential impact of carbon dioxide and methane on global warming using their respective GHG potentials (ISO, 2006d).

These steps could be followed by optional steps to express potential impacts in ways that can be compared. For instance, this applies when comparing the global warming impact of carbon dioxide and methane for two options, weighting them and identifying the most significant ones. At the end of the study all the results should be evaluated and reported (EPA, 2006). Impact categories could be grouped according to their region of effect, e.g. global warming has a global effect, whereas eutrophication has a local effect (ISO, 2006d).

The functions of the studied construction must be considered, as the environmental impacts of civil constructions, e. g. dykes, are different from those of dwellings or offices which are dominated by energy consumption. The impact categories included within the LCA studies carried out by researchers of building environmental impacts differ according to the goal of the study, data availability, and significance of the impacts. For instance, among the researchers who produced whole construction process LCAs, Adalberth (1997) studied four dwellings located in Sweden and calculated five different impacts (GW, A, E, OD, HT, EL-Table 5), however Peuportier (2001) studied three types of houses with different specifications located in France, and calculated twelve different impact categories.

Again among other researchers who produced LCAs of BMCCs, Asif et al. (2007) studied eight different building materials in a Scottish dwelling, and calculated one impact (GW), but Ortiz et al. (2009) studied green roofs in Spain and calculated eight different impacts. Within the literature of LCAs applied to whole buildings, the most commonly studied impacts were global warming, acidification, eutrophication, and ozone depletion, which were present in most studies, see Table 5.

Reference	BMCC	WPC	Content, country and year	Environmental impacts studied													
				En	**GW**	**A**	**E**	**OD**	**HT**	**EL**	**WC**	**DA**	**W**	**EC**	**RS**	**AR**	**O**
Adalberth et al		x	Life-cycle of four dwellings located in Sweden (2001)	x	x	x	x	x	x	x							
Ardente et al	x		LCA of a solar thermal collector, Italy (2005)	x							x		x		x	X	
Asif et al	x		LCA for eight different materials for a dwelling in Scotland (2005)	x	x												
Citherlet et al	x		LCA of a window and advanced glazing systems in Europe (2000)	x	x	x		x									x
Cole and Kernan		x	LCA of a three-storey, office building for alternative structure materials in Canada.	x													
Gustavsson and Sathre	x		LCA Sweden case study: wood and concrete in building materials (2006)	x													x
Junnila		x	LCA for a construction of an office: a Finland case study (2004)	x	x	x	x						x				
Junnila and Horvath		x	LCA of a high end office building in Finland (2003).	x	x	x	x						x				
Junnila et al.		x	Comparative LCA of office buildings in Europe and the United States (2006)	x	x	x	x										
Koroneos and Dompros	x		LCA of brick production in Greece (2006)	x	x	x	x			x							x
Koroneos and Kottas		x	LCA for energy consumption in the use phase for a house in Greece (2007)	x	x	x	x						x				x
Morel et al.	x		Comparison of energy embodied in local construction materials with imported ones, France (2000)	x													
Nebel et al	x		LCA for floor covering, Germany (2006)	x	x	x	x	x									x
Nicoletti et al	x		LCA of flooring materials (ceramic versus marble tiles), Italy (2002)	x	x	x		x	x			x					x
Nyman and Simonson	x		LCA of residential ventilation units over a 50 year life-cycle in Finland (2005)	x	x	x		x				x				x	

Table 5 - LCAs applied within the building sector in Europe & USA (continued on next page)

Reference	**BMCC**	**WPC**	Content, country and year	Environmental impacts studied													
				En	**GW**	**A**	**E**	**OD**	**HT**	**EL**	**WC**	**DA**	**W**	**EC**	**RS**	**AR**	**O**
Peuportier		x	Comparison of three types of houses with different specifications in France (2001)	x	x	x	x	x	x	x	x	x	x	x	x	x	
Petersen and Solberg	x		LCA by comparing wood and alternative materials in Norway and Sweden (2005)	x		x	x	x	x								
Prek	x		LCA of heating and air conditioning systems. Dwelling in Slovenia (2004)	x	x			x									
Saiz et al	x		LCA for green roofs located in downtown Madrid, Spain (2006)	x	x	x	x	x	x		x		x				x
Scheuer et al		x	LCA to a new University building in the USA (2003)	x	x	x		x		x			x				x
Seppala et al	x		LCA for Finnish metal products (2002)	x			x		x	x	x		x				x
Thormark		x	LCA of residential houses in Sweden (2001)	x													
Van der Lugt et al	x		LCA for using bamboo as building material in Western Europe (2006)	x													x
Wilson and Young	x		Embodied energy payback period of photovoltaic installations in the UK (1995)	x													
Yohanis and Norton		x	LCA of open-plan office building in the UK (1999)	x													

Continued **Table 5** - LCAs applied within the building sector in Europe & USA

Abbreviations: WPC, whole process of construction; BMCC, building materials and components combinations. Impact categories: En, energy consumption; GW, global warming potential; OD, photochemical ozone creation; WC, water consumption; DA, depletion of a biotic resource; A, acidification; HT, human toxicity; W, waste creation; EC, eco-toxicity; E, eutrophication; EL, energy consumption; RS, resources consumption; O, others; AR, air emissions.

The databases and tools presented vary according to study goal, users, application, data, and geographical location. According to Menzies et al. (2007), databases differ from country or region to another according to many factors including energy sources and supply assumptions, product specifications, manufacturing differences and complications in the economic activities. Each one of these factors can produce significant variations in the environmental impacts assessment, for instance, (whether delivered or end use) energy supply assumption can cause significant differences in the embodied energy calculations, as different countries have different energy sources, for example France depends more on the nuclear power, however the UK depends more on gas and electricity, this on its own is a fundamental difference in the energy sources, which consequently affects the environmental impact of production.

Impact category	Abbreviation	Scale	LCI data i.e. classification	Characterization factor
Global warming	GW	Global	Carbon Dioxide CO_2 Nitrogen Dioxide (NO_2) Methane (CH_4) Chlorofluorocarbons (CFC_S) 'Hydro chlorofluorocarbons' ($HCFC_S$) Methyl Bromide (CH_3B_r)	Global warming potential
Acidification	A	Regional Local	Sulphur Oxides (SO_X) Nitrogen Oxides (NO_X) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH_4)	Acidification potential
Eutrophication	E	Local	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates, and Ammonia (NH_4)	Eutrophication potential
Ozone depletion	OD	Global	Chlorofluorocarbons (CFC_S) Hydro chlorofluorocarbons ($HCFC_S$) Halons, and Methyl Bromide (CH_3B_r)	Ozone depletion potential

Table 6 - Commonly used WPC impact categories

3.4.4. Interpretation:

The final phase of LCA is "Interpretation". The purpose of this is to: "Analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA or LCI study and to report the results of the life-cycle interpretation in a transparent manner. Life-cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA or an LCI study, in accordance with the goal and scope definition of the study (ISO, 2006b)."

3.5. LCA Studies for Buildings

3.5.1. Building Materials and Component Combinations (BMCC)

Nearly two thirds of the studies listed in Table 5 relate to materials and components. Materials are naturally found in impure form, e.g. in ores, and extraction or purification not only consumes energy but also produces waste (Asif et al., 2007). Detailed consideration of materials and components themselves is beyond the scope of this study. Many industrialized countries have made steps towards environmental improvement of the construction process, building occupation and demolition, and these steps differ to the extent that building construction is strongly determined by local traditions, local climate and locally available natural resources. As a result, many LCA studies calculating the environmental impacts of BMCC have been done during the last fifteen years.

In 2001 a study in India focused on embodied energy in load bearing masonry buildings. A brickwork building and a soil–cement block building were compared, and the study showed that the total embodied energy can be reduced by 50 per cent when energy efficient building materials are used (Venkatarama Reddy and Jagadish, 2001). Another study of flooring materials in Italy showed that marble tiles are more environmentally friendly than ceramic tiles (Nicoletti et al., 2002). In Finland, Seppala et al. (2002) produced a Life-cycle Inventory (LCI) of steel plate and coil, steel bar, steel wire, stainless steel, copper, nickel, zinc and aluminium, as part of the Finnish Environmental Cluster Research Programme 1998-2000.

Researchers have compared timber to other framing materials in buildings. Borjesson and Gustavsson (2000) compared CO_2 emissions from the construction of a multi-storey building with a timber or concrete frame, from a life-cycle and a forest land-use perspective. The primary energy input (mainly fossil fuels) in the production of materials was found to be about 60-80 per cent higher when concrete frames were considered instead of timber frames. Lenzen and Treloar (2002) analysed the timber and concrete designs of the same building in terms of its embodied energy using an input-output based hybrid framework instead of the process analysis which Borjesson used. Their estimates of energy requirements and greenhouse gas emissions were double. Gustavsson and Sathre (2006) studied the changes in energy and CO_2 balances caused by variation of key parameters in the manufacture and use of the materials in a timber- and a concrete-framed building. Considering various production scenarios, the materials of the timber-framed building had lower energy and CO_2 balances than those of the concrete-framed building in all cases but one. Xing et al. (2008) compared a steel-framed office building in China with a concrete-framed one. The life-cycle energy consumption of the building materials 'per area' in the steel-framed building is 24.9 per cent that of the concrete-framed building, whereas, in the usage phase, the energy consumption and emissions of steel-framed building are both larger than those of concrete-framed building. As a result, the energy consumption and environmental emissions achieved by the concrete-framed building over its whole life-cycle is lower than the steel-framed one.

Asif et al. (2007) calculated the CO_2 emissions of eight construction materials for a dwelling in Scotland: timber, concrete, glass, aluminium, slate, ceramic tiles, plasterboard, damp course and mortar. The study concluded that 61 per cent of the embodied energy used in the house was related to concrete. Timber and ceramic tiles comes next with 14 per cent and 15 per cent, respectively, of the total embodied energy. Concrete was responsible for 99 per cent of the total CO_2 emissions of the home construction, mainly due to its production process. Nebel et al. (2006) studied the environmental impact of wood floor coverings manufactured in Germany, and performed analyses to help the industry partners to improve their environmental performance and use the results for marketing purposes. The study did not aim to compare products, but to produce an LCI and find the environmental impacts of this industry. Wilson and Young (1996) calculated the embodied energy payback periods of photovoltaic installations applied to UK buildings in 1995, and found that "the energy used in their manufacture is more than they can save in their life-time." In the case of the UK buildings studied, the embodied energy payback period for photovoltaic modules was 8-12 years and this set an agenda for research to improve the reliability of this technology in the UK.

This selection of LCA studies confirms the difficulty of making comparisons, because there are differences in the final products studied and their impacts. The methods of calculating the embodied energy in BMCCs used were different - process analysis, input-output data calculation, and hybrid analysis. Nevertheless these studies are very important for advancing sustainable development, because of the embodied energy and environmental impacts they calculated, and the suggestions they made to reduce the environmental burdens of buildings, through manufacture, and transport of various materials. Another important point is that these studies could be considered as data inventories, or benchmarks when undertaking a whole building LCA. Conservation of energy becomes important in the context of limiting GHG emission into the atmosphere, and reducing costs of materials (Venkatarama Reddy and Jagadish, 2003), and the embodied energy payback period should always be one of the criteria used for comparing the viability renewable technologies (Wilson and Young, 1996).

To promote environmental impact reduction the European Commission released the integrated product policy (IPP) in 2003, which aimed to enhance the life-cycle of products. The life-cycle of most construction products is long and involves many complicated procedures and stake holders (e.g. designer, manufacturer, assembly, construction, marketing, sellers, and final users). IPP is trying to improve the environmental performance of each phase of production by identifying products with high environmental impact reducing them through three stages: environmental impact products (EIPRO), environmental improvement products (IMPRO) and Policy Implications (EC, 2006c).

The first phase EIPRO of the IPP project identifies the products that have the greatest life-cycle environmental impact, and then assigns them to environmental impact categories. The second phase IMPRO identifies different methods or production scenarios to reduce the environmental impacts, considering technically feasible steps first followed by other socio-economic impacts. The third step is the implementation of the policy, and within this step there are two strategies used - environmental product declarations (EPD) and Eco-design. EPD is a strategy adopted for external communication, defined as "quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series of standards, but not excluding additional environmental information", committed to reducing the environmental impact of a product (EC, 2006b). One example of the EPDs is that of concrete roof tiles studied by Gambale, which is a company based in Italy certified to ISO 9001. The study calculated the environmental impacts of four types of concrete roof tiles per the functional unit, which in this case is tonne of product sold (production capacity – scrap capacity) (EC, 2006b). These EPDs are a source of data, but there are many risks in depending completely on them, especially when calculating environmental impacts of products from different countries. However, these EPDs could be used as background supportive data. Eco-design means considering the environmental burdens of the product at the earliest stage of product design. It is very important to enhance the environmental performance of the product because it can share in deciding the process and materials (EC, 2006a). Eco-design proposals include the environmental impact of the whole production-consumption chain (Sun et al., 2003).

Eco-design principles underpin the Green Guide to Specification (Anderson et al., 2009), which aims to guide designers and specifiers to make the best environmental choices when selecting materials and components. It gives environmental profiles of over 1200 common specifications for a range of building types. These profiles have been produced using data obtained with an LCA methodology that has not yet been published (Poirazis et. al, 2008), but is quoted as having "involved the widest possible consultation with … [a range of bodies] … [and] … the subject of more rigorous peer review procedures than its predecessors …" (Anderson et al., 2009). The LCA data sources were 28 product trade associations and manufacturers, supported by some of the databases listed in Table 4. However, in the interests of ease of use for practitioners the ratings are given as overall grades A+ to E and the build-up through the process is not shown. An overall grade gives insufficient information to allow producers to improve their manufacturing process, and the range of materials or components given could limit design innovation, since it is difficult to apply generic information to a specific situation with confidence.

Many researchers have been interested in studying the environmental benefits of using recycled, reused or recyclable, reusable materials in the building industry. A study by Erlandsson and Levin (2004) set a new method for reused materials, and confirmed that using reused materials is better for the environment than building with new, their case study data showing a reduction in environmental impact by up to 70 per cent. Selecting durable and renewable materials could also be an alternative for grouping materials, as well as recycling, reusing and recovering materials for optimum waste disposal (Sun et al., 2003).

The LCA calculations should assess all materials, particularly as some materials used in very small quantities have large environmental impacts, e. g. lead (Junnila and Harvath, 2003). A study comparing plastics to wood and concrete in Swedish dwellings found that although plastics were only 1-2 per cent by weight, their manufacturing energy was 18-23 per cent of the entire amount required for the three dwellings (Adalberth, 1997).

Researchers classified building materials in different ways. For example, Asif et al. (2007) categorized them into main families i.e. stone, concrete, metals, wood, plastics and ceramics. Junnila and Harvath (2003) classified them according to the Finnish national building classification system, and over 50 different materials were identified, while in another study by Junnila et al.(2006), there were 42 materials under the same Finnish building materials classification system. Sun et al. (2003) classified materials as glass and ceramics, ferrous metal, non-ferrous metal, paper, polymers or wood. All this confirms that building materials classification considerations differ according to national construction industry categorization or structure.

3.5.2. LCA for Dwellings (Whole Process Construction)

Four of the studies listed in Table 5 deal with dwellings. Adalberth (1997) studied the energy use during the life-cycle of three single-unit dwellings, built in Sweden in 1991 and 1992. The houses were prefabricated and timber framed. The study emphasized the importance of LCA to gain an insight into the energy use for a dwelling in Sweden. The functional unit was m^2 of usable floor area (i.e. gross area minus wall area), and the study assumed a 50 year life-span. The life-spans of different building components and materials were collected from the maintenance standard of the Organization for Municipal Housing Companies in Sweden to estimate how many times each would be replaced during the life of the dwelling. The study showed a difference between percentage energy and percentage by weight for materials (e.g. the concrete used was 75 per cent by weight of the whole, while the energy used to produce it is only 28 per cent of the production energy of the whole dwelling). Adalberth performed a sensitivity analysis on the building material data, energy use and electricity mix, which had been discovered to be of a greatest environmental burden and concluded that the greatest environmental impact (70-90 per cent) occurs during the use phase. Approximately 85 per cent and 15 per cent of energy consumption occurs during the occupation and manufacturing phases, respectively (Adalberth, 1997).

A study carried out in France as part of the EQUER project (evaluation of environmental quality of buildings) considered different phases of dwelling's life-cycle, using the functional unit of m^2 living area, with the sensitivity analyses based on alternative building materials, types of heating energy, and the transport distance of the timber. This study showed that the dwellings with greatest environmental impact were not those whose area is larger, and emphasized the importance of choosing materials with low environmental impact during the pre-construction phase (i.e. employing LCA as a decision making supporting tool during the design stage) (Peuportier, 2001).

The effect of including recycling potential within the life-cycle of low energy dwellings had been studied by Thormark (2002), for energy efficient apartment housing in Sweden. Over a 50 year life-span, embodied energy accounted for 45 per cent of the total energy requirement, and about 37-42 per cent of this embodied energy could be recovered through recycling. In a Japanese urban development case study, Jian et al. (2003) suggested that to reduce life-cycle CO_2 emissions timber dwellings were preferred to other materials, and that open spaces such as parks and green areas should be maximized to work as a breathing lung inside the development.

3.5.3. LCA for Offices (WPC)

Only six of the studies listed in Table 5 refer to offices. Some descriptive work on office buildings has been done, but there is limited research published on complete LCA of office buildings (Ortiz et al., 2009), although they are significant sources of energy use and emissions. There are no quantitative comprehensive studies which include all the phases of an office life-cycle (Junnila et al., 2006). Cole and Kernan (1996) suggest that a detailed focus on the embodied energy of every material or building component alone, without looking on their relative significance is insufficient. They examined the total life-cycle energy use of a three-storey generic office building, for alternative timber, steel, and concrete structural systems. The study considered the initial estimated embodied energy, maintenance embodied energy, operational energy and demolition, and again found predominance of energy consumption during the occupation phase, emphasizing the need to consider design alternatives to significantly reduce it. When that has been done, the significance of the embodied energy will increase and work should then emphasize alternative materials and processes to reduce the embodied energy. The embodied energy could reach 67 per cent of the operational energy over a 25-year period even when additional maintenance, refurbishment, or modification within the life-cycle of a building is also included (Cole and Kernan, 1996).

Yohanis and Norton (2000) calculated the life-cycle energy (operational and embodied) of a UK generic single-storey office building, using Early Design Model EDM, which is an integrated simplified energy model based on a proven well-established algorithm, and studied the energy effects on the capital costs. They found that there is a critical ratio of glazing which affects the balance between embodied and operational energy: embodied energy is higher below about 55 per cent glazing, but operational energy is higher above 55 per cent glazing. Heating costs decrease sharply with glazing ratio, reaching a minimum when glazing ratio is 15 per cent (Yohanis and Norton, 2002).

Scheuer et al. (2003) studied a new university building (75 years life-span, six storeys, and 7300 m^2 area, in USA). They identified 60 building materials and showed that the operational energy amounted to 97.7 per cent of the whole energy consumption, which can be explained by the long life-span. The energy of the demolition phase was only 0.2 per cent. The study translated the energy consumed in the life-cycle into environmental impacts - global warming 93.4 per cent, nitrification potential 89.5 per cent, acidification 89.5 per cent, ozone depletion potential 82.9 per cent, and soil categories waste generation 61.9 per cent. Data were taken from Simapro, Franklin Associates, DEAMTM, and the Swiss Agency for the Environment, Forests and Landscape. The study emphasized the need for data on unusual performance characteristics, or detailed evaluations of building features in the design stage, which they say is "impossible with current building data".

To find out the significant environmental impacts of a new office building over a 50-year life span in Finland, Junnila et al. (2006) carried out a comprehensive environmental LCA, including data quality assessment, establishing causal connections between the different life-cycle elements and potential environmental impacts. The operational energy of the building was responsible for most of the environmental burdens. The impact categories included acidification, climate change, eutrophication and dispersion of harmful substances (summer smog, heavy metals), but not ozone depletion and biodiversity loss due to lack of data. The results showed that the impacts of two life-cycle phases (operational and components manufacturing energy) seem to be significant. The study prioritized the life-cycle elements according to their environmental impacts as following; electricity use in lighting, HVAC, and power outlets; heat conduction through the structure; manufacture and maintenance of steel, concrete, and paint; water use and waste water generation; and office waste management (Junnila and Harvath, 2003). Within another study Junnila calculated the environmental impacts of another office building of approximately 24,000 m^2 gross floor area and a volume of 110,000 m^3. The study calculated the impacts of forty life-cycle elements and defined two hundred environmental aspects, and found that the most significant elements were again electricity used in power outlets, HVAC, lighting, but in this case also the internal surfaces in the maintenance phase. The impact categories studied were climate change, acidification, summer smog, eutrophication, and heavy metals. The study emphasized on the notion that a life-cycle assessment has to include all the building phases from cradle to grave, and insisted that studying some phases and neglecting others is not valid (Junnila, 2004).

A further step done by Junnila et al. (2006) compared a European office building with one from the United States. This comparison study assessed the two buildings throughout their full life-cycle, defining 42 different building materials in total. The comparison found that the ratios of emissions associated with different life-cycle phases to the whole emissions of each building in the two buildings cases are similar, while the Finnish building uses a third less energy and emits half the CO_2 emissions for the same functional unit. In the comparative study of concrete and steel office buildings by Xing et al. (2008), already mentioned, the life-cycle energy consumption of building materials per unit area is lower in the steel-framed building but the energy consumption and emissions are higher in the steel building. The life-cycle energy of the steel-framed office building was found to be 75.1 per cent that of concrete-framed one.

This work from the last 15 years is considered to be the most comprehensive as other researchers typically restricted their studies to the occupation phase, to improve the thermal comfort and reduce the energy use which accounts for a high percentage of the whole building life-cycle energy, especially if the building is not environmentally friendly, or if the assumed life-span is more than 50 years. However, there are indications that the average life-span of an office building is decreasing, with a trend in Europe to reconstruct or reconfigure office buildings constructed in the 1960s to meet the functional and aesthetic criteria of the new tenant (Junnila et al., 2006). Other researchers concentrated on only one or two environmental indicators because of lack of data, time limitations, and significance of aspect (Asif et al., 2007; Thormark, 2002).

The use of glass cladding systems has become a trend for architects designing office buildings, to create buildings which are airy, light and transparent with more access to daylight, but their energy efficiency is questionable. To optimize glass area, Poirazis et al. studied the impact of high percentage glazing in office buildings by calculating the building operational energy at 30, 60 and 100 per cent glazed area. The lower the glass ratio, the more the energy efficient the building is, but the most energy efficient 100 per cent glazed alternative results in only 15 per cent higher total energy use (Poirazis et al., 2008). The balance between environmental sustainability and occupant comfort concerning the design of windows for office buildings had been studied by (Menzies and Wherrett, 2005). The study examined four office buildings in the UK with double glazed windows of different specifications and U values, and calculated the energy needed to maintain each building at the same temperature during working hours. Occupant comfort was studied by holding a post-occupancy survey, showing that sustainable efficient windows can be more comfortable by joining the building and window designs together, but the final result showed no relationship between the window factor and the level of the environmental sustainability in the windows of the office buildings.

The Carbon Trust's Energy Consumption Guide (ECG19) categorizes offices into four main groups namely, naturally ventilated cellular, naturally ventilated open plan, air-conditioned standard and air-conditioned prestige, and is a reference or guide for office occupiers to know if their energy bills are reasonable. The study concentrates on the occupation phase of the office buildings, and explains 'how and where' the energy goes. The study uses m^2 treated floor area as functional unit and ranges between the good practice and typical cases (Foxon and Trust, 2003).

3.5.4. Sensitivity Analyses

As mentioned earlier, life span of office buildings is considered in most cases to be 50 years or more (Heijungs et al., 2005), and the current trend is to demolish the late 1960s buildings (Junnila et al., 2006). Moreover, other studies suggest that a realistic service life of a building is around 15-30 years (UNEP, 2003); (Seo and Hwang, 2001). The future of the building is highly valued in LCA studies, as it might have a considerable influence on the whole life results, which is not considered in most building designs. Possible changes in building systems during the life of a building might drive the environmental impact of this building by another route.

Sensitivity Analysis is not a standard practice (Ross et al., 2002), although some studies within the literature have considered it. Peuportier (2001) assumed four alternative scenarios; he changed the type of heating energy used, and discovered that it has a major influence on the results (Peuportier, 2001). While Adalberth

(1997) found from considering alternatives that energy mix could influence the results by up to 45 per cent.

Interviews held with architects who are in charge of office buildings designs in Scotland show that the service life of building materials is neglected, and obsolescence which is the feature of buildings is not considered in most cases. According to Lemer (1996) service life of materials is defined using a very limited rationale, and the service life could be shorter than is currently accepted (Lemer, 1996). Ashworth suggested that while reliance may be placed on actual recorded performance data for the life expectancies of building components, it has been shown that such data are also based upon insufficiently rigorous information. When attempting to derive an estimate of component and material life expectancy, it is very likely to be incorrect, as the data bears little resemblance to the actual values of building component life expectancy (Ashworth, 1996). Another study noticed that buildings undergo significantly more renovations to all systems (structure, enclosure, services, interior finishes) than is commonly assumed by designers (Slaughter, 2001).

Therefore, it appears that sensitivity analysis is the least well developed and applied stage of LCA, and this is reflected in the large differences between the findings of various studies.

3.6. Conclusion

Life-cycle assessment of buildings is less advanced than in other industries, but researchers are working to enhance the possibilities of adopting LCA as a decision making support tool within the design stage. It is clear that LCA is well explained, and its methodologies are well established and accessible to users, but there are still many impediments to its use for buildings, and these set the research agenda for the future.

The main problem is the building, whose production process is complicated, and whose life span is long and includes future phases which are based on assumptions. There is little standardization within the building sector, so there is a clear lack of data inventory. Researchers are working hard to overcome this problem, but the nature of the building industry makes it difficult to have an international dataset available for all users, which is needed to make the life-cycle assessment studies comparable. There should be an internationally accepted framework, protocol, and conversion tools based on different factors, to enable the comparison between one LCA study and another. The currently available datasets are typically not transparent, and most of them are based on local and simple materials but not components or composites. There is a need to produce accurate local datasets with the possibility to convert their results to an internationally comparable form. Among the literature cited within this chapter, there are no two studies which could be directly compared, due to differences in goal and scope of the study, methodologies used to achieve these different goals, and data used.

More studies have calculated the embodied impacts of building materials and component combinations than have been concerned with the whole process of building construction. There is a need to hold whole life-cycle assessment studies to establish the effect of alternative materials on the energy performance of the buildings, and to find the optimum relationships between them. At the building scale, more has been done to evaluate the environmental impacts of dwellings, possibly because of their prominence in the building stock and their lesser complexity than non-residential buildings, especially offices, which are considered to be of high significance in terms of their greenhouse gas emissions. This is a particular concern in views of the importance of office buildings within the building stock, as described in chapter 4. It is clear in the literature that not all impact categories were present, because researchers highlighted the significant ones, but what is not significant in a single building can be highly significant at the community or regional level.

Considering the overall environmental impact of buildings is difficult because the 13 or more impact categories in Table 5 are measured in different units. Simply adding the impacts is insufficient and it is necessary to first reduce them to a common scale, and then apply weighting factors to account for their relative importance. In the BRE methodology (Anderson et al., 2009) the emissions in each impact category are normalized by comparing them to those emitted by the average European citizen in one year, thus producing a single dimensionless number for each category. This number is multiplied by a weighting factor (referred to as a valuation factor in ISO 14040) obtained by consulting a panel of 10 experts (Aizlewood et al., 2007, Hamilton et al., 2007) and the numbers so produced are totalled and scaled to 100. Thus the environmental impacts are scored according to their perceived importance, with the highest proportion (21.6 per cent) allocated to CO_2-equivalent emissions, water extraction next at 11.7 per cent, then others down to 3.0 per cent for eutrophication, 0.20 per cent for photochemical ozone creation and the lowest proportion (0.05 per cent) to acidification.

A similar scoring approach (but with different categories and values) is used by the UK's Code for Sustainable Homes to force reductions in the environmental impact of new housing (Sartori and Hestnes, 2007). This approach is subjective and the normalization and weighting process is variable both in time and across geographical boundaries. Furthermore, it is susceptible to manipulation to suit the political or other agenda of the specifying authorities, who may wish to concentrate on particular impacts of local significance without regard to the global situation. Simplifying the information relating to product lifecycles to make it more accessible and easily understood has to be balanced against the need to align the objectives and boundaries of LCA studies to avoid information being used erroneously or out of context. A full LCA of a product provides useful and accurate information, but is costly and time consuming, while using generic data and information in a specialized application could lead to a wrong choice.

This chapter reviewed life-cycle assessment studies within the literature and introduced LCA as a beneficial tool for environmental management which can be applied in all building life stages for different reasons; the next chapter will explain the use of life-cycle assessment as a method for assessing the carbon emissions of buildings.

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Chapter 4 - Methods

4.1. Introduction

Chapters 2 and 3 discussed the literature on offices and LCA and concluded that there is little LCA data on office buildings. The objective of this thesis is therefore to add Scottish office buildings life-cycle assessment information to the growing international literature. This chapter discusses the research methods available to address this objective and introduces the work that was done.

4.2. Research Design

In response to the identified research objectives, a process by which these objectives could be addressed and fulfilled efficiently was needed. This is usually guided by different research philosophies and approaches which in turn are informed by epistemological understandings (Alalouch, 2009). Various terms are used within the literature to determine the research philosophy and epistemology. *Objectivism and Subjectivism* are seen as the main epistemologies or knowledge claims (Creswell, 2003). The research in this thesis tends to fall under the objectivism way of thinking. Objectivism claims that facts happen in the real world independently of our consciousness and our task is to discover them, and that is a matter of time and efforts. On the other hand, subjectivism claims that subjective experiences of individuals impose meanings on an object and hence, meaning is independent of the object itself (Crotty, 1998).

Theoretical perspective guides the methodology and links it to a philosophical stance. Methodology is the strategy of choosing the methods and linking them with the results; and Methods are the techniques employed for data collection and analysis in response to the research objectives (Alalouch, 2009). The researcher who wrote this thesis is independent; he seems to have no influence on the results of this real world research. Thus the research in this thesis has a positivistic orientation (Remenyi et al., 1998). And the researcher interpretation is *"what makes sense of an existing reality"* (Alalouch, 2009).

Real world research can investigate a closed system or an open system, as scientific laws are about the causal properties of realistic structures. *"Salt will dissolve in water, however sometimes it does not"* (Robson, 2002). To test this, the researcher has to set a closed system of laboratory experiments in which all the parameters are under his control. While in the case of the realistic research in this thesis, it is not possible to reach this level of closure, as we are dealing with tendencies and probabilities, thus the system here is open. Definite prediction in open systems is impossible as parameters are not fixed, but explanation of previous cases is possible (Robson, 2002). The actual configuration of a structure or a process changes from one case to another, especially, in the case of buildings and construction industry, as *"buildings are unique creatures"*.

In the realist research, to answer the questions *"how"* and *"why"* a case study method is recommended, especially when the research investigates an open system over which the investigator has limited or no control (Yin, 2009). The studied phenomenon *"building life cycle"* is in its real life context, and the boundaries between the phenomenon and the context are not clearly evident (Yin, 2009). There is another point which adds value to the choice of case study as a research method; multiple sources of evidence (drawings and specifications of a building, company documents, environmental statistics, interviews and observation) had to be used to collect the data needed. The chosen method also supports the goal of the study to gain in-depth knowledge of the cases; it helped to understand *how* and *why* certain life-cycle phases and elements contribute more to the environmental impact than others. Figure 16 presents the stages of case study method.

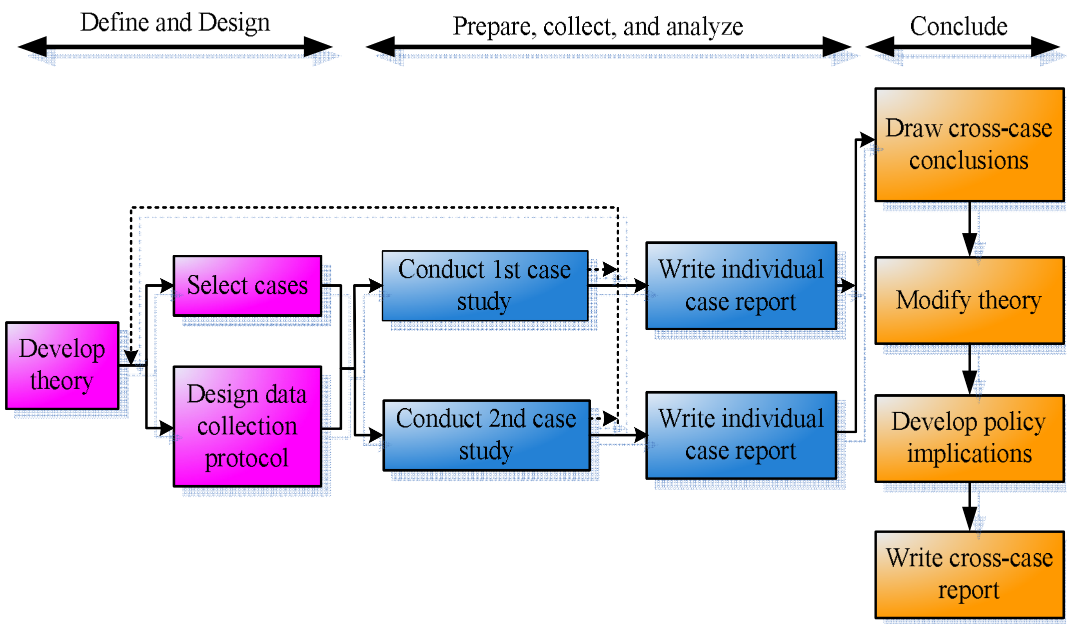

Figure 16 - Case study method (Yin, 2009)

Within the aims of this research the environmental characteristics of office buildings in different contexts were discussed, and the findings of multi-case studies are usually considered more convincing than a single case study (Yin, 2009). "*Analytical conclusions independently arising from two cases will be more powerful than those coming from a single case alone*" (Yin, 2009). Within each of the case studies, there are embedded units of analysis; quantitative analysis was used to address the embodied carbon in building materials, operational carbon of buildings, and carbon emitted through the construction phase and end of life activities. These units were analysed quantitatively using the LCA method (ISO, 2006b). This includes numerical evidence and the application of mathematical analysis, which represents the *"positivistic approach"* (Remenyi et al., 1998), mentioned early in this chapter.

Within each case the analysis of the embedded units *"life-cycle tools and phases"* is conducted. Then the interpretation of the results on each case level is treated as a factor in a pattern-matching analysis. The patterns or the interpretations of each single case are compared between the cases. At the end of this process the multiple-case conclusions are written, which are the conclusions of the research.

To assure the quality of this study, it was necessary to design a method to overcome the uncertainty of the results, and estimate the impact of this uncertainty. Sensitivity analyses are used as a quantitative method, and a data quality matrix developed by Weidema and Wesnaes (1997) is used.

The sensitivity analyses used are based on "what-if", and cornerstone scenarios. The "what-if" scenario is the more widely used of the two approaches in LCA studies (Pesonen et al., 2000). When the researcher is familiar with the research problem, and has pre-set hypotheses based on available data then a what-if scenario could be used to compare two or more options. These scenarios make some specific changes to achieve benefits in the short and medium term of application. The results of a study using "what-if" scenarios are typically quantitative comparisons of the selected options: e.g. alternative A is better than alternative B by x per cent. "*This type of research could also be defined as one offering operational information in the case of short or medium term decision-making situation"* (Pesonen et al., 2000).

The alternative is called the cornerstone scenario approach. It produces a base case study for further research rather than quantitative results. In the cornerstone approach the researcher chooses several options, which can be very different, in order to get an overall view of the studied field - these alternatives then serve as 'cornerstones' of the studied field.

The results of the cornerstone scenario approach can point out a potential direction of future development or at least give some information about alternative paths of development in the studied area that are certainly not possible (Pesonen et al., 2000). The cornerstone scenario approach offers a tool for long term planning and the nature of this type of study and the information gained from it is more strategic than in the "what-if" scenario approach. Strategic information refers to large and possibly qualitative changes of large scale systems with long time horizons (CHAINET, 1998). Cornerstone scenarios can offer new ways of seeing the world, which allows the decision-makers to "think out of the box".

It is important for the researcher to start scenarios at more general level, and work in further research to study more specific ones. Wack (2002) stated that a researcher cannot start with a specific focus, because he may miss the key issues: *"You must wide-angle first to capture the big picture and then zoom in on the details"* (Wack, 2002).

ISO 14040 stated that LCA studies could be applied in areas like: product development and improvement, strategic planning, public policy making, marketing, and others. As it has long term benefits, cornerstone analysis can be more appropriate for typical strategic planning and public policy planning research. However, it could be applied in parallel with "what-if" scenarios within other areas (Pesonen et al., 2000).

To compare "quantitatively different options or alternatives" in the study the "what-if" scenarios are used to test some specific changes within the building. The results of the cornerstone scenarios are used to produce base information and fundamental results to be compared with other cases in future research. The scenario analysis is performed for the processes contributing the most to the result as recommended by (Heijungs et al., 2005). The ranges of variation used in sensitivity analysis are determined based on empirical data derived from the literature.

In parallel with the quantitative analysis, there should be a quality check, thus a qualitative data framework driven from LCA studies within the literature is used (Lindfors and Ministers, 1995). There are six indicators to assess the quality within this framework, and each of them has five quality levels. The quality level ranges from 1 to 5, where 1 means the best and 5 means the lowest quality. Weidema and Wesnaes (1997) presented the quality framework matrix with explanation to all indicators levels. Their research conducted a multi-user test to investigate the repeatability of a similar data quality framework that has been used here. They concluded that the deviation of scores between different users were surprisingly low and could be kept at an acceptable level. In addition, most LCA researchers confirmed their satisfaction with the usefulness of the qualitative data estimation framework produced by (Weidema and Wesnaes, 1997).

4.3. Research Stages

The steps in the research described in this thesis are summarised in Table 7.

Input	Stage and Methodology	Output
Historical work to-date LCA studies	Literature review.	Problem identification General assumptions Boundaries and limitations Data quality Assurance Sensitivity Analysis Validation
Literature Interviews Questionnaires Meetings Data requests Site visits Observations	Data collection	Bill of quantities Construction process information BMCC environmental impact Inventory data
Bill of quantities Construction process information BMCC environmental impact Inventory data Life spans information	Modelling	Initial embodied energy Recurring energy End phase energy
Building specifications Construction drawings Materials U values	Building simulation	Estimation of use phase energy
Life cycle energy consumption	Classification Conversion	Environmental impact

Table 7 - Research stages in this thesis

4.3.1. Literature Review

For the purpose of the research in this thesis, a literature review was used to understand the environmental impacts of buildings, and to build a comprehensive background about LCA. Other studies of building LCA were derived from literature to be used for verification and confirmation of results. However, the extensive studies of office building LCA are relatively rare. Literature review was also conducted for enhancing the quality of the interviews, and of the sensitivity analysis (Corbin and Strauss, 2008).

4.3.2. Data Collection and Quality Assurance

The data collection strategy was drawn and detailed to achieve the goals of this study and assure the quality of research. This strategy consisted mainly of two stages before the final acceptance. Data collection and verification processes were done in parallel to shorten the time conducted for this task as much as possible. There were some unexpected circumstances beyond the control of the study holder, which delayed the process and affected the pre-set quality targets. These circumstances will be detailed later within this chapter.

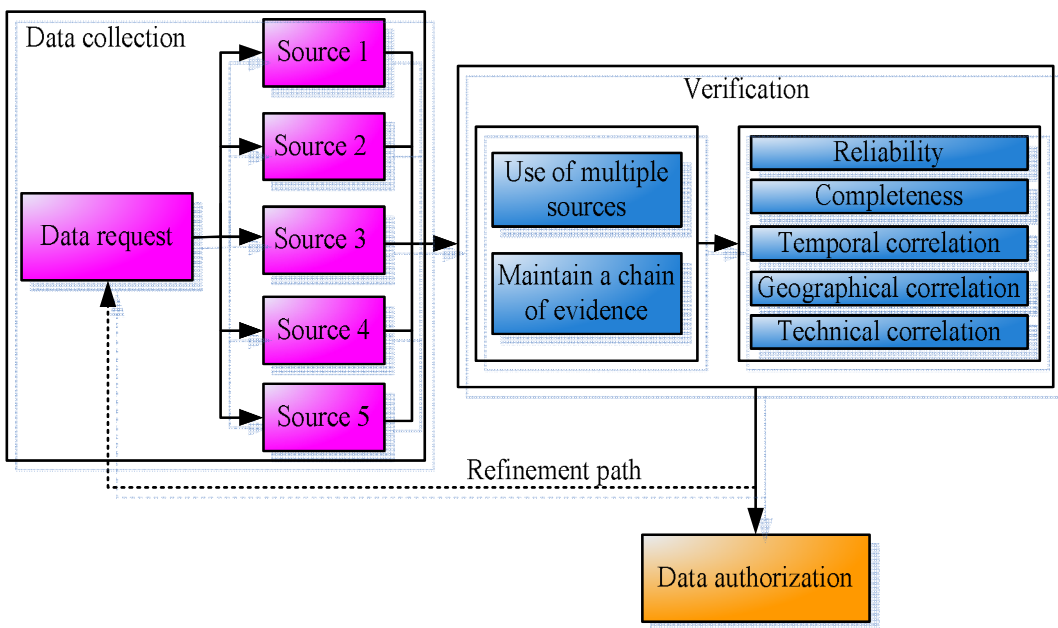

Figure 17 - Data collection strategy.

There were two types of data to be collected: i.e. building data and inventory data. Building data is all the data related to the building (i.e. building specifications, materials quantities, building components and combinations, building systems and services, construction process data, energy simulation models, building life span, materials and components life spans, and end of life expected scenarios). Inventory data is the embodied energy and carbon in the materials and components.

Data collection started by searching for the architects who designed office buildings in Scotland. The search was conducted through the Royal Incorporation of Architects in Scotland (RIAS). Then all the architects who designed offices recently were contacted by email, and phone conversations took place. Many of the architects showed interest in the research by replying to the emails, but few of them were able to share data. The financial crisis was a key barrier, as the companies were suffering financial problems due to the lack of projects, and thus lack of staff. It was quite a challenging task to convince some architects that this is a suitable time to share in such research. Finally, three companies accepted initially to share their data.

Meetings with architects put the data collection process on track, in which the architect was a key player in securing the required permissions from building owners. They explained the importance of the research and the lessons which could be learnt from it for future projects. The architect built communication networks between all stakeholders by introducing the contractors to the research project. It was possible to go through the easy path, and get the "as designed" building bill of quantities from the quantity surveyors, but the most accurate bill of quantities was acquired by contacting the subcontractors and copying their actual orders and as built bill of quantities (BOQ).

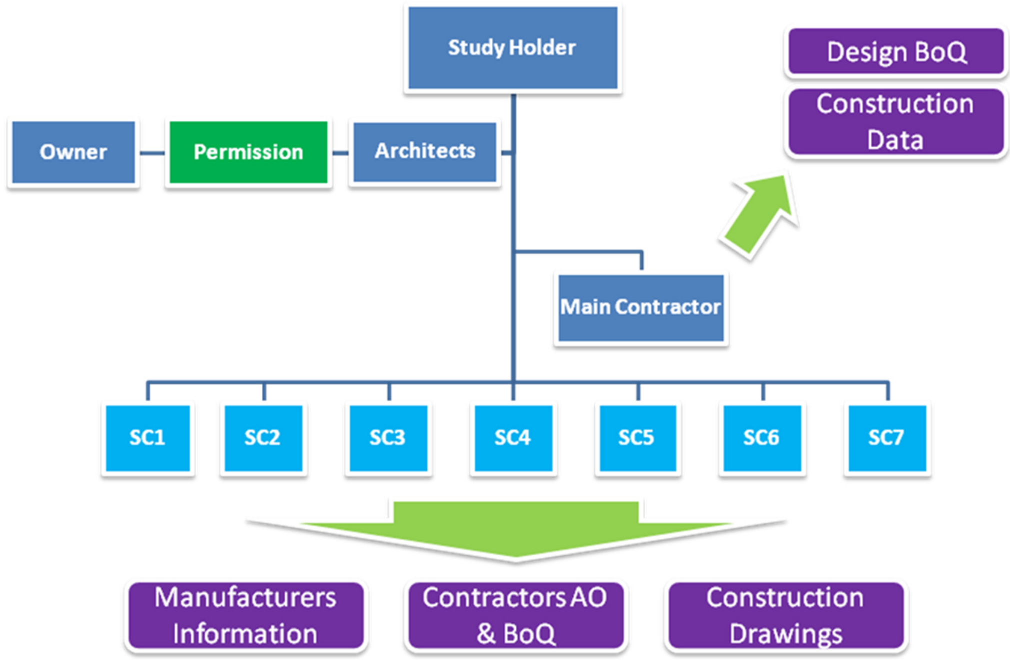

Figure 18 – Case study building data collection.

All construction drawings, details, design BOQ, as built BOQ, materials specifications including manufacturer's details, three dimensional models, interviews and direct observations are multiple sources of evidence used to achieve the goal of this study.

Inventory data presents the embodied energy and carbon emissions associated with the production of a building material or component from cradle to gate. It is beyond the scope of this study to investigate and calculate the embodied energy and environmental impact of materials and components, but verification of such information is very critical to assure the quality of research. Inventory data was collected by visiting the manufacturer's websites when available, and the local academic data was present as backup to fill the data gaps.

The majority of the carbon data came from manufacturers data associated with Bath University Inventory of Carbon and Energy (Hammond and Jones, 2011), and the UK Building Blackbook (Franklin and Staff, 2010). Data availability was one of the study limitations, so where exact information was not available for an item, inventory data for a similar item was used. Construction phase data, including transportation of materials to construction site and other onsite activities was collected through interviews held with the main contractor and project managers. Data sheets were completed by the project managers to estimate the emissions of this phase.

The necessary data to estimate the annual carbon emissions was collected from the building services engineers who created models in the Integrated Environmental Solutions (IES) building performance simulation software, and the U values of the materials used in outer shell are obtained from the manufacturer's data. The results of these models were verified using modelling software (ECOTECT). Data used for recurring carbon calculations was collected from manufacturer's information when possible, and industrially verified estimations were used when the accurate data was absent. Normal maintenance was included within the research while any refurbishment towards future improvements was not counted. Literature review shared as a data source for verification purposes.

Data verification is the second stage of data collection strategy. It is a critical task to assure the quality of the work. Data collected for the purpose of this study was verified on principles according to (Yin, 2009, Weidema and Wesnaes, 1997): As one of the quality assurance procedures, it is necessary to use multiple sources of evidence when possible, but within the limitations and boundaries of the study. If it is not possible to use multiple sources of evidence, the source which enhances the quality of the study was chosen. This was based on measures related to parameters addressed in the data quality matrix presented by (Weidema and Wesnaes, 1997), see Table 3 in Chapter 4

Building data which was extracted from the actual orders of subcontractors and the bill of quantities was cross-checked against the design bill of quantities, construction details, and exact measurements, which was a difficult and time consuming task. But it was necessary to follow this route to achieve the quality target of this study. The study achieved a good level of quality using the matrix presented by (Weidema and Wesnaes, 1997), see Table 8.

Data Quality Maximum score = 1 Minimum score = 5	Acquisition method		Independence of data supplier		Representativeness		Data Age		Geographical correlation		Technological correlation	
Case building	A	B	A	B	A	B	A	B	A	B	A	B
Building materials	2	2	1	1	2	2	2	2	2	2	2	2
Construction	2	3	2	2	2	3	2	2	2	2	2	3
Heating service	2	2	2	2	1	1	1	1	1	1	1	1
Electrical service	2	2	2	2	1	1	1	1	1	1	1	1
Maintenance	2	2	2	2	3	3	2	2	2	2	3	3
Demolition	3	3	2	2	2	2	3	3	2	2	3	3

Table 8 - Data quality matrix average scores of case buildings A and B

Building data passed the verification processes, and got the scores presented in Table 8. The data was verified data partly based on assumptions, representative data from sufficient sample of sites, less than 3 years different from year of study, collected from area under study, and data from processes and materials under study but sometimes from different enterprises. The same scores were achieved by the inventory data because manufacturer's data was cross-checked against national and international data and academic data presented by Bath University (Office) data which is an academic, transparent, and up-to-date database. It is less than three years old and a national source of embodied energy and carbon information, which makes the study more reliable as using local data will enhance the quality of LCA results (Menzies et al., 2007).

4.3.3. Boundaries and Limitations

LCA is based on system thinking. This means that the studied building is considered as a complete system consisting of other sub-systems, which in turn consist of materials and processes associated with energy consumption and environmental impacts (Consoli et al., 1993). This building is part of a larger system, and the boundaries of the study determine what is and what is not included within the system. The region outside the system is known as the system environment.

The unit process and flows represent the system in LCA (ISO, 2006b). Data of the system is collected to the smallest portion of the product system- the unit process. The flow is the material and energy inputs and outputs to and from the unit process. The unit processes are interlinked by the flows and the output of the first unit is the input of the second and so on (Consoli et al., 1993). For example, the output of the production of one kg of concrete is an input to the production of one cubic metre of reinforced concrete, and one of the inputs of a kg of concrete is a kg of cement, see Figure 19.

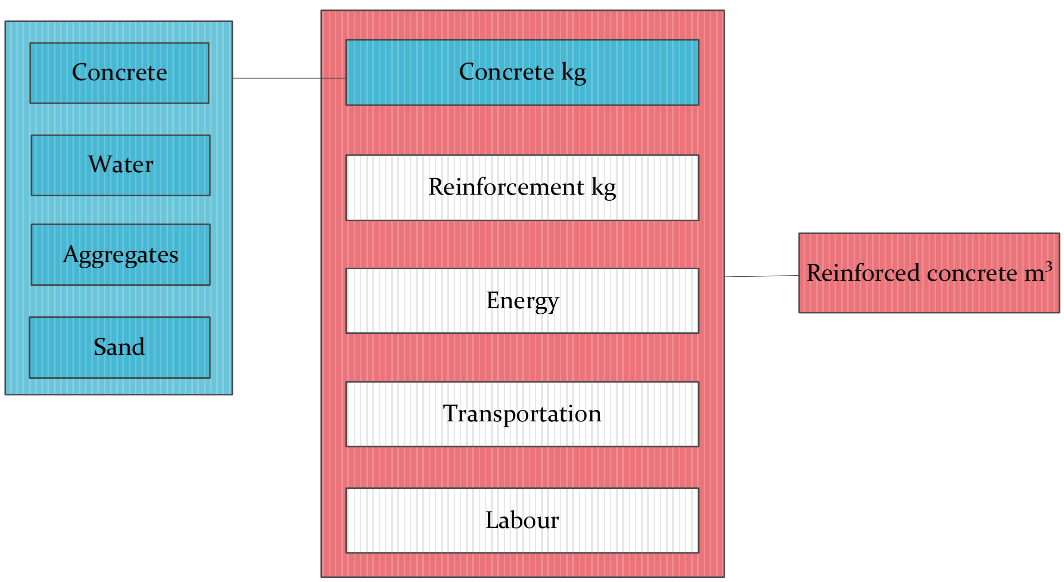

Figure 19 – Inputs of a cubic meter of reinforced concrete

The boundaries of the study have to be stated clearly. This is for the investigator to keep control of the study, and for the user to appreciate the results in light of these boundaries and limitations.

LCA methodology has many limitations which are stated clearly within the literature (Khasreen and Banfill, 2010). ISO 14040 stated that LCA is limited by the subjective choices of the holder, the limitation of impact assessment models, the possibility of mistakes in representing the regional conditions, limited accessibility to data, lack of spatial and temporal dimensions, its complexity, difficulty of obtaining usable results, risk of biased use, and the amount of data required being too large (ISO, 2006d).

The scope of the LCA in the research described in this thesis covers the life-cycle of two new office buildings in Scotland. Fifty years of use was assumed to be the basic service life of the buildings. In the comparison, the results are presented per gross floor area of the buildings. The LCA included all the life-cycle stages of an office building: extracting and processing raw materials, manufacturing building materials, construction process, building operations (electricity, heating and other services), maintenance, and demolition. All the phases included transportation as relevant. The quality of the data was targeted at the level of "good", which corresponds to the second highest level (two of five) in the selected framework (Weidema and Wesnaes, 1997).

The electricity use of the buildings included also the electricity used by the office equipment (through the power outlet) and the basic service life of a building is not assumed to include any major refurbishment activities. Minor refurbishment activities are included in maintenance. The effects of major refurbishment to achieve greener building are discussed in the scenario analysis. All the secondary inputs anticipated to be significant for the goal of the study were included in the study and traced back to extraction and landfill, e.g. fuels for the machinery and equipment, spillage and packaging. Minor secondary inputs were excluded from the system e.g. capital equipment, materials used in cleaning, secondary inputs from design and other similar services, and the transportation of and the food for employers. The CO_2 emissions from the burning of renewable fuels were not assumed to have an impact on climate change.

The building data is limited by some small assumptions, cut-offs allocation, and gaps. These can have a significant influence on the results of the LCA study, and should always be stated clearly for transparency reasons. The buildings are owned, designed, constructed, and operated by different companies, and their construction was finished in 2009-2010.

The following building elements were included in the study: construction site (e.g., excavation and backfill for pavements and services), substructure, foundations, structural frame, external envelope, roof, internal complementary (e.g., doors, partition walls, suspended ceilings, railings), internal surfaces, and mechanical and electrical services. The only category of the classification not included in the study was the materials used in the internal equipment (e.g., refrigerators and furniture). The main source of data was the as built bill of quantities, the architectural and engineering drawings, and the architect's specifications.

The boundaries within the academic database used are cradle-to-gate. However, even within these boundaries there are many possible variations that affect the absolute boundaries of this data. One of the main problems of utilising secondary data resources is that of variable boundaries since this issue can be responsible for large differences in results. The academic database has its ideal boundaries, which it aspires to conform to in a consistent manner. However, with the problems of secondary data resources there may be some instances where modification to these boundaries was not possible. The ideal boundaries are listed in Table 9.

Item	Boundaries treatment
Delivered energy	All delivered energy is converted into primary energy equivalent, see below.
Primary energy	Default method, traced back to the 'cradle'.
Primary electricity	Included, counted as energy content of the electricity (rather than the opportunity cost of energy).
Renewable energy (inc. electricity)	Included.
Calorific Value (CV)/Heating value of fossil fuel energy	Default values are Higher Heating Values (HHV) or Gross Calorific Values (GCV), both are equivalent metrics.
Calorific value of organic fuels	Included when used as a fuel, excluded when used as a feedstock, e.g. timber offcuts burnt as a fuel include the calorific value of the wood, but timber used in a table excludes the calorific value of the wooden product.
Feedstock energy	Fossil fuel derived feedstocks are included in the assessment, but identified separately. For example, petrochemicals used as feedstocks in the manufacture of plastics are included. See above category for organic feedstock treatment.
Carbon sequestration and biogenic carbon storage	Excluded, but ICE users may wish to modify the data themselves to include these effects.
Fuel related carbon dioxide emissions	All fuel related carbon dioxide emissions which are attributable to the product are included.
Process carbon dioxide emissions	Included; for example CO_2 emissions from the calcination of limestone in cement clinker manufacture are counted.
Other greenhouse gas emissions	The newest version of the ICE database (2.0) has been expanded to include data for GHGs. The main summary table shows the data in CO_2 only and for the GHGs in CO_2e.
Transport	Included within specified boundaries, i.e. typically cradle-to-gate.

Table 9 - Inventory data boundaries (Hammond and Jones, 2011)

The construction phase of the building included all the materials and energy used in the on-site activities. Data were collected for the use of electricity, heat and steam on site, use of equipment, transportation of building materials to the site, materials used on site (needed in the construction processes, but not permanently attached to the building such as formwork, temporary structures, etc.), and waste management. The data were mainly collected and ascertained by interviews with the project manager.

The operation phase of the building was divided into heating services and electricity services. The energy consumption calculations of the building were performed using the Integrated Environmental Solutions (IES) software. The estimated heat and electricity consumption values were drawn from the models. For case A, the energy consumption estimation was later double checked against ECOTECT software.

The maintenance phase included all the life-cycle elements needed during the 50 years of maintenance: use of building materials, construction activities, and waste management of discarded building materials. An estimated 75 per cent of building materials was assumed to dumped to land fill and 25 per cent recovered for other purposes such as in the recycling to new products. Maintenance did not include any modernization or other similarly fundamental improvement measures. The building materials required in maintenance were derived from the drawings and specifications of the building, and the service life of each material was estimated based on appropriate guidelines derived from the component life survey results estimated by Building Cost Information Service (BCIS) data and the gaps were filled using literature data. The entire building was assumed to be demolished at the end of its life and the materials sent to landfill or recycled as discussed earlier in this thesis. Energy production data were collected from the UK national statistics data.

4.3.4. Embodied Energy Calculations

Materials used in buildings start their life-cycle as raw materials, and their production processes start by the extraction task, and end by transportation to site, and this involves environmentally harmful activities including burning fossil fuel. Carbon dioxide and other emissions are the result of this activity. The production process should be studied carefully as many factors can affect the emissions associated with a process. For example, a tree could be watered manually by a farmer, or could be watered using a diesel pump, so the embodied carbon differs from a case to another.

The energy embodied in a building is the sum of the embodied energy in all materials, systems, and building components. These could be named as initial embodied energy (EE_i), and could be expressed as:

$$EE_i = \sum m_i E_i + E_c \qquad (1)$$

Where EE_i = initial embodied energy of the building; m_i = quantity of building material (*i*); E_i = energy embodied in material (*i*) per unit quantity; E_c = energy emitted at site for construction of the building.

4.3.5. Recurring Energy Estimations

Many of the materials used in building construction have a shorter life than the building life span. These materials will be replaced during the life of the building, and the frequency of replacing these materials is determined by the difference between the material and the building life. The more the difference, the more frequently the material will be replaced. In addition, buildings require regular maintenance. For this, there is a need to estimate the embodied energy in the afore-mentioned activities by calculating the recurring energy which could be expressed as:

$$EE_r = \sum m_i E_i [(L_b / L_{mi}) - 1] \qquad (2)$$

Where EE_r = recurring energy of the building; L_b = building life span; L_{mi} = life span of material *i*.

The internal partitions and doors, finishes and building services are replaced, refurbished and maintained more frequently than the structure and envelope which comprise the majority of the initial embodied energy. Lifecycle energy analysis must account for the changes in embodied energy associated with building maintenance and improvements. It is useful to distinguish between regular repainting, re-carpeting, replacement of systems, lamps, etc. and major periodic refurbishment due to changes in tenancy or office restructuring.

Maintenance and replacement occur periodically over the life of a building. An approach which accounts for maintenance and replacement is identified in (Optimize, 1991). Maintenance is assumed to involve replacing less than 100 per cent of a material or component. Maintenance can be categorised into two types as follows.

- Maintenance incurred during a completed life-cycle of a material or component. For a product which completes its life-cycle, the number of maintenance (repair) cycles required is the product life/repair interval corrected for the possibility of forgone repairs near the end of the product life.

- Maintenance incurred during the incomplete life-cycle of a product due to the expiration of the building. For the last replacement of a product, the number of repair cycles will depend on the years remaining before the life of the building expires rather than the product life.

Replacement refers to the total replacement (100 per cent). The number of times a component is replaced is given by the building life/product life corrected for possibility that if the replacement occurs near the end of the building life, non-essential repairs and replacements would not be done. Replacement may be as a result of functional reasons at the end of a product's useful life, aesthetic reasons or due to the replacement of another associated element in an assembly. These are not included within the analysis of this research.

Currently, for many building types, particularly in the commercial and retail sectors, major refurbishment often involves substantial reconstruction and is being undertaken at increasingly shorter intervals (John et.al, 2009). Fit-out consists of internal partitions and doors, floor, wall and ceiling finishes and mechanical and electrical services. These elements are replaced more frequently than structural and envelope elements and use greater proportions of energy intensive materials, e.g. plastics, copper, etc. According to Howard and Sutcliffe (1994) the embodied energy figures associated with basic, medium and top grade office fit-out as 0.17, 0.23 and 0.34 GJ/m^2/year respectively, assuming frequent replacement annualized from a 60 year building life. Equivalent figures for infrequent replacement are 0.10, 0.13 and 0.17 GJ/m^2/year. Averaged over the same building life, the initial embodied energy of the office building was 0.08, 0.09 and 0.1 GJ/m^2/year for the three grades of accommodation. These figures suggest that the embodied energy associated with building fit-out is always greater than the initial embodied energy and, for highly frequent, top-grade changes; the difference can be as much as three times.

In this thesis analysis, all future replacement materials were assumed identical to those being replaced and their energy intensities assumed to be at current levels with no allowance for improvements in manufacturing techniques over the intervening years. The estimated values of the maintenance and replacement embodied energy costs are therefore greater than will occur in practice. Over a 25-100 year time frame, materials and the construction processes can be anticipated to go through significant changes. Between 1971 and 1986, there was a 20 per cent decrease in the energy intensity for steel, a 24 per cent decrease for non-ferrous metals and a 33 per cent decrease for cement.

4.3.6. Operational Energy Estimations

Since the LCA study was done at the start of the building usage phase and time limitations made monitoring the building during use impossible, and also the buildings are not fully occupied at the time of writing this thesis, the energy usage during the occupation phase was estimated using energy modelling software (IES-VE), industrial software used by services engineers and accredited by CIBSE.

The operational energy is the energy emitted during the use of the building. This is the energy consumed to heat and cool the building, ventilate it, light it, and drive equipment. Operational energy could be expressed as:

$$OE = E_{oa} L_b \qquad (3)$$

Where OE = operational energy; E_{oa}= annual operational energy.

U-values, life span, and other building specifications were collected from the services engineers who designed the services of the building.

4.3.7. End of life Energy Estimations

Life span of office buildings differs from structure to another, but it is widely accepted in the literature that offices generally last for 50 years (Khasreen et al., 2009). There is currently a trend to knock down the offices built in the late 1960s, so the life span of these buildings is not justifying this assumption (Junnila et al., 2006). However, some of the building items can last more than this life span and others can be re-used in different tasks. Material recycling is very important to decrease the environmental burdens of the subsequent buildings. Some other materials could be categorized as non-recyclable materials, and must be disposed to a waste treatment site or landfill. The energy consumed to knock down the building, clear the site, and transport the disposed materials is called the end of life energy, and the carbon emitted during these activities is the end of life carbon. There is a discussion around the issues of attributing the end of life carbon to the building itself or to the next building that will use recycled materials. In some materials, such as steel or aluminium, the use of recycled material can confer savings of more than 50 per cent in embodied energy (Chen et. al, 2001). In 2009, Jones stated that in LCA the benefit of recycling may be considered as an ‘environmental credit’ (benefit).

The use of recycled materials avoids the higher burdens of primary material production. But this environmental savings lies in between two adjoining product systems: the system upstream of the recycling process, which produced the end of life scrap materials; and the system downstream from the recycling activities, which will consume the recycled material. The benefit must be allocated between the two adjoining systems (Jones, 2009).

In this research, it was helpful to assume one scenario for both buildings which is local and similar to scenarios assumed in the literature. This makes the study as comparable as possible. The chosen scenario assumes that demolished materials will be transported up to 50 kilometres out of the city. It assumes that 75 per cent of the materials will need transportation because they will not be used on site again (Saunders, 2010). The recyclable materials will not affect the carbon estimation of this building, and their effect on any further construction is outside the study boundaries. Each tonne of demolished materials consumes 15 kg CO_2 in general. Other scenarios in regard to reuse or recycling might be considered within the interpretation phase.

The end of life energy emissions are expressed as:

$$DE = E_d + E_t \qquad (4)$$

Where DE= end of life (demolition) energy; E_d= energy of building destruction; E_t= Energy of transportation to site.

4.3.8. Embodied Carbon Calculation Methodology Example

For the research within this thesis two methods were followed to calculate the embodied carbon of a building component. These were applied to reach the final result of carbon dioxide emissions expressed as kg of CO_2. The first method was applied when manufacturer's data for the component was available. The second method employs the manufacturer's data or alternative verified data sources which specify the amount of CO_2 for a kg of material or component. Where possible, both methods were used as part of the verification process. A detailed example of the way embodied carbon of the concrete works was calculated from the bills of quantities and the carbon inventory data are given in Appendix B. This process was repeated for all the other building items, systems, and components.

For example, the embodied carbon in the curtain walling system of case study building A was calculated using those two methods. The breakdown of curtain walling system into materials and components is presented in Table 10.

Material	Kg CO_2
Glass	61920.21
Aluminium profiles	60069.6
Epdm rubber	19233.8
Polyetherimide	751.6
Hinges	847.79
Clips	294.7
Screws	218.6
Locks	1190.3
Handles	1269.95
Others	1560.4
Total	**147356.95**

Table 10 – Carbon embodied in curtain walling materials

The glass weight calculations were based on the glass area (m^2) multiplied by manufacturer's provided data in kg/m^2 for each glass panel and not on the glass density per cubic meter. The carbon data was carefully allocated to each panel according to glass type to get a kg CO_2 figure for each panel, and then the sum was calculated.

This process was repeated to all other components, items, and systems. For example, to calculate the embodied carbon in a cavity wall the materials and components within the systems were calculated. This includes the quantities of concrete blocks, bricks, mineral wool insulation, and mortar, then each of these quantities was multiplied by the appropriate carbon value, and then the sum was calculated. Special care was given to allocation activities to avoid duplications.

4.4. Selection of Cases

The two cases selected to achieve the aims of the research in this thesis were both newly built office buildings in Edinburgh. The number of selected cases is recommended by Yin suggestion that a multiple case study should involve two or three cases (Yin, 2009). The cases were chosen based on logic so that all the cases have similar common characteristics, which make them representative of the targeted group of buildings: Both cases are newly built office buildings in Edinburgh, but they have significant differences which allow generalization of the study results. This kind of sample, collected with a specific purpose in mind, is called a judgment or a purposive sample (Remenyi et al., 1998).

Yin emphasized the significance of theoretical categories as factors guiding the choice of cases (Yin, 2009). In the study, the following principal criteria were used: office buildings should be new, and they should be designed, constructed, and used by different organizations in order to avoid the risk of having similar results due to the workings of an individual organization (Junnila, 2009). The Scottish offices were, in addition, expected to be situated in Edinburgh.

As mentioned earlier in this chapter, this research is an open system, and the researcher is studying real cases. The researcher has no control over all parameters, thus there were issues which affected the case selection such as the interest of the owners to participate in the study, data completeness, and availability, but there was a pre-set criteria which were used to select the cases. The buildings were designed by different design teams and built by different construction companies. This allows the researcher to generalize from the results as the case studies represent the current trend of office buildings in Scotland.

4.5. Conclusion

This chapter has described the methods used in the methodologies underpinning the present research. These have been designed to fulfil the research objectives and were informed by previous literature on the subject. The methodologies correspond with the following results chapters of the present thesis. The next chapter describes the case study buildings in detail.

Chapter 5 - Case Study Buildings

5.1. Introduction

This chapter presents a detailed description of the case study buildings, the systems, and the component combinations used within them. This helps the reader to understand the differences in the results and relate them to the differences in building characteristics, systems and materials.

The specifications of case study buildings presented here are derived from the architect's specifications, construction drawings, and contractor's data. This increases the level of data transparency which increases the quality score of the life-cycle assessment study as explained in the discussion chapter.

5.2. Description of Case Study Building A

Building A was a high-quality office building spread over 7 floors, with floor plates offering flexible sub-divisions completed in 2010. The office space was developed on a 1.5 m space planning grid, with a minimum of 2.75 m clear floor to ceiling height, and the building had a "very good" BREEAM Rating. The total floor area of the building was 11972 m^2 as detailed in Table 11.

	Net Office Area	Gross Internal Area
Basement	0	931
Ground	1007	1730
First	1333	1614
Second	1413	1664
Third	1408	1658
Fourth	1400	1650
Fifth	1378	1629
Sixth	845	1096
Total	8784	11972

Table 11 - Case study building A, schedule of areas m^2

The basement of the building was used to accommodate main plant room, and car parking. It does not occupy the whole plot area; it is rather spread on 931 m^2 GFA only. There is no control on the temperature of the basement, and the heating and cooling system is not applied to the basement area. The parking ramp access is located at the east elevation, and the parking area is half the basement area, with parking spaces for 16 cars, and more than 40 bicycles. For basement floor plan see Figure 20.

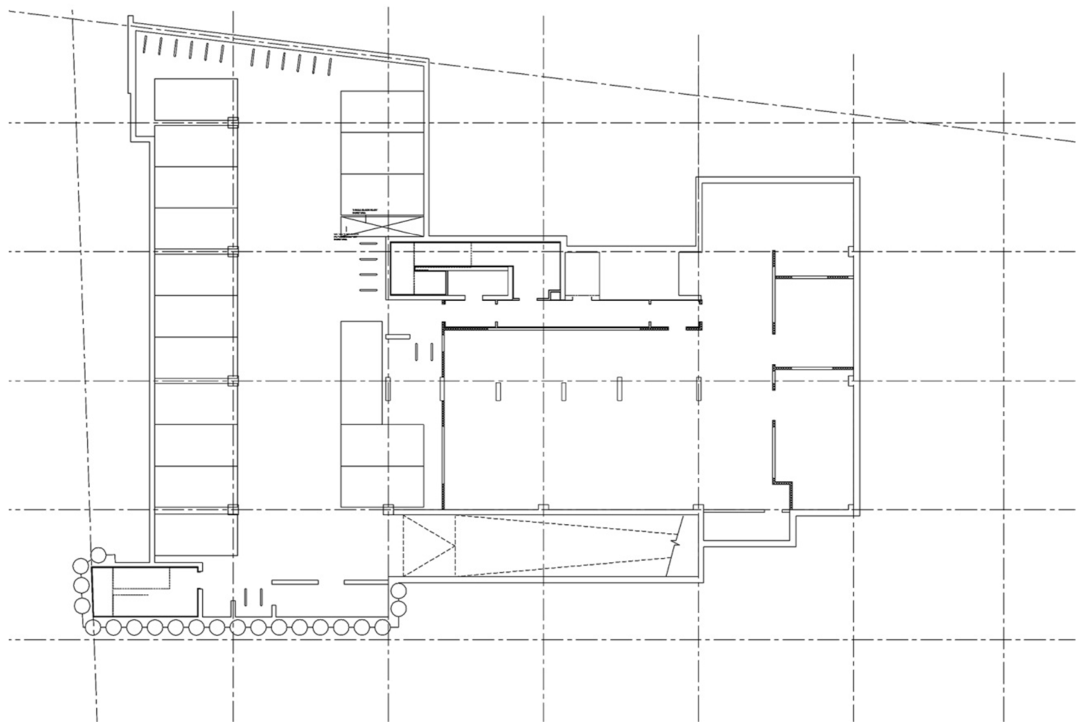

Figure 20 - Basement floor plan of case study building A

The main entrance was located at the north elevation of the building, and it opens at double height entrance foyer leading to the central core and lifts. There were office areas to the south, east and west of the entrance foyer within the ground floor and the majority of office area was distributed from first to sixth Floor with associated toilet facilities, see Figure 21. The access to the parking ramp is located at the east elevation.

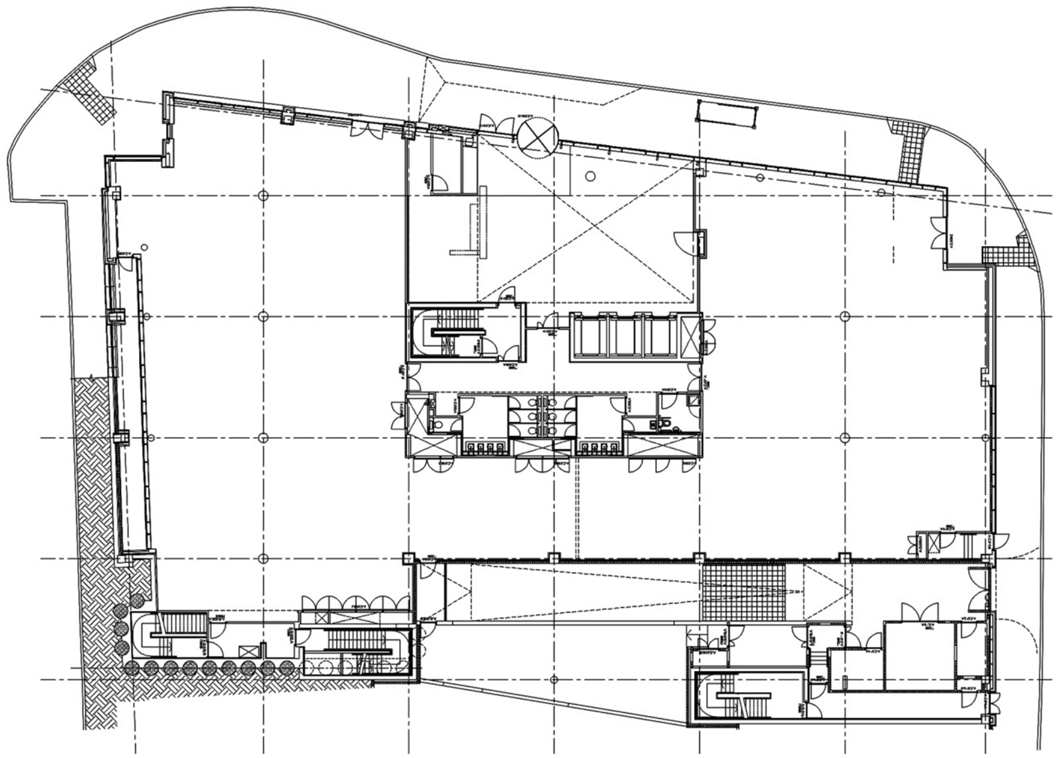

Figure 21 - Ground floor plan of case study building A

As presented in Table 11, the office space is the main function of the building which makes 74 per cent of the total gross floor area of the building. The other 26 per cent of the building area is used as to serve the office spaces, i.e. there is no other function rather than offices in the building. This is applied to all building floors respectively as the area of offices differ from floor to another according to the differences of the external envelope design and to the foyer which reduces the office area in the ground and first floor, see Figure 21 and Figure 22.

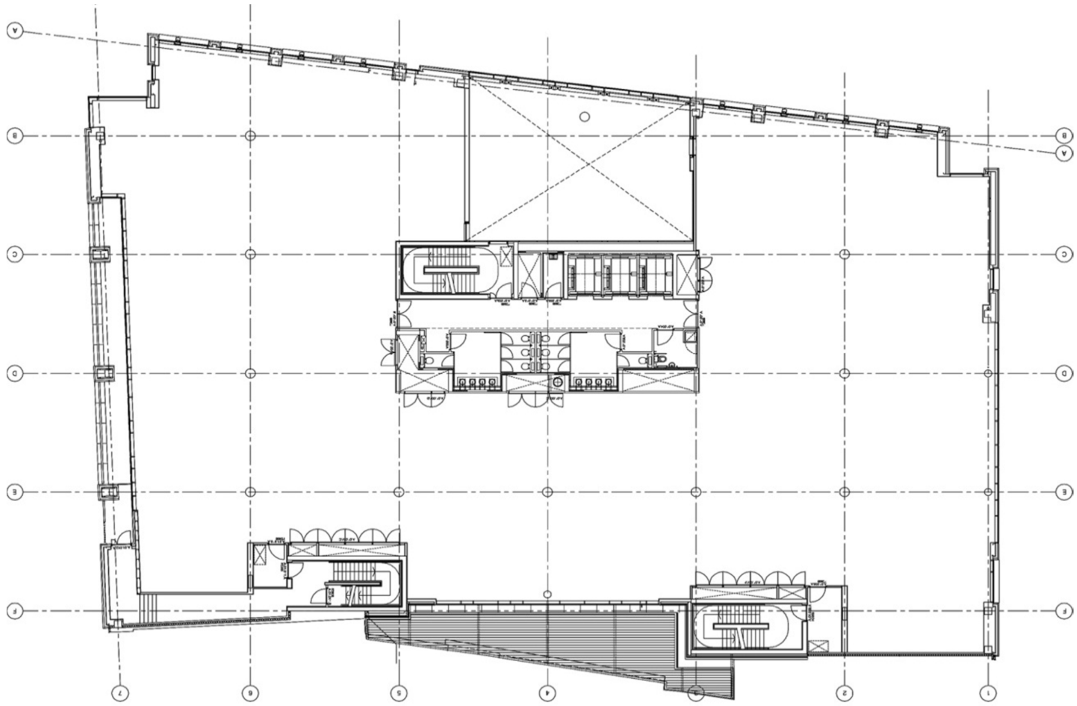

Figure 22 – First floor plan of case study building A

The Second to Fifth floors are identical, and office spaces are spread over the whole floor area except the services area. The access doors are designed on the bases that one or two companies may occupy one floor, and the design is flexible enough to make other suggestions, see Figure 23 and Figure 24.

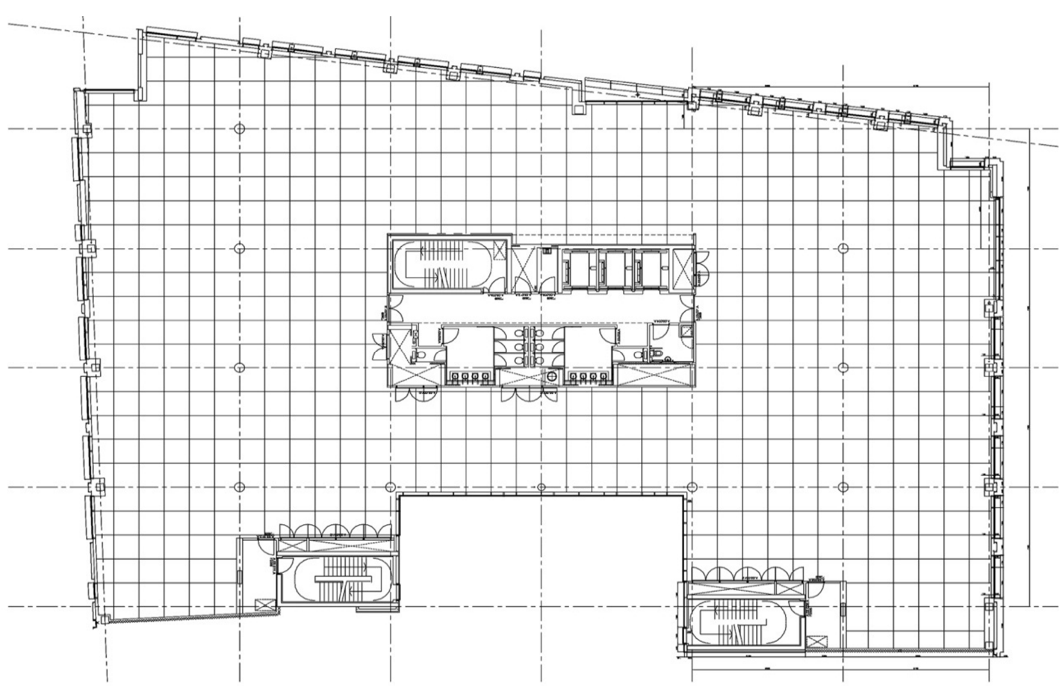

Figure 23 – Identical upper floors plan of case study building A

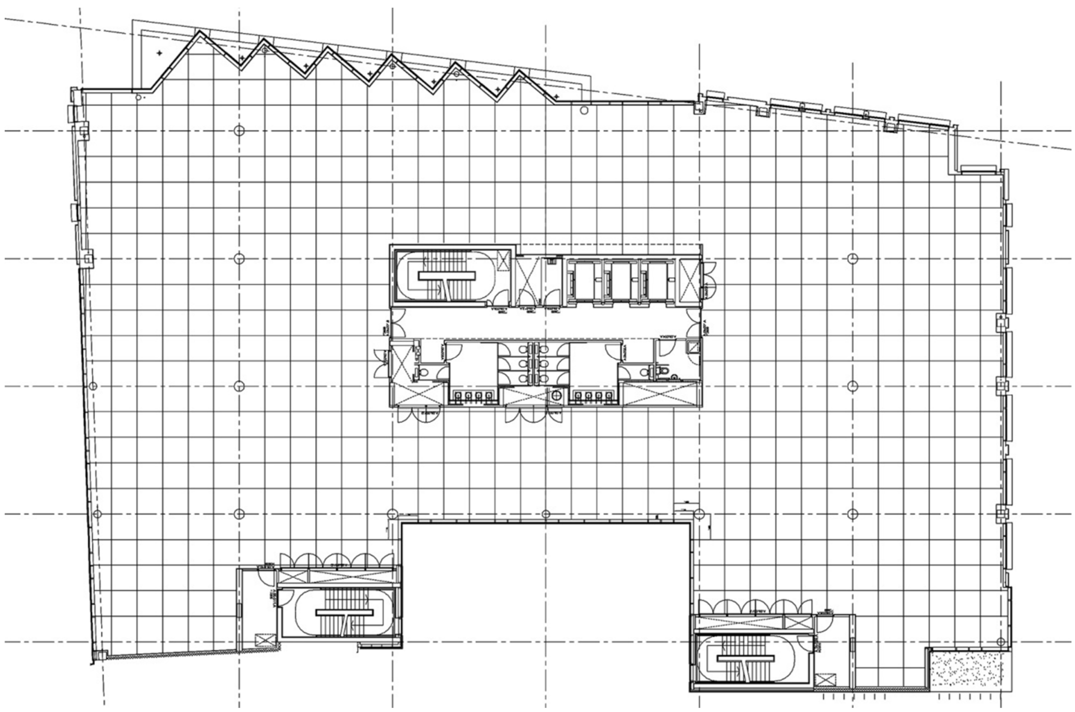

Figure 24 – Fifth floor plan of case study building A

The last floor is steel structured, and it is designed to be smaller than the other floors. The office area in this floor is 845 m^2 only, however, the other features of office spaces are still present in this floor. The services are similar to the other services areas and the office space is designed on the same bases, see Figure 25.

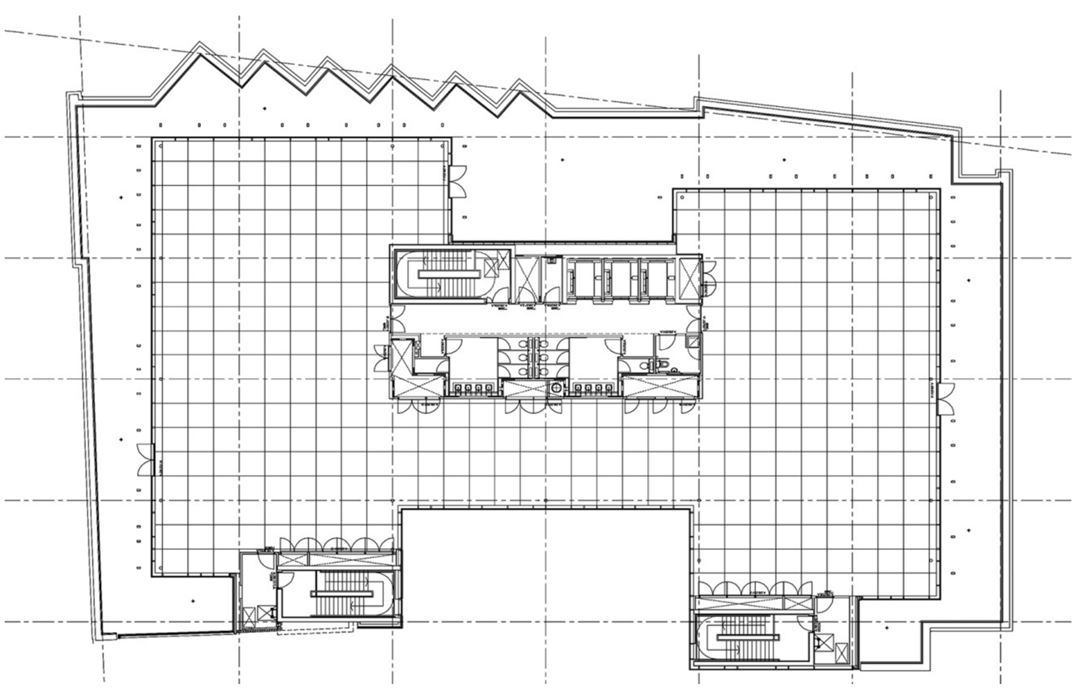

Figure 25 – Sixth floor plan of case study building A

The external envelope of the building is designed to fit Edinburgh city pattern, and to be as son of the surrounding structures. The use of natural local stone as the main material is clear in Figure 26, and the other dominant material on the outside appearance of the building is Glass.

Figure 26 - Case study building A, view from northwest (Google, 2010)

The height of all building floors is approximately similar, apart from the parking space which is one meter less in height than the rest of the building. The typical clear height is designed to be 2700 mm, as presented in Table 12.

Level	Structural slab to slab	Typical clear height
Basement	2750 mm	2100 mm
Ground to fourth floor	3700	2700
Fifth floor	3800	2700
Sixth floor	3620	2700

Table 12 - Storey heights of case building A

5.2.1. Structure

Ground investigation showed bedrock to exist at shallow depths (1.0m to 2.0m) across the site where the bedrock was sedimentary, comprising mudstones, siltstones and sandstones and had an allowable bearing capacity of 400kN/m^2.

All foundations for the development were taken to rock, and the concrete used for structural foundations was of RC40 grade. The walls to the basement were formed in 300 mm thick reinforced concrete, of minimum grade of RC40, and the slab of the basement was 300mm thick and constructed monolithically with pad foundations for the superstructure columns which were cast integral with the basement walls from foundation level to ground floor level. The basement was fully watertight and constructed in accordance with the general requirements of British Standard (BS8102:1990).

The building was of reinforced concrete framed construction up to sixth floor level. Above the sixth floor, the penthouse style roof structure was steel framed. The column grid was generally a 9.0 m x 7.5 m arrangement which was consistent with the recommendations of The British Council for Offices (BCO). These columns were a combination of cast insitu reinforced concrete and pre-cast concrete columns to suit the contractors' preferred construction method.

The ground floor was, in turn, a combination of ground bearing reinforced concrete slabs, and suspended slabs to the basement roof which comprises 75 per cent of the total ground floor area. The suspended slab was a 250mm thick, two-way spanning post tensioned slab. The suspended office floors were generally 250 mm thick, post-tensioned concrete slabs, supported by 600 mm diameter internal columns and 450 mm square perimeter columns.

5.2.2. External Envelope

As clearly shown in Figure 27, a 40mm thick granite base course was formed below all sandstone walls around the ground floor to provide a durable finish at street level. The majority of the façade was formed with a combination of 75mm thick natural sandstone cladding fixed with stainless steel corbel angles and restraint ties. The insulated inner wall leaf was formed from structural metal framing, OSB board and tyvek breather membrane. Natural sandstone mullions were located between areas of glazing within the large window openings.

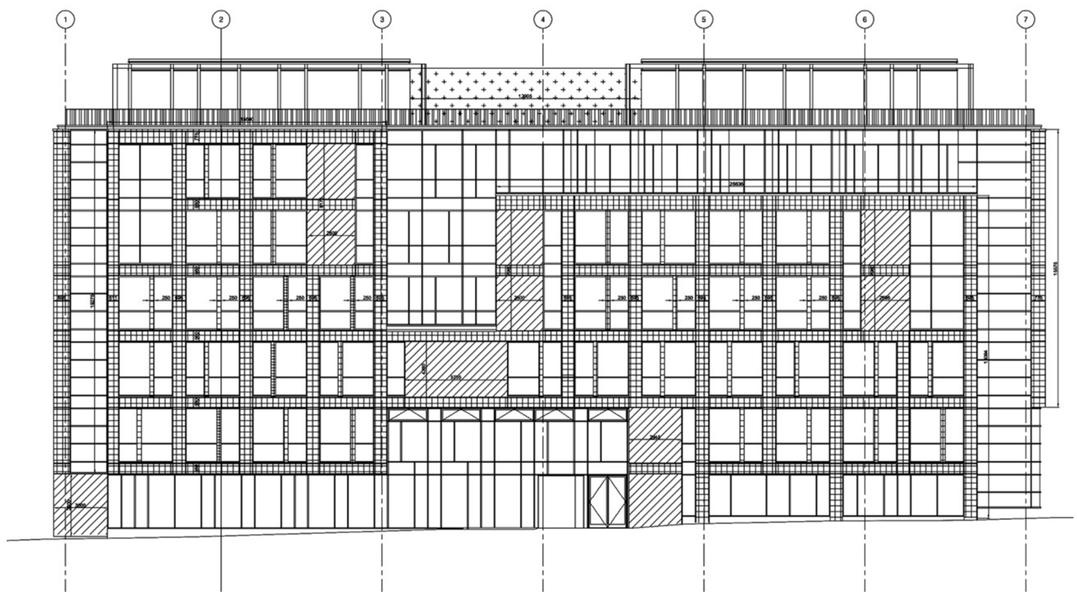

Figure 27 – North elevation of case study building A

All glazed areas were formed in a curtain walling system. Double-glazed units in the vision areas had clear transparent inner panes and clear transparent outer panes with “low E” coating. At sixth floor level, the façade steps back creating a roof terrace with a feature steel tracery structure surrounding the curtain walling elevation.

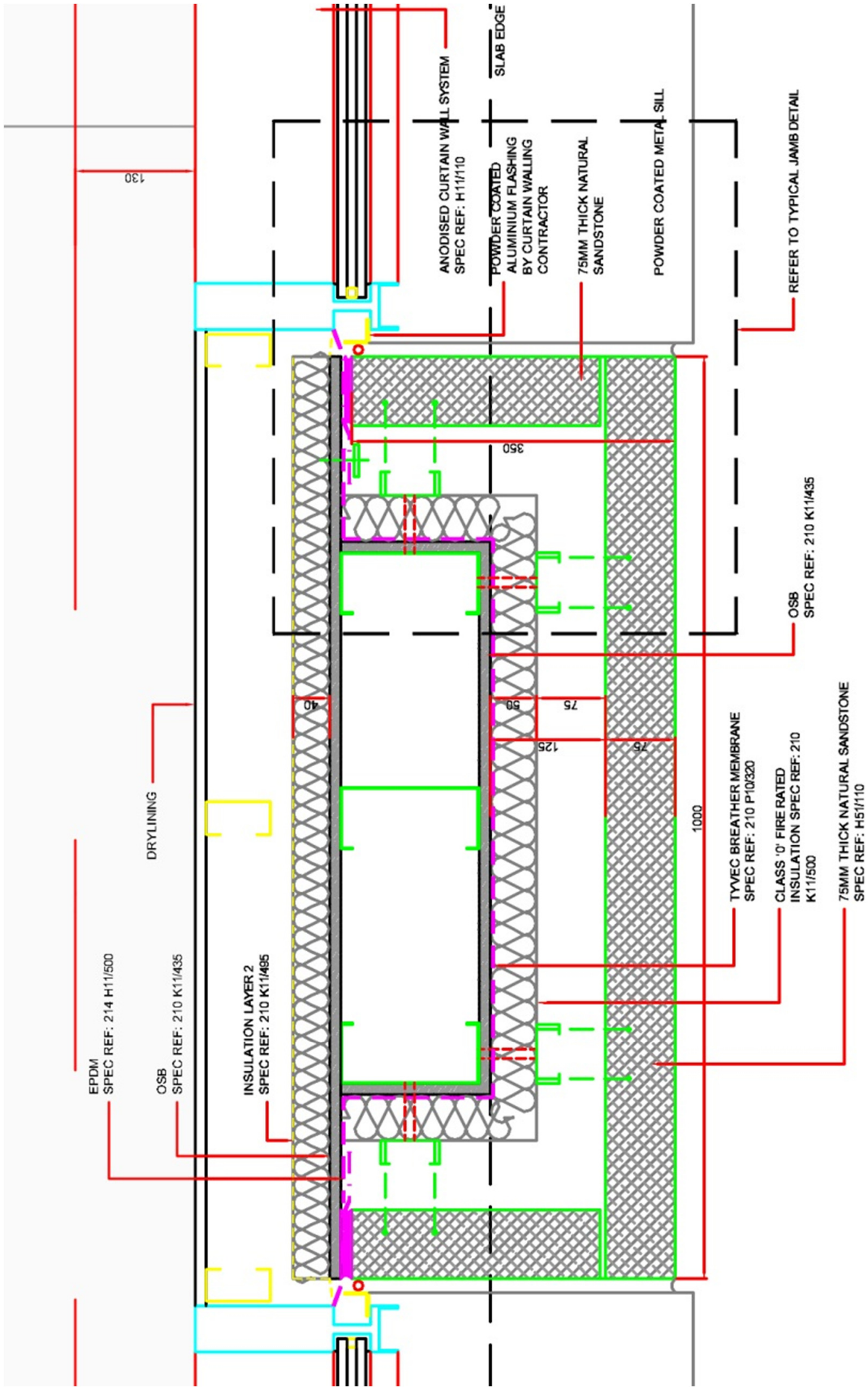

Figure 28 – Wall detail for building A

The main office roof was formed with a structural metal deck laid to create 1:80 falls on stooled Z purlins with a vapour control layer, extruded polyurethane insulation board and a waterproof membrane. The completed assembly provided a maximum 'U' value of 0.25 W/m^2 K, with integral rainwater gutters, rainwater outlets and special eaves detailing which incorporated a profiled cope section to give the appearance of a slender roof edge.

The sixth floor terrace was formed with a concrete roof slab, laid flat without falls, three-layer asphalt tanking membrane, asphalt waterproof membrane, and an extruded polystyrene insulation board. Then, it was finished with a combination of pebble, textured concrete paving and timber decking, where the completed assembly provided a maximum 'U' value of 0.25 W/ m^2 K.

5.2.3. Internal Fabric

The floor was in general a 150 mm high (overall), medium grade raised access floor compliant with PS MOB PF2/PS/SPU & BS EN ISO 9001. It was formed using 600 x 600mm raised access panels of high density particle board core fully encapsulated with a galvanised steel finish and supported at all corner by floor bonded pedestals. The components of the raised access floor were not zinc electroplated.

The floor of the toilet area and the stair cores area consisted of ceramic tile flooring laid on a granolithic screed topping to insulation upfill to make up the difference in floor levels to adjacent raised access floors. Internal curtain walling box sections had a polyester powder coated finish and a painted plasterboard finish was chosen for the unglazed areas of walls with 55mm high painted redwood skirtings.

In the toilets area splash back panels below wash hand basins mirrors were laminate faced panels fixed with timber gravity battens to walls while splash back panels behind the wash hand basins were white powder coated glass panels with drilled holes for the tap ware. Wash hand basin mirrors above the glass splash back panels were full width in the recess with integrated paper towel dispenser and feature uplighting along the top edge.

For the stair cores, painted plasterboard walls were used around the perimeter with a central feature wall of oak veneered panels rising from ground floor to midway between first & second floors with integrated LED feature lighting. Again, painted plasterboard walls were used in the core corridor with oak veneered panels with integrated LED feature lighting opposite the lift entrances and stainless steel surround detail to lift door openings.

In the office areas, toilets, and stair core areas the ceiling consisted of 600mm x 600mm perforated polyester, painted galvanised mild steel access tiles with tegular edges and incorporating a fleece lining. The suspension grid was recessed from the surface of the ceiling to express the tegular edge ceiling tiles. Blind boxes were formed in the detailing of the plasterboard bulkheads at the perimeter of the suspended ceiling adjacent to the glazed areas. Cavity barriers were installed at no more than 20 m centres.

The majority of the perimeter structural concrete columns were concealed behind plasterboard lining. Any exposed columns were circular with a painted finish to the concrete surface. The material used for doors was oak with clear vision panels, and stainless steel push and kick plates and stainless steel ironmongery. The architraves and frames were made from painted wood.

In toilet areas the riser doors were MDF faced solid core, painted with oil paint and fitted with Stanley pivot hinges. The toilet cubicle doors were fitted with gravity hinges, cubicle locks with indicator/emergency release devices, coat hooks and door buffers. A black granite vanitory unit with white round vessel basin 40cm with a wall mounted single lever control washbasin mixer tap was used. The WC was ideal Standard "black + white" range with concealed dual flush cistern. The rear walls of toilet cubicles were formed of laminated faced panels with a concealed lighting recess formed at the top of the panels. Oak veneered doors with stainless steel push and kick plates and high quality stainless steel ironmongery were fitted.

Stairs were constructed in precast concrete with insitu concrete landings with painted mild steel stringer plate and flat bar balustrades with hardwood timber handrail. There was a painted redwood skirting at the landings except for the flights between the ground and the first floor (inclusive) that have hardwood skirting. Hardwood veneered doors with clear vision panels, stainless steel push and kick plates and stainless steel ironmongery were used.

5.2.4. Mechanical Engineering Services

Domestic hot water was provided by electric water heaters located in the core area on each floor. Hot water distribution was in copper pipework to BS 2871: Part 1 with lead free joints thermally insulated throughout. Quantities and locations of water heaters were selected to avoid the necessity for trace heating on the hot water pipework runs.

Natural gas was provided from the utilities meter location to the low temperature hot water boilers located in the plant area. All pipework was adequately painted and identified. All gas pipe routes were adequately ventilated. Gas supply was to boiler installation only. Fundamental design criteria were as follows in Table 13.

External design conditions	All building	Summer	24º C db 17º C wb
		Winter	4º C db 100 per cent rh
Internal design conditions	Offices	Summer	24º C (max)
		Winter	22º C (max)
	Toilets	Summer	
		Winter	22º C (max)
	Staircases	Summer	
		Winter	19º C (Woolley and Kimmins)
Fresh air supply rates	12 l/s/person		
Design occupancy density	1 per 10 m^2		
Air change rates	6 air changes per hour		
Cooling capacity	Lighting load	15 W/m^2	
	Small power load	25 W/m^2	

Table 13 - Fundamental design criteria for building A HVAC system

The office area within the building was provided with comfort cooling / air conditioning using a variable refrigerant flow (VRF) system. This system provided simultaneous heating and cooling. The VRF system was comprised of indoor ducted ceiling void fan coil units and outdoor condenser units connected together via R410a refrigerant copper lines. Each zone was served by a group of indoor fan coil units and one master control box that mixed the gas and liquid refrigerant in the correct proportions to offset the system heating or cooling demand. Each indoor fan coil unit was complete with a drip tray and condensate connection. All condensates were collected via copper drainage pipework and discharged to suitable locations to comply with local drainage authority regulations.

Each group of VRF units was controlled by a room or a return air duct mounted thermostat. Each individual fan coil unit or group of fan coil units was complete with an LCD remote controller. The outdoor condensing units were located externally at ground level and were fitted with high static / resistance fans to overcome the resistance of the acoustic louvers. The indoor fan coil units comprised an in-ceiling void ducted fan coil types. Also, to ensure good air circulation around the outdoor units, high level turbo fans were installed within the external ground floor area.

LTHW Heating was provided to air handling plant and perimeter / core radiators / under floor heating system. The heat source was natural gas-fired boilers located in the basement plant room. This plant room also contained pumping systems and pressurisation equipment. LTHW heating pipework was installed in dedicated risers, ceiling voids etc. Heating pipework was an insulated black mild steel pipework.

Fresh air was provided by a centralised air handling unit located in the basement plant room and supplied conditioned fresh air through galvanised metal sheet ductwork to the ceiling void mounted VRF units. The air supply handling units comprised the following sections: Damper / Silencer / Filter section / Heat recovery / Fan / Heating coil / Silencer. Various additional supply systems were provided to toilet / core areas and cleaners cupboard etc. Office extract air was removed by a centralised AHU located in the basement plant room. Exhaust air was discharged via louvers into the ground floor ramp. The exhaust air handling unit(s) comprised the following sections: Silencer / Filter section / Heat recovery / Fan / Silencer / Damper. Fire dampers were provided where ducts penetrated fire compartments and barriers. Various additional extract systems were provided to toilet / core areas, lift motor rooms, and cleaner's cupboards, etc.

5.2.5. Electrical Engineering Services

A new Scottish Power substation provided the electricity supply to the development. Office supplies had separate meters per lettable floor area (2 no. per floor). A separate landlord's meter was provided for common areas and plant. The main switchboard comprised fuse switches to serve central plant, lifts, landlord's fixed equipment and distribution units throughout the building. A landlord sub-switchboard and distribution boards were provided within the plant room to accommodate electrical supplies to plant and equipment. Distribution cabling generally comprised cable trays within risers from the main switchboard to serve lighting and power distribution boards and fixed equipment within each tenanted floor. Each floor was metered at source by the electricity supply company. A network of data cable trays were installed from telecom intake points (basement plant areas) to vertical risers within landlord's areas only. There was no data containment provided within the office areas. A network of light duty cable trays was installed throughout to accommodate cabling installations associated with fire alarms, door entry, CCTV supplies etc.

Lighting within office areas comprised recessed modular fluorescent luminaires in accordance with CIBSE Guidelines for offices with visual display terminals. The design maintained illuminance at the working plane was 350-400 lux. High frequency ballasts were used to control light fittings. Decorative and feature lighting was used in main entrance and specialist areas. Ancillary areas (such as plant rooms, stores, core areas, etc.) utilised surface and/ or recessed fluorescent sources, with local switches. A fully automatic lighting control system was installed to all office areas, corridors and stairs to allow the individual time scheduling and control of each lettable floor and modularity for extending to cellular offices. Presence detectors were installed throughout.

Lighting control modules (LCM) were installed within the ceiling voids to group a maximum of 8 fittings from a single LCM. Connection to light fittings was via a proprietary multicore plug connector lead. Emergency lighting was installed in accordance with BS5266 and comprised a system of maintained illuminated signs and non-maintained self-contained luminaires. Inverter packs were used with normal service luminaires within open plan office areas. The system operates for a period of 3 hours in the event of local circuit or mains power failure. Self-test facilities were provided for all emergency lighting with control and reporting via a designated P.C. Lighting and emergency lighting were wired using single core cables in a modular wiring containment system for lighting, emergency lighting and fan coil units.

A lightning protection system was provided to comply with BS6651. The entire electrical installation was earthed in accordance with BS7671. An analogue addressable fire alarm system was installed with electronic sounders and manual call points located throughout. The installation complied in all respects with BS5839: Part 1, and met the recommendations and requirements of the local authority and fire officer. A central control and indication panel was provided within the main entrance. The panel monitored and showed status of the fire alarm zones throughout the building and would activate sounders in the event of an alarm. Interfaces were implemented to connect mechanical ventilation and provide shut down under alarm condition. Electrical supplies and control cabling were provided to accommodate the installation of stair smoke ventilation systems.

A CCTV system was installed to cover the main entrance doors and the external perimeter of the development, and a disabled call system was provided to all disabled toilets, linked back to a central audio / visual alarm panel within the main entrance.

5.3. Description of Case Study Building B

Completed in 2009, Building B was part of a development comprising three office buildings. With total area 19,582 m^2, and the development provided efficient and flexible office accommodation capable of accommodating tenants from 219 m^2. Each building had a reception, highly specified in order to cater for the needs of modern tenants.

Figure 29 - Case study building B view from southeast (Google, 2010)

Building B is shown in Figure 29, and was a high-quality office building spread over six floors, with floor plates offering flexible sub-divisions. The office space was developed on a 1.5 m space planning grid, with minimum 2.75 m clear floor to ceiling height, and the building was of "very good" BREEAM Rating. The total gross floor area of this building is 16780 m^2 as detailed in Table 14.

	Net office area	Gross floor area
Basement	0	2606
Ground	1302	2470
First	2040	2610
Second	2134	2610
Third	2133	2610
Fourth	1815	2256
Fifth	1256	1613
Total	10680	16780

Table 14 - Case study building B schedule of areas m^2

The building was designed in accordance with this outline specification, the Building Standards Technical Handbook for Non-Domestic Buildings, May 2006 Edition and generally in accordance with "The British Council for Offices Guide 2005 – Best Practice in the specification of offices". Materials and standards of workmanship complied with the relevant British Standards Specifications and Codes of Practice.

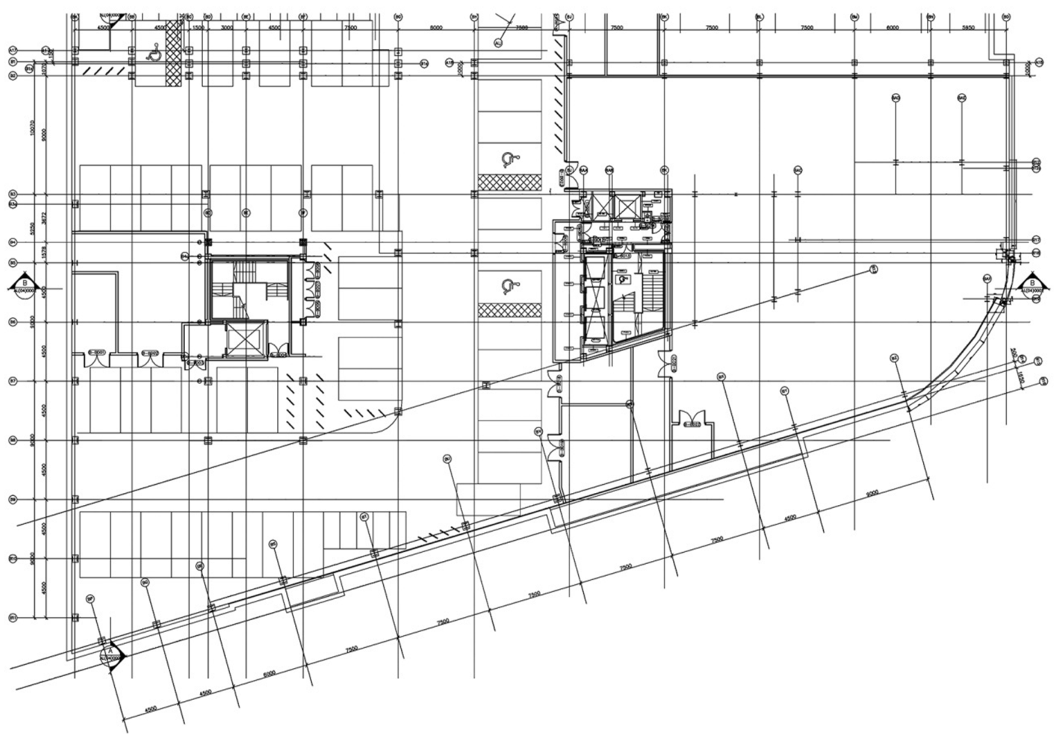

Figure 30 – Basement floor plan of case study building B

The parking is located within the basement which is shared with two other buildings. The basement is spread over a large area under the development and the part allocated to the case study building occupies all the plot area under this building. The basement accommodates plant rooms, services, 44 car parking spaces, and bicycles spaces, see Figure 30.

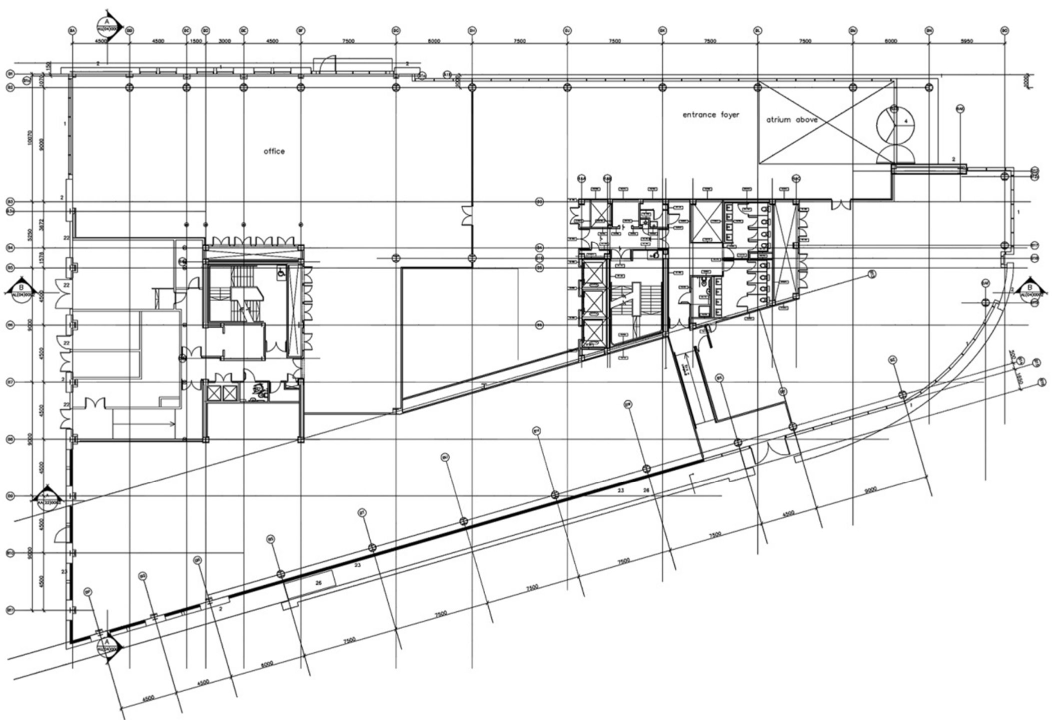

Figure 31 – Ground floor plan of case study building B

The main entrance to the building is located at the east elevation, with access to two office spaces, one retail shop at the main elevation, and access to upper floors via core services area. The office space area in this floor is not as large as upper floors, because the foyer and retail shops are located within this floor, see Figure 31.

The upper three floors are identical, and each of them consists of large flexible office space and two services cores. The office space can be subdivided into multiple spaces according to the occupant companies. There is an atrium within all floor spaces which provide the inner space with natural light within the day time, see Figure 32.

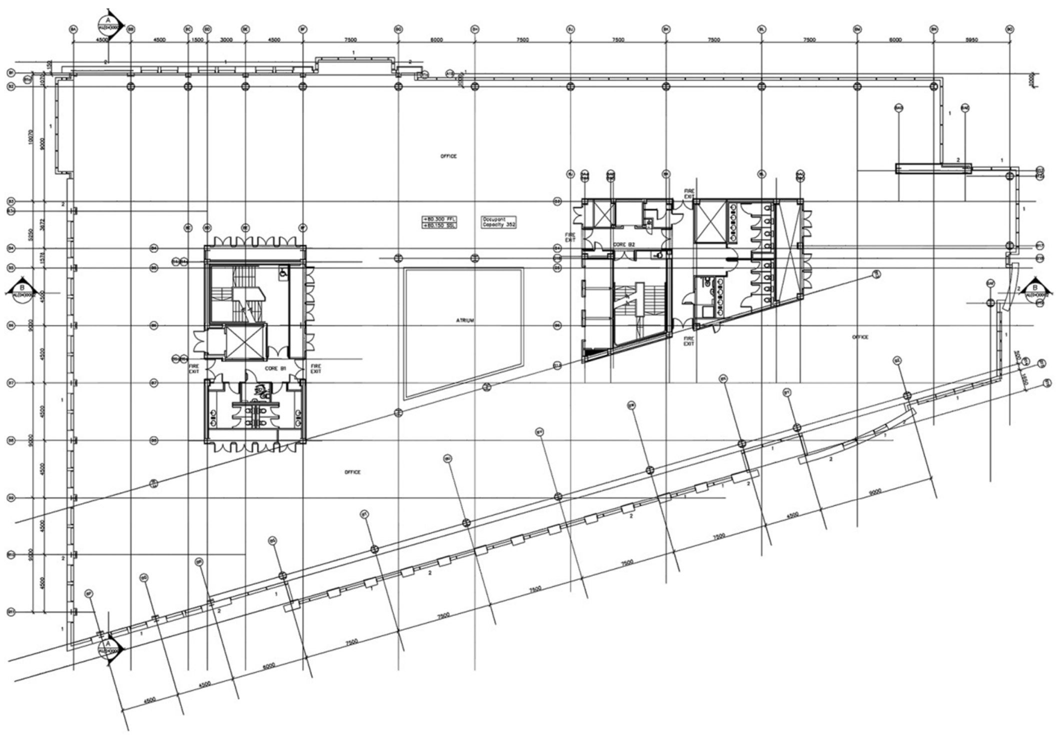

Figure 32 – Identical upper floor plan of case study building B

The fourth floor is similar to the lower ones, but at the west elevation, the external façade step back from the main elevation to make a terrace. This make the office space smaller in this floor, see Figure 33. The fifth floor external envelope is set back from all directions which make the office space much smaller than any other floor approximately 1256 m^2, as seen in Figure 34.

The plant is located at the top of the fifth floor covered by an open covering area, over the core services spaces. The fifth floor external envelope consists of curtain walling, dominated by transparent glass, with doors open to the terrace at all elevations.

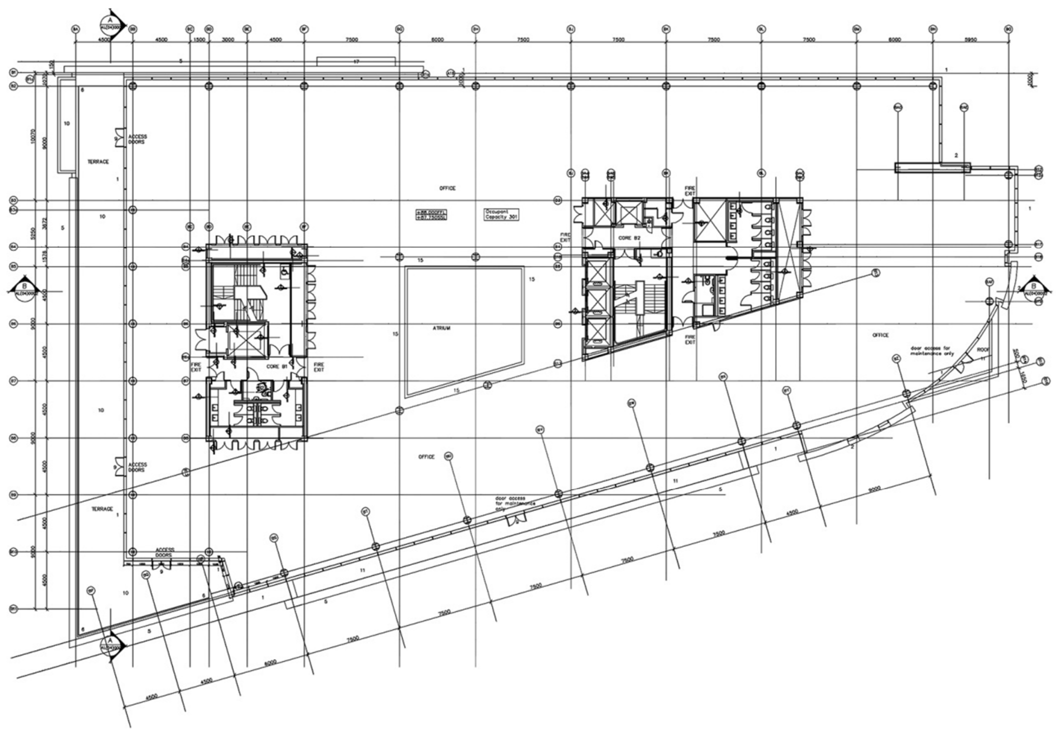

Figure 33 – Fourth floor plan of case study building B

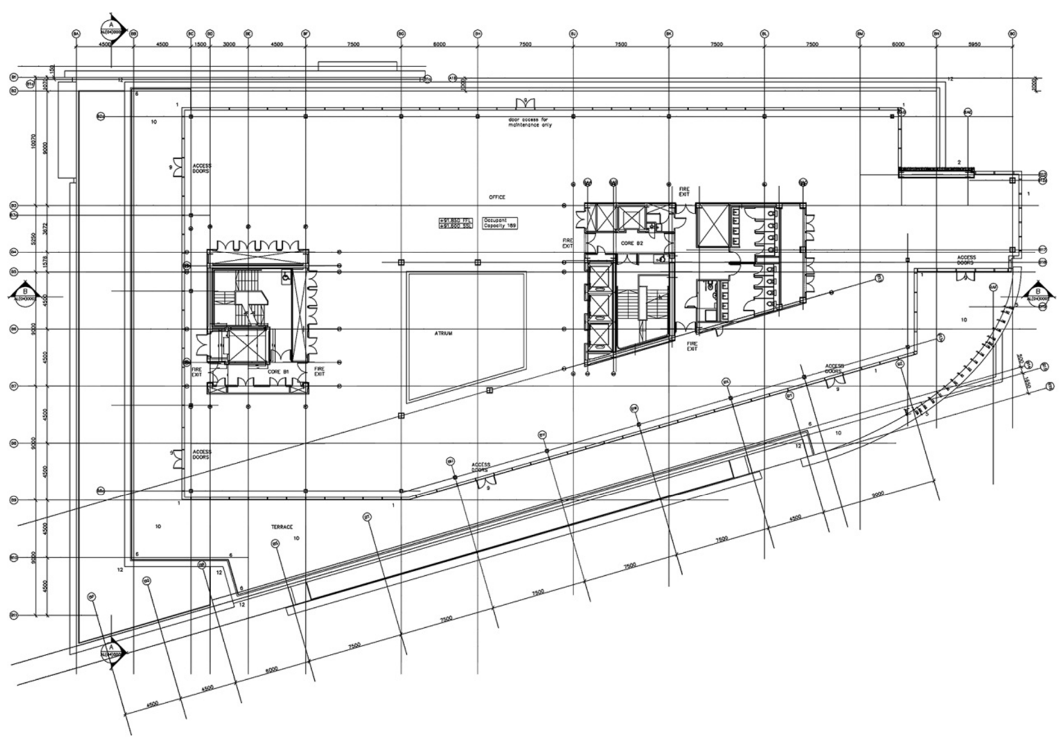

Figure 34 – Fifth floor plan of case study building B

5.3.1. Structure

The basement provided storage, plant along with car parking for 52 cars including 3 disabled person car spaces, 102 bicycles and 27 motorcycle spaces. Also contained in the basement were: water tank rooms, sub-stations, various mechanical / electrical rooms and staircase / lift lobbies. The primary steel frame construction starts from basement level. The basement walls retaining all sides of the basement were formed by use of a reinforced concrete wall including waterproofing membrane. The basement slab was constructed in reinforced concrete and was connected to the reinforced concrete retaining walls and main column pad foundations. The minimum clear unrestricted height below structure and services was 2.050m for all car parking bays and car access routes.

Prior to construction commencing, a detailed site investigation was undertaken to confirm the exact ground conditions. Suitable bearing strata existed below the lower basement slab level. The building frame was founded on reinforced concrete pads integrated with the basement slab. The perimeter columns bear onto the perimeter retaining wall base.

Steelwork was generally designed in accordance with BS.5950:Part1:1990, and with Consulting Engineer's recommendations. To satisfy building regulations to columns and beams, fire protection was added where they were not encased in solid material. Overall stability of the building was provided by braced frames that extended the full height of the building. These were distributed around the structure and designed to transfer lateral forces from each floor / roof level down into the foundation.

The steelwork was based on structural grid of up to 7.5 x 14m. The frame was calculated to accommodate dead loads such as services, suspended ceilings and raised access floors. All beams to floors from ground to roof were constructed of steelwork. The planning grid for the building was based on a notional 1.5 m grid in both directions.

Upper floor construction comprising proprietary metal decking with insitu concrete slab off structural steelwork was designed to carry an imposed loading of 4 + 1 kN/m^2 for partitions. The insitu concrete slab was lightly tamped to receive raised access floor installation. The floor beams were designed to limit the natural frequency of the floor to no lower than 4HZ. Floors generally were a composite floor 150mm thick. Stairs were constructed in pre-cast concrete.

5.3.2. External Envelope

The roof construction was designed to accommodate dead loads such as services and suspended ceilings and external finishes. In addition to the dead loads, it was designed to accommodate imposed loads for a roof with no access, other than cleaning and maintenance, in accordance with BS6399: Part3:1998. All flat roof areas were single ply membrane or similar on extruded polystyrene rigid tapered insulation. Finish was a combination of pebbles and concrete paving slabs on adjustable pedestals. Roof lights over atria were framed toughened and laminated glass supported on a trussed frame system, see Figure 35.

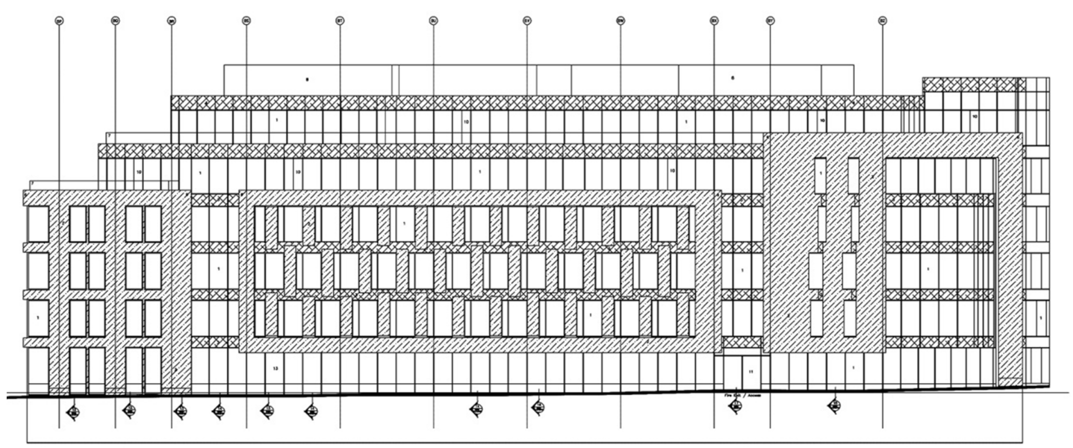

Figure 35 – South elevation of case study building B

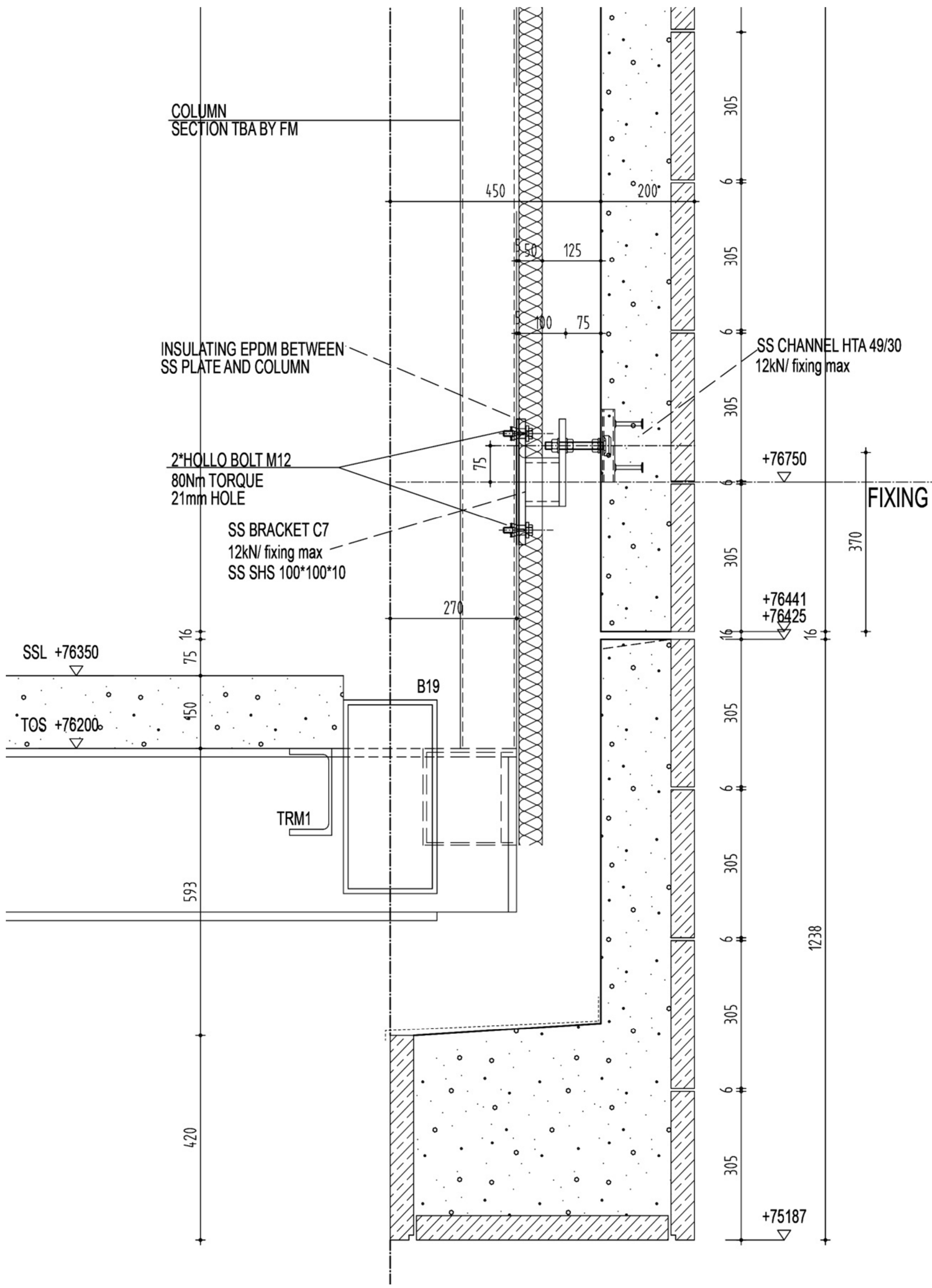

Figure 36 – Wall detail section for building B

Curtain walling system was a thermally broken high performance curtain walling system with clear transparent double glazed units and an anodised or standard polyester powder coated finish. The curtain walling face caps were a combination of standard and feature extruded aluminium sections. Glazing to areas of solar gain had clear transparent inner and outer panes with a “low E” coating. Non-vision glass above ceiling levels was single glazed opaque panes with insulation to rear. Precast concrete panels were faced with natural stone facing which was a combination of sandstone and granite.

Doors to Office Receptions were of a fully automatic operation, 3000mm diameter, fully glazed revolving door set with stainless steel ironmongery and a glass disabled access door, with stainless steel ironmongery. Doors to balcony areas and doors to fire escapes were integral fully glazed units that were aluminium framed polyester powder coated contained within the curtain walling system, with stainless steel ironmongery.

5.3.3. Internal Fabric

Within the office Reception area, high quality ceramic floor tiles were laid on insulation and screed. This finish continued through the main core and into the atria. Walls within the reception area were painted plaster finish. A metal framed suspended plasterboard ceiling was used throughout with features incorporated such as recessed slots.

Generally, all internal doors forming access to office areas were solid core, fire rated where required, timber veneered with hardwood frame. Office doors had fire rated vision panels. Ironmongery was brushed stainless steel.

Office areas had fully accessible, fully encapsulated steel raised access floors with 150 mm from top of slab to top of access floor system, which was glued to top of the concrete floor slab. The floor slab below was lightly tamped and treated with two coats of dust inhibitor. Office areas had a carpet tile finish; anti-static heavy contract grade loop pile carpet tile, adhered to access floor. Cores and common circulation areas had a solid tile floor finish laid on insulation and screed. Skirting, generally, was painted MDF in office area and ceramic tile in other areas.

A minimum clear floor to ceiling height of 2700mm was used. Open plan office ceilings had perforated polyester painted galvanised mild steel access tiles incorporating fleece lining. Ceiling heights in core circulation and toilet areas was 2400 mm. All internal walls received plasterboard dry lining taped and filled, while all areas within the offices and cores, including stairs, received an emulsion paint finish.

Toilet partitions and cubicle doors were full-height timber veneer effect laminate to both faces. Floor finishes were slip resistant ceramic tiling to match general circulation areas. Finishes to walls were generally painted emulsion. Ceiling finishes were plain metal 600 x 600mm clip access ceiling with moisture resistant plasterboard border and edge trim.

5.3.4. Mechanical Engineering Services

The systems were designed, specified, and installed in accordance with 'The British Council for Offices Guide 2005 – Best Practice in the specification for offices', the CIBSE guides, all applicable British Standards, codes of practise, the current building regulations and good practise.

The office areas were heated and cooled with a 4-pipe fan coil system, recessed within the ceiling voids. The basement car park was mechanically ventilated according to Building Control requirements. Plant rooms were primarily located at basement level.

External conditions	All building	Summer	28ºC db 20º wb
		Winter	-3.5ºC db -3.5ºC wb
Internal conditions	Offices	Summer	
		Winter	21ºC ± 1.5ºC dry resultant
	Toilets	Summer	
		Winter	18ºC minimum db
	Staircases	Summer	
		Winter	18ºC minimum db
Fresh air supply rates	12 l/s air / person		
Occupancy density	1 per 10 m^2		
Air change rates	6 air changes / hour		
Cooling capacity	Lighting load	15 W/m^2	
	Small power load	15 W/m^2	
	People load	50 W/ Person	

Table 15 - Fundamental design criteria for building B HVAC system

The mechanical services systems were based on the design criteria mentioned in Table 15. The office installed load was met by fan coils installed on the basis of an equipment gain of 15W/m^2.

The external air infiltration rate was taken as 1 air change per hour in winter and 0.5 air changes per hour in summer. This assumes that the windows were inoperable. This was the minimum air infiltration rate utilised in calculations and was applied to both occupied spaces and ceiling voids.

Component	U-Value W/m^2k
Pitched roofs	0.20
Flat roofs	0.25
Walls	0.30
Walls (Glazing)	1.7
Walls to car park	0.6
Ground floor slab	0.25

Table 16 - U values for building B external envelope

The ground floor was fully insulated as it separates the office from the car park, which was at external ambient temperature.

The air conditioning system was based on ceiling void mounted fan coils designed for open plan offices based on the design criteria in Table 15. Structural bays were split and served by more than one fan coil unit to allow for future flexibility if cellular offices were installed as the system was designed to accommodate future perimeter cellular offices. At the perimeter, one fan coil unit was provided within each structural bay, which covered an area of 6 m x 7.5 m. At the internal zones, one fan coil unit covered an area of between 50-80 m^2. All core and lobby areas were served by a mechanical extract system. Radiators were only fitted in external staircases. The reception area was provided with a separate heating system.

The building heating requirement was met by two gas fired boilers located in the basement plantroom, serving a low temperature hot water (LTHW) system. The entire heating system was selected to incorporate an overload capacity of at least 20 per cent and the central boilers selected to achieve two at 75 per cent of the total load, in order to provide redundancy in case of failure or maintenance. Flue gases were discharged above the roof by means of a stainless steel double skin flue system.

Duty and standby heating pumps were provided complete with automatic changeover on failure. The heating and cooling systems were effectively controlled to maintain the required temperature and avoid simultaneous heating and cooling. The LTHW systems were provided with chemically treated water dosing equipment.

The building cooling requirements were met by at least two packaged air cooled chillers at roof level, the chillers utilised low ozone depletion refrigerants and were CFC and HCFC free. The chillers had a minimum of two 50 per cent refrigerant circuits and were rated above the normal external design condition.

They were mounted on piers with anti-vibration mountings. Chilled water was distributed to the fan coil units via vertical risers and branched pipework in the ceiling voids.

The office areas were provided with fresh air ventilation by central air handling plant. A ductwork distribution system delivered tempered, filtered and fresh air to each ceiling mounted fan coil unit. Extract air was drawn from the office areas utilising the ceiling void as a return air plenum via exhaust grilles. Fresh air was drawn from the Roof, and the exhaust air was discharged at street level and at roof level. The supply air was filtered, heated and cooled as required to meet the design parameters. Exhaust air was removed from the toilet areas at a minimum of 10 ach via dedicated twin extract fans located within the roof level plantroom. Domestic hot water required to serve the office areas, including showers, was guaranteed by means of local electric water heaters located within the ceiling void of the toilets.

The office engineering services were controlled and monitored by a building management system incorporating distributed intelligent outstations controlling all mechanical services installations. The system was complete with a central supervisory workstation which was located at the reception desk.

5.3.5. Electrical Engineering Services

The systems were designed, specified, and installed in accordance with 'The British Council for Offices Guide 2005 – Best Practice in the specification for offices', British Standard 7671, the CIBSE guides, all other applicable British Standards, Codes of Practise, Building Regulations, Health & Safety Guidelines, CDM Regulations and good practice.

The building was provided with a high voltage metered supply from a ring main unit located in a new Scottish Power high voltage switch room at ground level of the building. An HV transformer and low voltage switchgear were provided at basement level. The general office lighting provided a maintained illuminance of between 350 - 400 lux at the working plane. Supply to the building's main distribution was based on 35 W/m^2 after diversity between small power requirements of departments and floors.

The main distribution system for the building (B) consisted of a main low voltage switchboard, sub-metering, sub-main distribution, cable distribution and distribution boards. The distribution system within the buildings consisted of multicore cables installed on cable support systems, feeding tenant's distribution boards on each level, mechanical services and the Landlords services distribution boards. Separate distribution cables were provided to supply main air conditioning/mechanical plant, lifts, etc.

Lighting throughout was in the spirit of the guidance provided by CIBSE LG7 2005 Interior Office Lighting publication. The fluorescent luminaires in the office areas were complete with high frequency dimmable control gear. Lighting generally was designed to achieve an installed power load of 12W per m^2 or less. An automatic lighting control system was installed throughout.

To complement the lighting environment, specialist lighting was installed in all "public" areas such as receptions atria and stairways to enhance the environment. Car park and plantroom areas were illuminated via IP54 rated linear fluorescent luminaires complete with prismatic diffusers and switched via local wall mounted switches. Emergency lighting design complied with BS 5266 and ICEL guidance and incorporated test facilities.

External lighting provided a feature lighting solution which complimented the external façade / glazing profile, whilst still provided adequate access and security lighting around the building perimeter. This was provided to the main facades of the building.

A CCTV system was provided consisting of external dome cameras mounted on the buildings at high level, discrete cameras covering the entrance/exit doors, and cameras covering the basement car park. An intercom system with CCTV identification was also provided at each main entrance linking to the main reception. An access control system was provided at the main reception area of each building.

5.4. Characteristics of the Case Buildings

The cases were chosen based on replication logic so that all the cases having significant differences in their characteristics would still produce the same result. Remenyi (1998) calls this kind of sample, collected with a specific purpose in mind, a judgment or a purposive sample. Case study buildings were selected according to pre-set criteria to fit the study objectives, these criteria include the following:

Both case study buildings are new-build offices in Edinburgh, which are designed by different teams and built by different companies. Both cases are considered by architects and constructors as typical new-build office buildings and they represent the current trend of building in Scotland (Saunders, 2010).

The first building structure used reinforced concrete as the main structural material, different from the second building which is steel structured. The parking in the first building is small in comparison to the one under the second building; this made a huge difference in the embodied carbon. The plot area is smaller in the first case study building, but the building is one storey higher. On top of that, there was an existing building in the first case which required demolition, underpinning, and other activities, while this was not present in the second case.

Both buildings were built and started operating within the last 3 years in Edinburgh, which makes them representative of new-build offices in Scotland.

The current architectural trend of building in Scotland is based on matching the city patterns, and the new-build offices are regulated to fit within this pattern. In both case studies, the use of materials with colours matching the surrounding structures makes them sons of the surrounding environment. The planning permission in Edinburgh concentrates on this match.

Both buildings are built for investment by letting office spaces to companies, thus the office space is dominant in both buildings. The offices were designed and specified at a high level of employee comfort and cheap to run criteria to attract occupants. Not so long after construction completion, both buildings were let completely and fully occupied, and the building systems started working at their default projected capacity.

5.5. Conclusion

Having now described the methods and the case study buildings in chapters 4 and 5, the next chapter presents the results of the life-cycle assessment.

Chapter 6 - Carbon Dioxide Emissions

6.1. Introduction

After presenting the case study buildings, and describing their specifications within the last detailed chapter, it is clear the level of detailing the study dealt with. This chapter presents the results of the methods used to analyse the data of the case buildings presented in this thesis.

The chapter includes a detailed carbon emission calculations and estimations of different life-cycle phases, elements, components, structures, and materials. It looks at the building from different perspectives, and gives the reader a good understanding of all different building activities carbon dioxide emissions.

6.2. Carbon Dioxide Emissions of Case Building A

The study included the analysis of five major phases of building life, starting by the carbon embedded in materials and component combinations, followed by the analyses of the emissions associated with construction activities, then operation phase, maintenance, and end of life carbon dioxide emissions estimations.

The analysis started by contacting the architects who agreed to release the design specifications, and construction drawings. The architect established connections among the researcher and other stakeholders. Meetings were set with different bodies to maintain the data quality at high standard; more explanations could be found in next chapter. Architects and subcontractors were the main sources of building data used for this case study. It is very important to note that this research is held at an early stage of the building life, thus some of the calculations are based on estimations and similar activities emissions data, as explained earlier within this thesis.

6.2.1. Total Life Cycle Carbon

In most typical case study buildings presented in the literature (Khasreen et al, 2009), the embodied energy was responsible for 15–20 per cent of the total life cycle carbon emissions. In this case study it is found that embodied carbon of materials is responsible for 17 per cent of the whole life-cycle carbon emissions if we included the construction phase, see Figure 37.

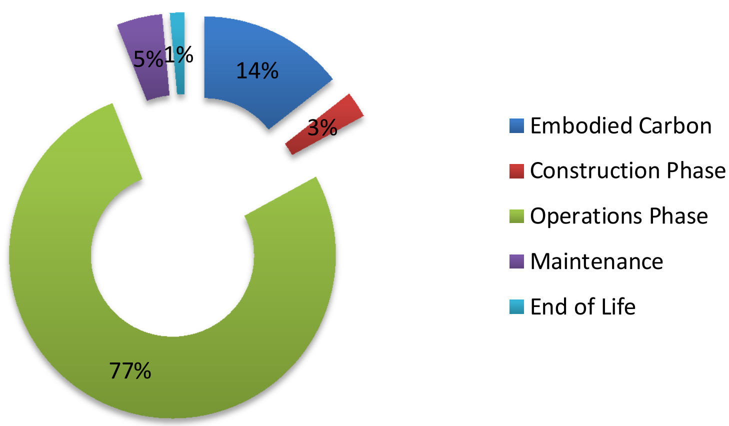

Figure 37 – Building A life-cycle phases carbon dioxide emissions ratios

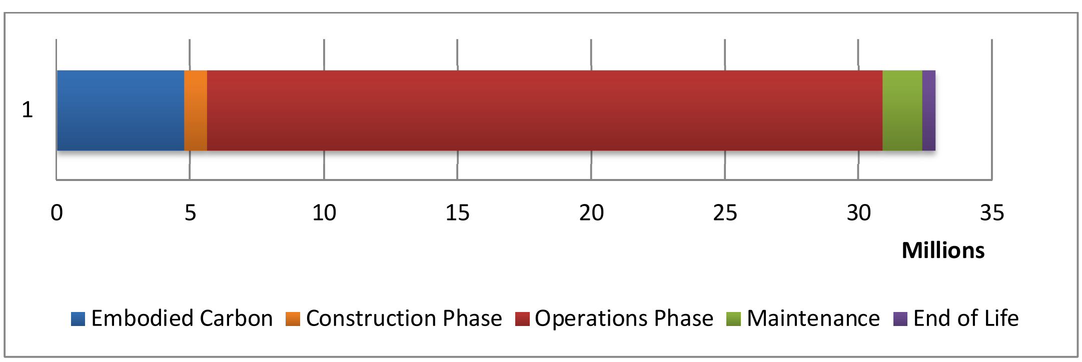

Figure 38 – Different life-cycle carbon emissions of Building A

The estimated total life-cycle carbon for Building A is 32,834 tonnes of CO_2 respectively. The breakdown of this number is explained in the following paragraphs.

6.2.2. Embodied Carbon

Analyses were process based, and two detailed examples of the way embodied carbon of the concrete works and of the curtain walling were calculated from the bills of quantities and the carbon inventory data are given in Appendix B. The level of care and attention to detail needed in this process should not be underestimated. The process was repeated for all the other building items, systems, and components. In summary, these analyses showed that the embodied carbon of case study building materials came to a sum of 5325 tonnes of CO_2. Most of these emissions (approximately 3200 tonnes of carbon) are embedded in the main structure of the building. Figure 39 presents embodied carbon of the different systems. Interior works is the second biggest contribution followed by building construction phase, at approximately 856 tonnes of carbon.

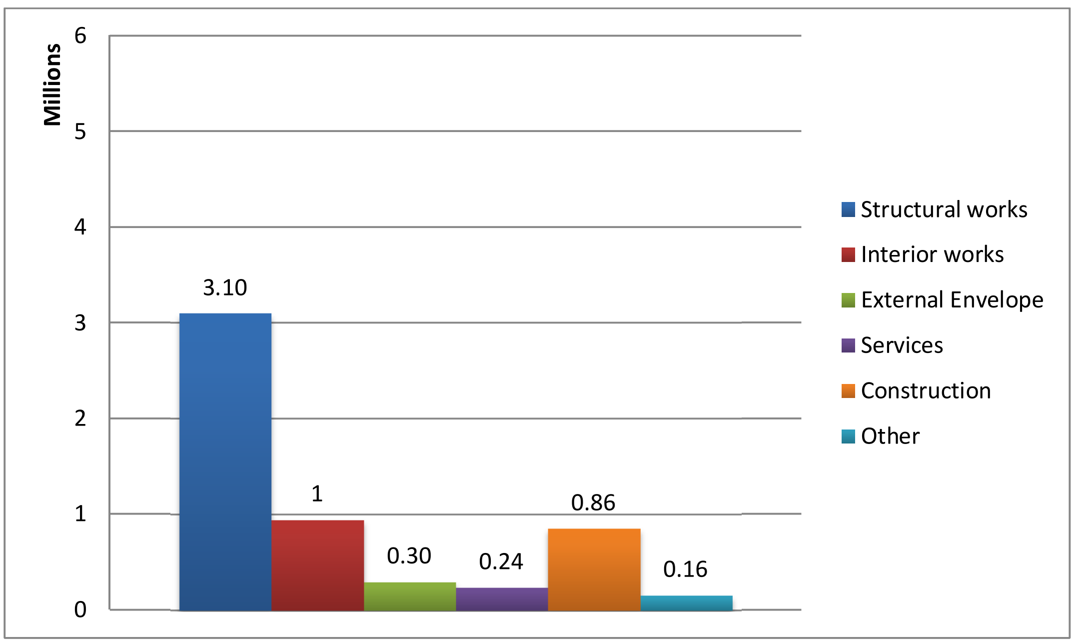

Figure 39 - Embodied carbon of different building systems for building A (kgCO_2)

Process based analyses are time consuming, but it is generally agreed that they are more accurate than any other type of life-cycle analyses. The level of detailed understanding was set to come up with accurate results respectively.

Comparisons between different ways of calculating embodied carbon took place to assure the correctness of the calculations and raise the quality of the research. For instance, to calculate the carbon embodied in the reinforced concrete, there was a possibility to use multiple ways. The first is to use the inventory carbon data which gives the Carbon Emission (CE) per cubic meter. Another way uses the unit $kgCO_2/kg$ of reinforced concrete; this method uses the data of used concrete after adding the appropriate reinforcement emissions. And the third way subdivides the cubic meter into materials (cement, sand, aggregates, water, and reinforcements) then work on finding the weight and the emission of each one. In this case carbon data which uses the unit $kgCO_2/kg$ for each material is used. Careful attention is needed in order not to mix units up in the same calculation.

Figure 40 shows that cement in the structure is responsible for approximately 1745 tonnes of carbon emissions, and is the most polluting material, followed by reinforcement which is responsible for approximately 705 tonnes of CO_2 for the whole building.

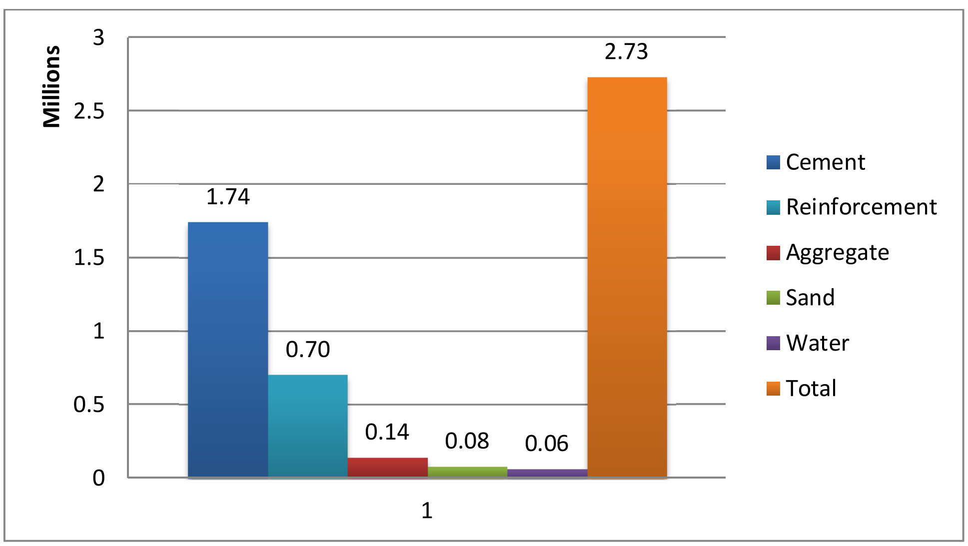

Figure 40 - Carbon embodied in reinforced concrete ($kgCO_2$)

Concrete excluding reinforcement emitted 2028 tonnes of carbon, and was the key pollutant among the other components of the main structural frame as presented in Figure 41. It was followed by the reinforcement bars, then excavation, underpinning, drainage system, waste disposal, and other activities.

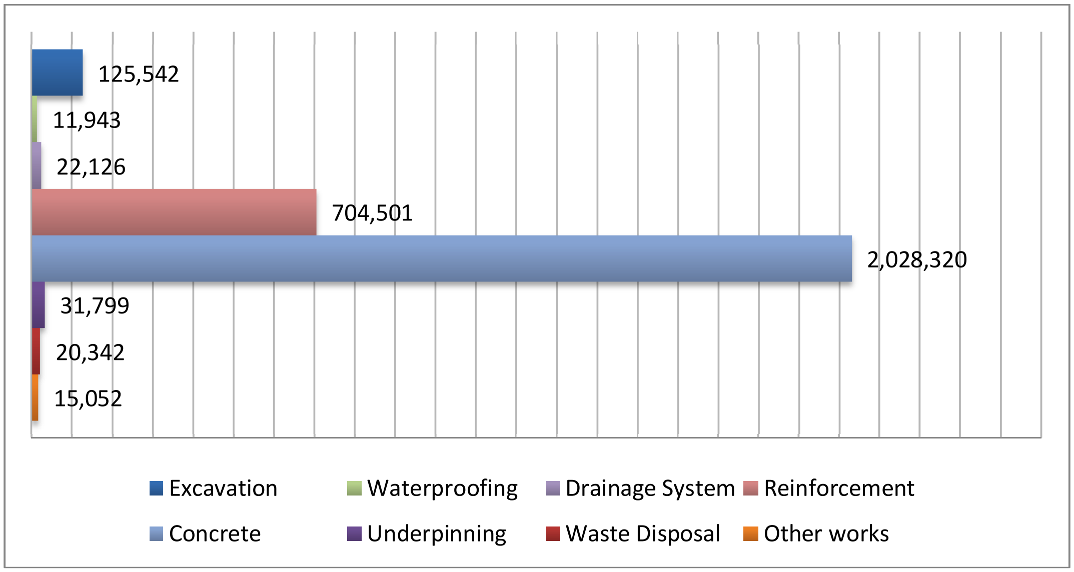

Figure 41 - Carbon embodied in structure ($kgCO_2$)

6.2.3. Operations Phase

This phase is a key player in the total carbon emissions over the 50 year life. Electricity use over the life-cycle of this building was the major factor, which is responsible for up to 89.4 per cent of the carbon emissions of the use phase. The other 10.6 per cent is emitted by natural gas consumption.

Table 17 presents the carbon emissions of different operations over a year. The total comes up to 505 tonnes of carbon per year. If the whole life-cycle of the building is considered, the number will be multiplied by 50. The numbers used in the display energy certificate of the building is the total of carbon emissions excluding the equipment emissions. In this case the carbon consumption of the building is 30 kg/m^2 per year. If we consider the equipment emissions, this number will go up to 42 kg/m^2 per year. And if we consider the embodied carbon, the number will be higher. It could go up to 52.5 kg/m^2 per year if the whole life cycle emissions were considered. HVAC system emits more carbon than lighting and equipment, but as noted in Figure 42 and Figure 43, the ratio is as follows: 38 per cent for HVAC system, 32 per cent for lighting, and 30 per cent for equipment.

Systems	HVAC gas CE ($kgCO_2$)	HVAC elec. CE ($kgCO_2$)	Lights elec. CE ($kgCO_2$)	Equip elec. CE ($kgCO_2$)	Total elec. CE ($kgCO_2$)	Total CE ($kgCO_2$)
Summed total	53315	136101	161056	154878	452034	505350

Table 17 - Carbon dioxide emissions of systems over a year of operation

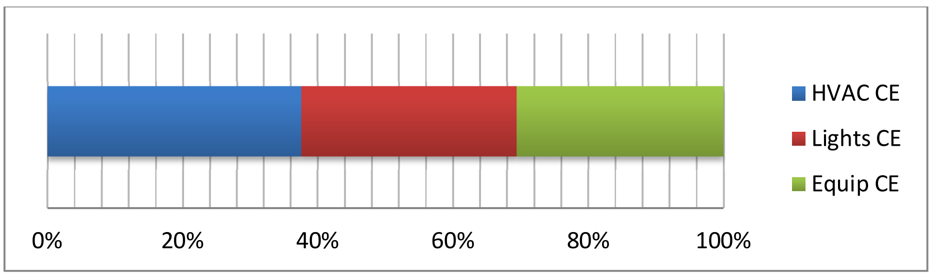

Figure 42 – Operation systems carbon dioxide emission ratios

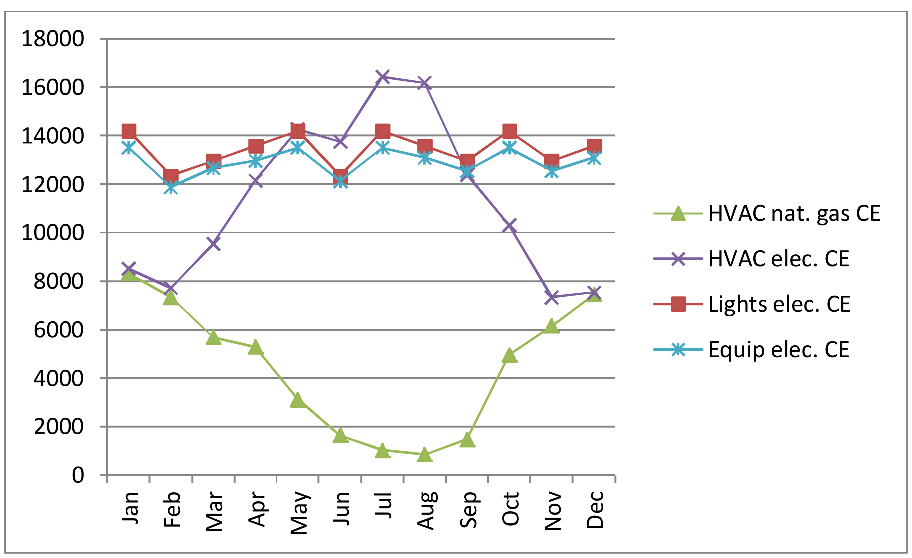

Figure 43 - Carbon emissions of systems over a year of operation ($kgCO_2$)

6.2.4. Maintenance Carbon

Maintenance of building A excluding any major refurbishment is estimated to emit 1492 tonnes of CO_2 most of which are related to interior works maintenance approximately 1126 tonnes of CO_2 followed by services maintenance then external envelope and structure, see Figure 44.

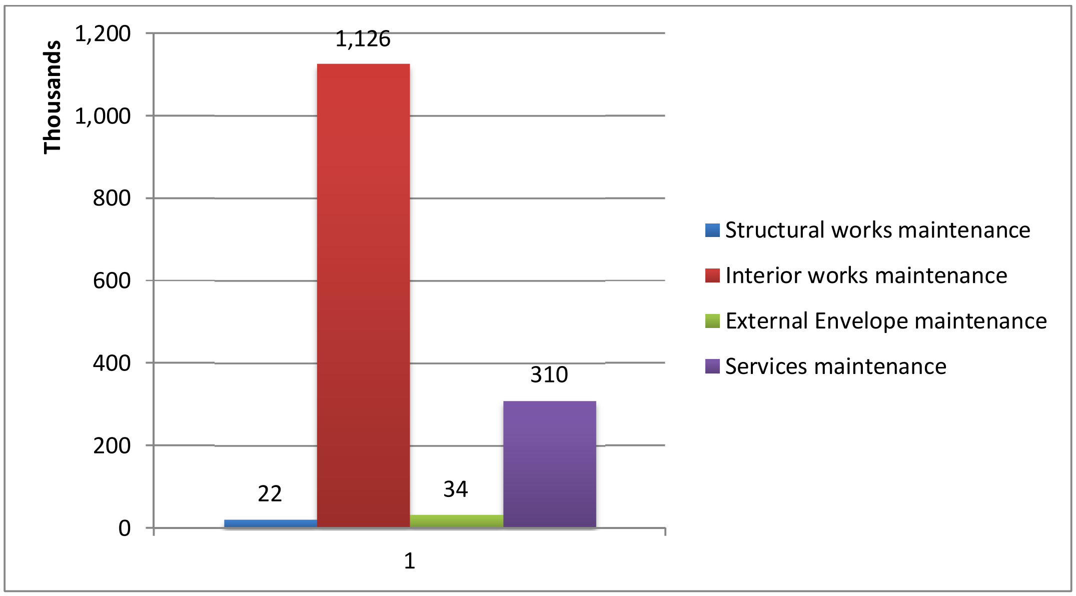

Figure 44 – Maintenance carbon dioxide emissions of building A

6.2.5. Deconstruction and Demolition

Building demolition as mentioned earlier in this thesis is based on an assumed demolition and recycling scenario. A sum of 75 per cent of the materials will need transportation because they will not be used on site. Being possible to be recycled materials will not affect the embodied carbon of this building, but benefits will be gained by next building, and this is outside the study boundary. It is found that the demolition plant emissions and waste transportation will be responsible for 475 tonnes of CO_2.

This estimate is based on data collected from site reports of UK buildings demolition energy consumption and carbon emissions. Each tonne of demolished materials consumes 15 kg CO_2 in general.

6.2.6. Conclusion

This case study of building A has added a life-cycle assessment study of office building in the UK to the growing literature. As presented, in a typical new-build office building in Scotland the largest contribution to CO_2 emissions is from the operational phase. Embodied carbon in this office building contributes 14 per cent of the whole life-cycle carbon emissions. Construction and end of life treatment are responsible for not more than 4 per cent of the whole life-cycle carbon emissions, while the maintenance scenarios assumed in this study is responsible for 5 per cent of the total life-cycle emissions, see Figure 45.

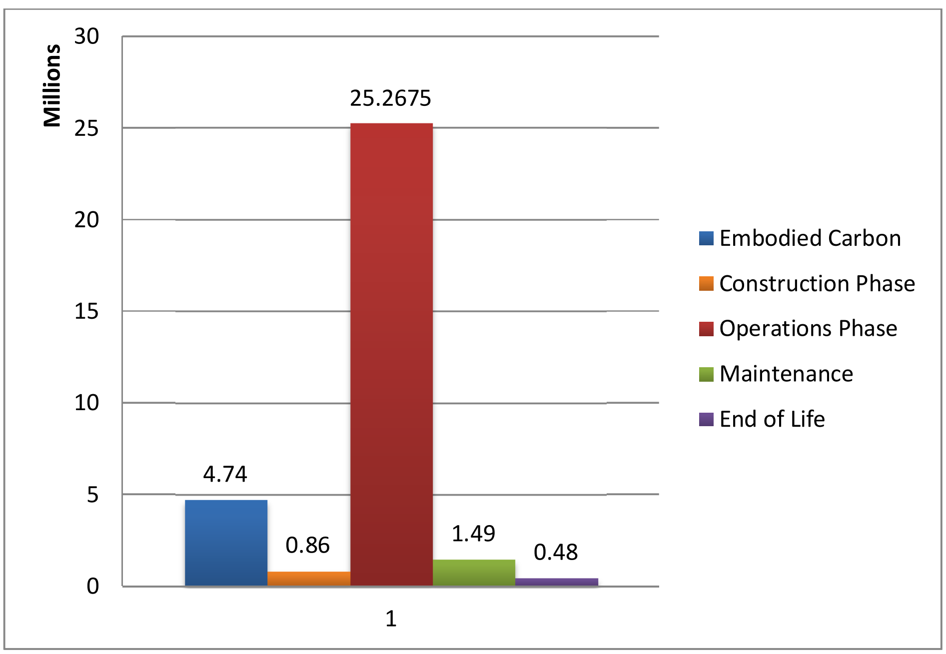

Figure 45 - Carbon emissions of different life phases for building A

6.3. Carbon Dioxide Emissions of Case Building B

As presented in chapter 6, building A and building B have common features, which make them suitable for the purpose of this research study. However, Building B is different from building A in many other features which make them random cases of new-build offices in Scotland. These differences are illustrated in chapter 6, and interpretation of these differences will be explained in chapter 8.

6.3.1. Total Life Cycle Carbon

As already noted, in most typical case study buildings presented in the literature (Khasreen et al, 2009), the embodied carbon was responsible for 15–20 per cent of the total life-cycle carbon. In this case study it is found that embodied carbon of materials is responsible for 16 per cent of the whole life-cycle carbon emissions, and this ratio can be 19 per cent if we add the construction phase activities to the number, see Figure 46.

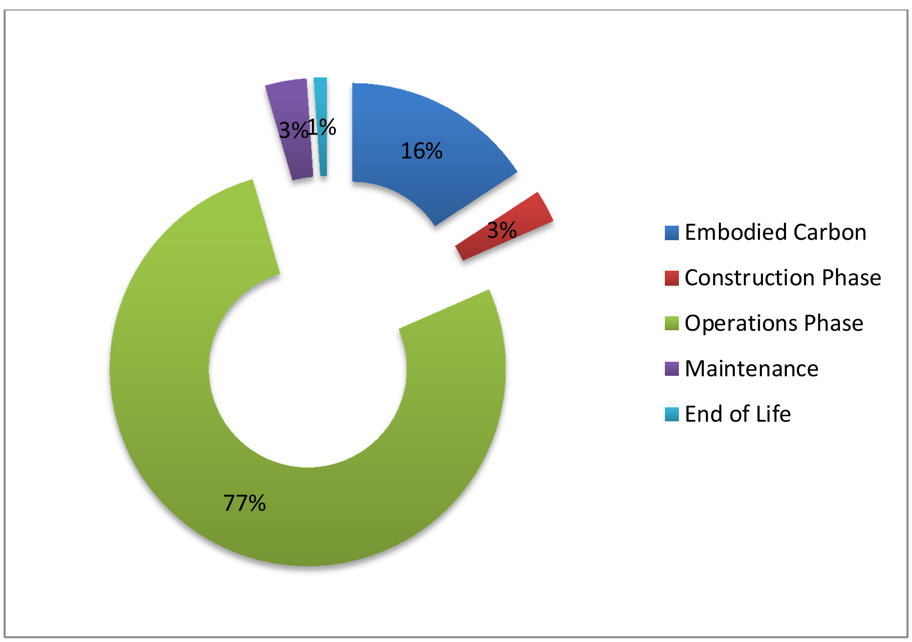

Figure 46 – Building B life-cycle phases carbon dioxide emissions ratios

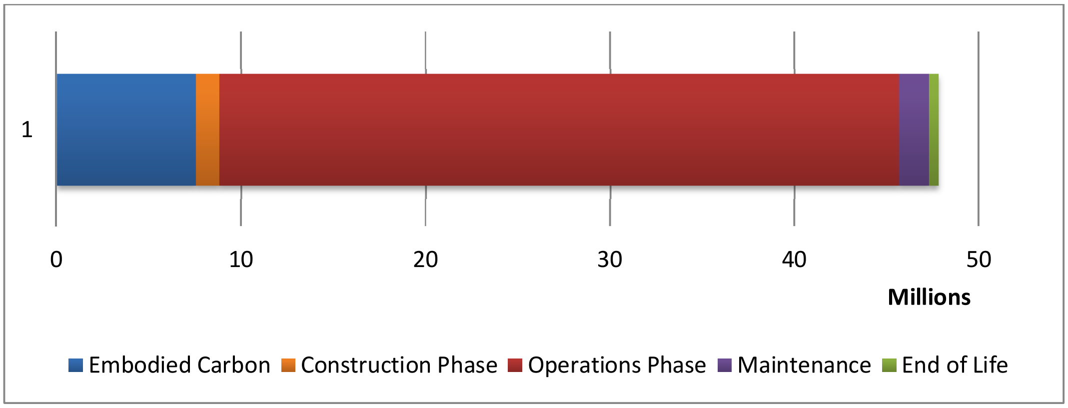

Figure 47 – Different life-cycle carbon emissions of Building B

The estimated total life-cycle carbon for Building B is 47,768 tonnes of CO_2. The breakdown of this number is explained in the following paragraphs.

6.3.2. Embodied Carbon

Similar analyses were used for the second case study. These analyses showed that embodied carbon of case study building materials came to a sum of 8815 tonnes of CO_2. Most of these emissions (5036 tonnes of carbon) are embedded in the main structure of the building. Figure 48 presents embodied carbon of the different systems. Interior works is the second biggest contribution to the embodied carbon followed by building construction phase which is responsible for approximately 1282 tonnes of carbon.

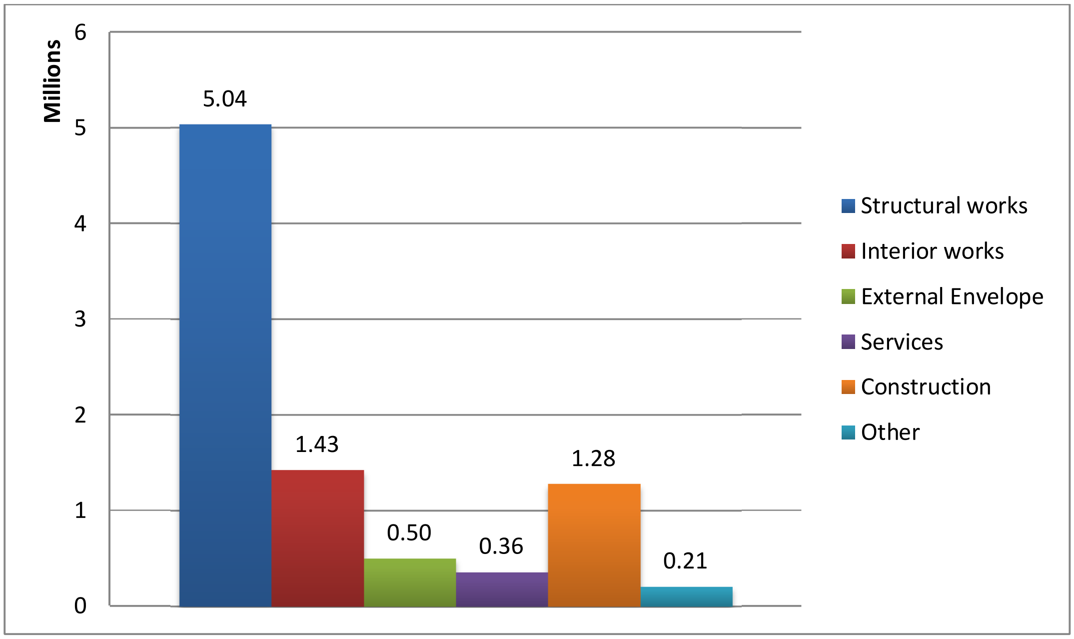

Figure 48 - Embodied carbon of different building systems for building B (kgCO_2)

Similar analysis were used to calculate carbon emissions of this building, these analysis are time consuming, but it generates reliable results as stated by different research publications.

In this case study, the architect played a core role to secure permissions and build connections with the owner, contractor and sub-contractors. Data was cross checked using different methods of calculations in similar process to the calculation of first case study building.

This building is steel structured, and has a large parking space within the basement which required large quantities of reinforced and normal concrete used for building retaining walls, foundations, back filling concrete, and ground and upper floors. This makes the building structure different from the first case study building which had a concrete structure with smaller basement. This affected the embodied carbon of the building structure as follows:

Structural steel is the main responsible for emissions as presented in Figure 49. This was followed by concrete which was responsible for 1866 tonnes of carbon emissions. Reinforcement bars comes after concrete with 232 tonnes of carbon emissions. Excavation is another significant aspect which emitted 79 tonnes of carbon.

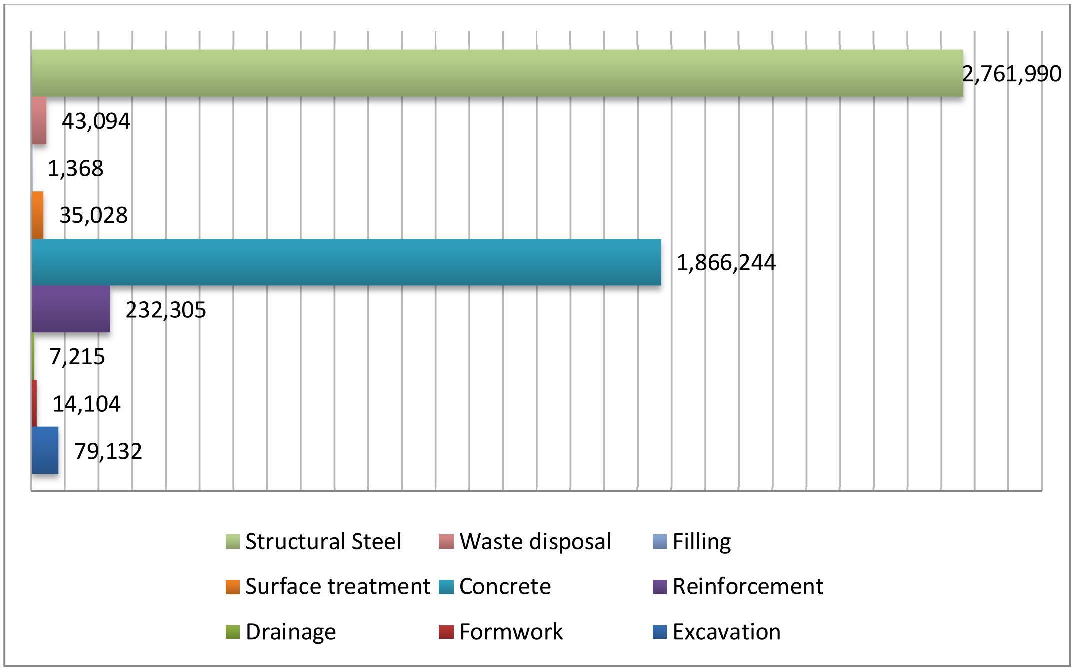

Figure 49 - Carbon embodied in building B structure ($kgCO_2$)

6.3.3. Operations Phase

The same life time is expectation is used in both case study buildings. The building is supposed to live for 50 years in service. The operations phase includes activities related to internal climate control, heating, cooling, artificial lights, and power necessary for running equipment. This phase is a key player in the total carbon emissions over the 50 year life-cycle. Electricity use over the life-cycle of this building was the major factor, which is responsible for up to 87.9 per cent of the carbon emissions of the use phase. The other 12.1 per cent is emitted by natural gas consumption.

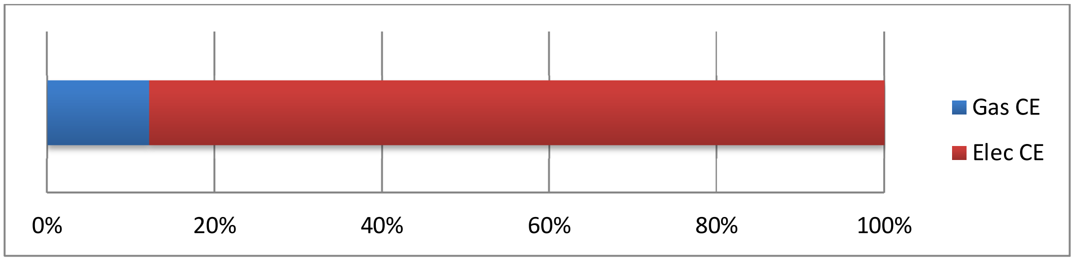

Figure 50 – Gas verses electricity emissions during building B life

The carbon emissions of different operations over a year are presented in Table 18. The total comes up to 736.5 tonnes of carbon per year. If the whole life-cycle of the building is considered, the total operation phase will be 36,822 tonnes of carbon emissions which make 77 per cent of the total life-cycle emissions.

The numbers used in the display energy certificate of the building is the total of carbon emission excluding the equipment emissions divided by building area, as the unit used for the certificate is $kgCO_2/m^2$ per year. In this case the carbon consumption of the building is 32 kg/m^2 per year. If we add the equipment emissions, this number will go up to 43 kg/m^2 per year. And if we consider the embodied carbon, the number will be higher. It could go up to 57.5 kg CO_2/m^2 per year if the whole life cycle emissions were considered.

Systems	System gas CE ($kgCO_2$)	System elec. CE ($kgCO_2$)	Lights elec. CE ($kgCO_2$)	Equip elec. CE ($kgCO_2$)	Total elec. CE ($kgCO_2$)	Total CE ($kgCO_2$)
Summed total	89265	224117	271935	151131	647182	736449

Table 18 - Carbon emissions of systems over a year of operation

In spite of the different from the first case study, HVAC system still emits more carbon than lighting and equipment, but as noted in Figure 51, the ratio is as follows: 42.5 per cent for HVAC system, 37 per cent for lighting, and 20.5 per cent for equipment.

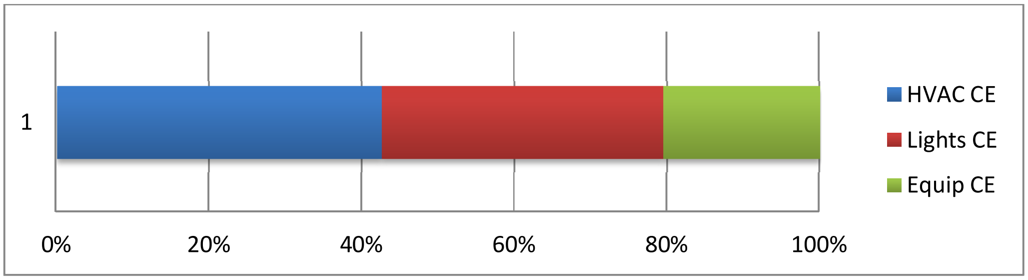

Figure 51 - Carbon emissions of different operations (kgCO_2)

6.3.4. Maintenance Carbon

Maintenance of building B excluding any major refurbishment is estimated to emit 1629 tonnes of CO_2 most of which are related to interior works maintenance approximately 1140 tonnes of CO_2 followed by services maintenance then external envelope and structure, see Figure 52.

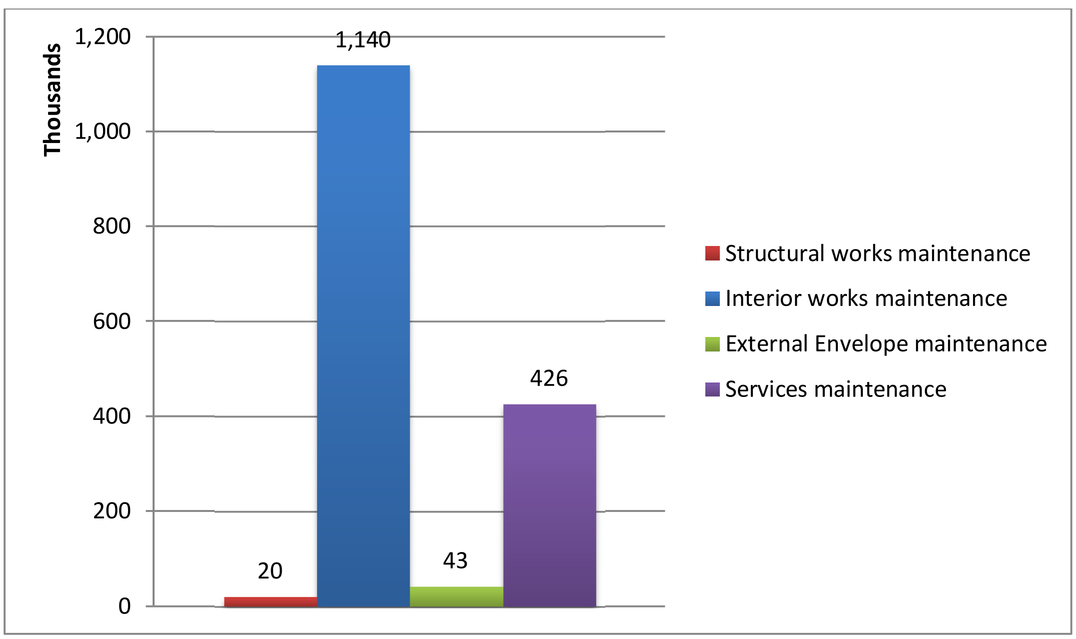

Figure 52 – Maintenance carbon dioxide emissions of building B

6.3.5. Deconstruction and Demolition

The same scenario was used for both case studies as presented in paragraph 6.2.5. A sum of 75 per cent of the materials will need transportation because they will not be used on site. It is found that the demolition plant emissions and waste transportation will be responsible for 520 tonnes of CO_2.

This estimate is based on data collected from site reports of UK buildings demolition energy consumption and carbon emissions. Each tonne of demolished materials consumes 15 kg CO_2 in general. End of life treatment for this building does not count more than 1 per cent of the whole life-cycle phases, see Figure 53.

6.3.6. Conclusion

This case study of building B has added a life-cycle assessment study of office building in the UK to the growing literature. As presented, in a typical new-build office building in Scotland the largest contribution to CO_2 emissions is from the operational phase. Embodied carbon in this office building contributes 15.7 per cent of the whole life-cycle carbon emissions. Construction and end of life treatment are responsible for not more than 3.7 per cent of the whole life-cycle carbon emissions, while the maintenance scenarios assumed in this study is responsible for 4 per cent of the total life-cycle emissions, see Figure 53.

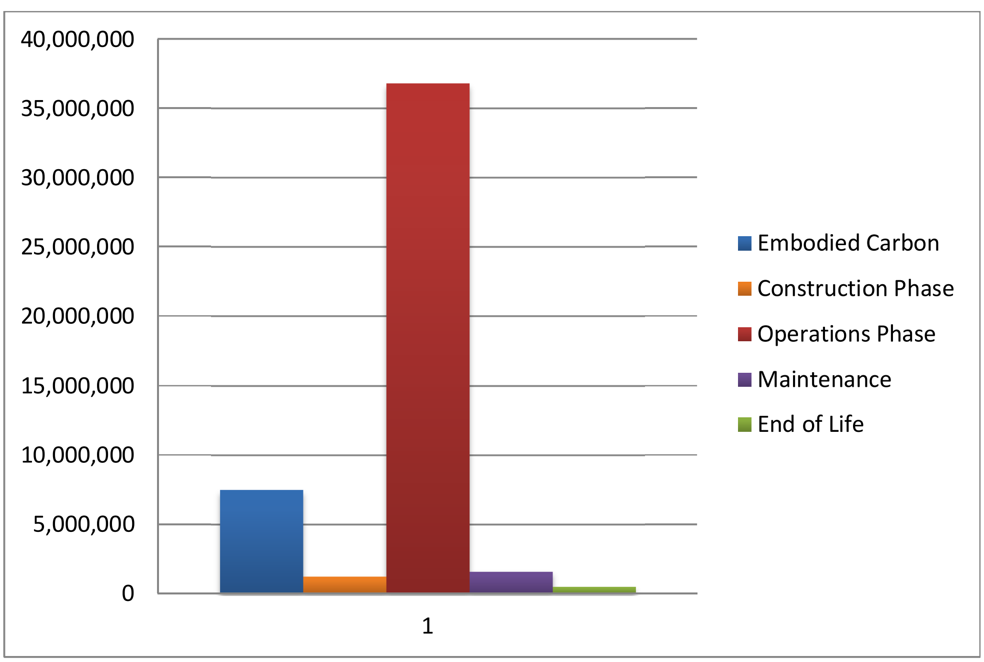

Figure 53 - Carbon emissions of different life phases for building B

6.4. Significant Aspects

Looking at the whole life-cycle emissions of the building, after the previous calculations and estimations, and using the life-cycle assessment as a prediction tool allows the designers to review their work and get benefits for future building projects. A key task as benefit of these presented numbers is to find the weak points in the process and identify the most significant polluting materials, or activities to find solutions and recommendations for carbon emissions reduction.

These preliminary case studies serve as base cases to perform sensitivity analyses, based on "what if" scenarios. For example, reducing the glazing ratio is found to cause a slight increase in the embodied carbon but a significant decrease in the operational carbon. Another example might draw attention to the ratio of wall insulations and U values which have significant effect on operational energy. Moreover types of HVAC systems and other building technologies might reduce the total emissions of the buildings.

In most of these sensitivity analyses, the possibility of investing carbon is present, and an increase in the embodied carbon might result in huge savings in operational carbon emissions. This is an avenue for such research which can only be undertaken following definition of base case studies such as this one for buildings in Scotland.

The significant environmental aspects of the office building's life cycle are specified in this paragraph. The determination of significant environmental aspects is valuable, for example, in environmental management, where it is used to prioritize environmental work in a company or in a project. The significant environmental aspect is defined as an element of an organization's activities or products that have or can have significant impacts on environment (ISO 14001, 1996). The environmentally significant aspects were selected in order of magnitude so that in each impact category the selected aspects cover large percentage of the impact in the given category.

6.4.1. Materials and component combinations

In Table 19, aspects are considered significant if their ratio is higher than 1 per cent of the total embodied carbon. These aspects are highlighted in bold within the table, and explained in this paragraph.

Activities	Case building A	Case building B
Structure	**65.4**	**66.9**
Underpinning	0.7	0.0
Excavating	**2.6**	**1.1**
Filling	0.1	0.0
Formwork	0.1	0.2
Concrete work	**42.8**	**24.8**
Waterproofing	0.3	0.2
Disposal systems	0.5	0.2
Reinforcement	**14.9**	**3.1**
Steel	**3.0**	**36.7**
Surface treatment	0.1	0.1
Waste disposal	0.4	0.6
Interiors	**20.0**	**18.9**
Dry lining	**9.2**	**4.6**
Flooring	**4.9**	**10.2**
Ceilings	**4.0**	**2.6**
Door sets and joinery	0.6	0.2
Metal works	0.4	0.4
Block works	0.9	0.9
External envelope	**6.3**	**6.7**
Curtain walling	**3.1**	**3.6**
Cladding works	**2.4**	**2.1**
Roof works	0.8	**1.0**
Electrical and mechanical systems	**5.1**	**4.8**
Other	3.3	2.8
Total embodied carbon	**100**	**100**

Table 19 – Activities contributing to embodied carbon (per cent)

Using the information presented in Table 19, it is clear that building structure is the main activity responsible for carbon emissions in both case studies. Within the structure emissions of building A concrete has the biggest contribution, followed by reinforcement bars. Regardless the fact that building B is steel structured, steel is the main activity responsible for carbon emissions followed by concrete which was responsible for 24.8 per cent of the embodied carbon. This is because the parking provided in building B is larger than in A, and the concrete used for constructing the structure of the basement is counted within the embodied carbon calculations. See Figure 54.

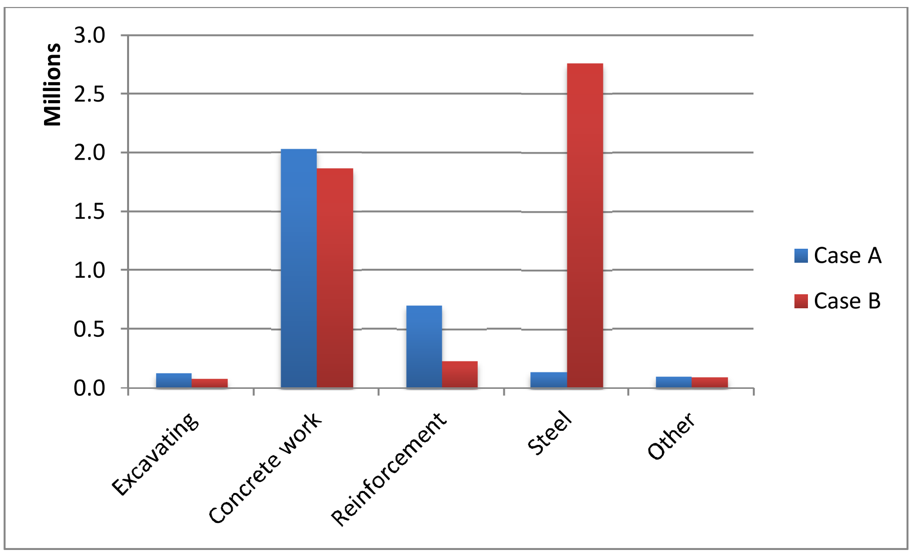

Figure 54 – Structural systems emissions (kg CO_2)

Interior works has the second biggest amount of carbon dioxide emissions among the rest of other systems. The presence of raised access flooring in case building B makes flooring the biggest contributor accounting for 770 tonnes of carbon emissions, followed by dry lining which is responsible for approximately 350 tonnes of carbon emissions.

In building A, the dry lining is the main pollutant responsible for 435 tonnes of carbon emissions, followed by flooring. In both cases ceiling activities is the third significant aspect accounting for 4 per cent of the embodied carbon of building A, and 2.6 per cent in B, as presented in Table 19.

Other activities and components like door sets and joinery activities, metal work, and block works are not considered to be significant in this study, however, they could be more significant than other components in other cases as buildings are unique creatures, and study holder should deal with each case separately. For example, in older offices, closed systems were used and office space was not open as in current trend buildings. This increases the numbers of door sets and increases the block work and other activities, and may make them more significant than the aspects which are considered significant in this study.

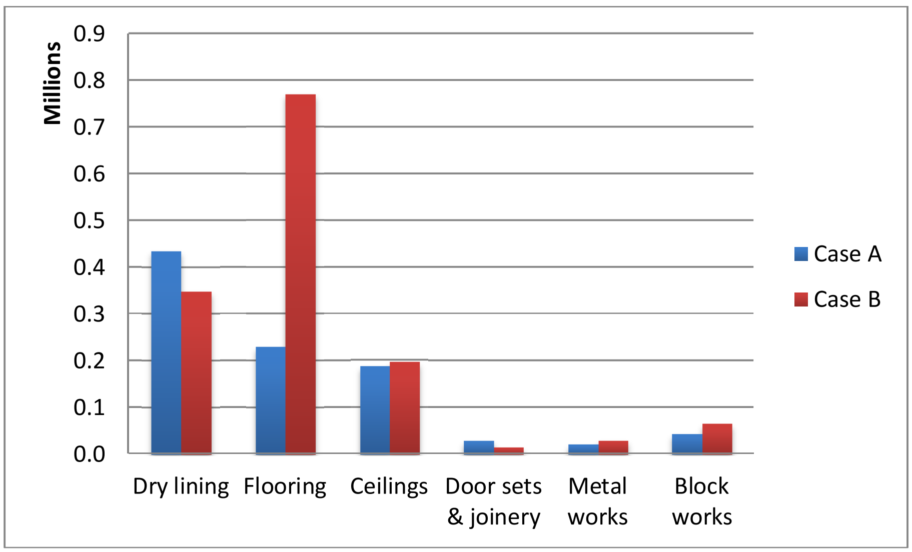

Figure 55 – Interior works carbon dioxide emissions (kg CO_2)

The use of natural stone within the external envelope is generally considered to have a good impact on the carbon dioxide emission of buildings. Particularly in these cases, this study emphasizes the importance of this item, as it has low embodied carbon figures, for instance a locally quarried kg of natural stone respectively has 0.06 kg of carbon embedded in it. In addition to that, the use of natural stone with an external wall structure helps the designers to easily achieve the advanced level of U-value for office buildings 0.1 W/m²K recommended by the Low Carbon Building Standards Strategy For Scotland (Sullivan, 2007).

In both cases the external envelope was responsible for not more than 7per cent of the total embodied carbon, while in other cases presented in chapter 4 the external envelope could be responsible for up to 20 per cent of the embodied carbon. For building A, curtain walling accounted for 146 tonnes of carbon emissions, followed by cladding works at 115 tonnes of CO_2 emissions then the roof works. Similar to that order, within the second case curtain walling was responsible for 271 tonnes of carbon emissions, followed by cladding work at 156 tonnes, then roof works at 75 tonnes of CO_2.

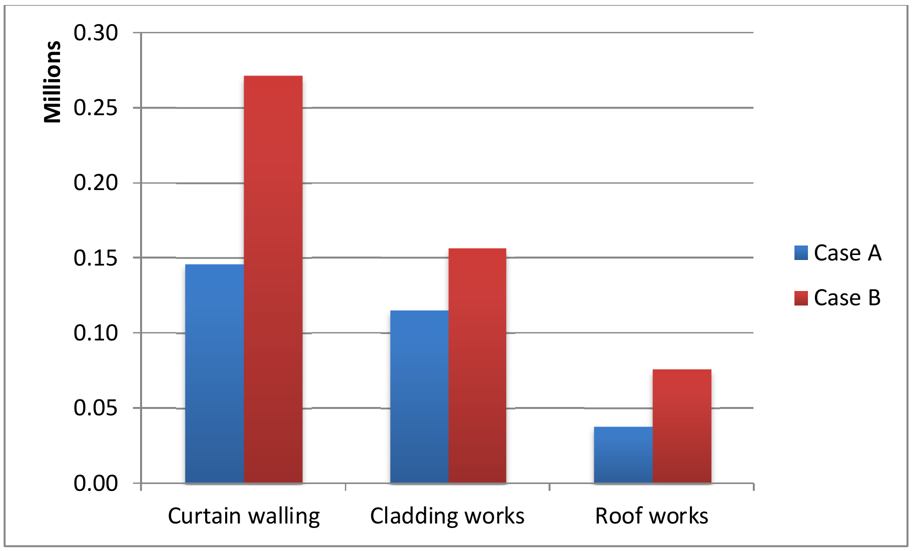

Figure 56 – External envelope carbon dioxide emissions (Kg CO_2)

6.4.2. Construction activities

In both case studies interviews were held with construction managers to get construction phase data. Data sheets and information tables were completed by the on-site managers and supervisors to calculate the carbon dioxide emissions of the construction phase. The information included formwork data, numbers of people working on-site, plants used for building activities, and waste removal data. Plants emissions were found the main contributor to carbon emissions responsible for 525 tonnes of carbon in building A and 813 tonnes of carbon emissions in building B. This was followed by transportation activities in the two case studies, and then come in order other aspects like waste removal, accommodation and formwork respectively. See Figure 57.

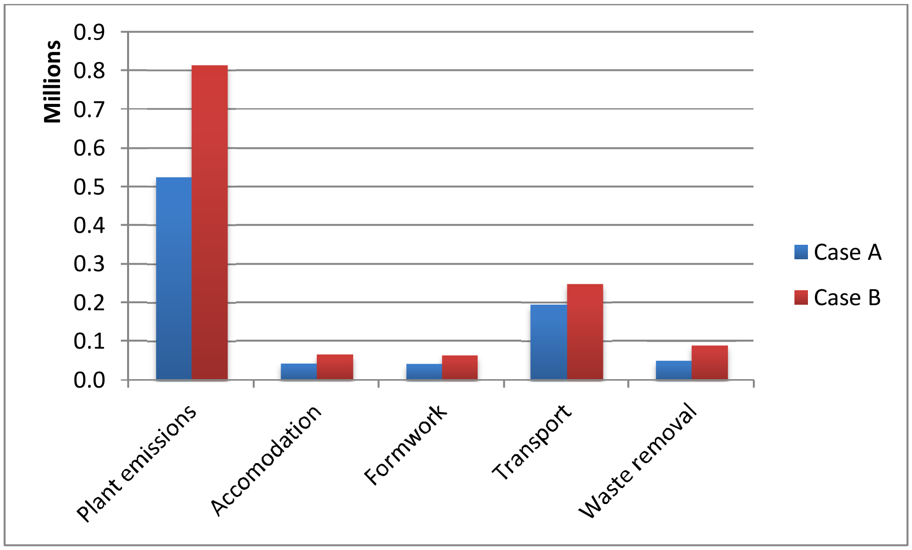

Figure 57 – Carbon dioxide emissions of construction phase activities (Kg CO_2)

Construction phase activities in total are responsible for 856 tonnes of carbon emissions in building A and 1281 tonnes for building B, see Figure 58. This makes the contribution of construction phase to the whole life-cycle carbon emissions of building A only 3 per cent and this is similar to building B. However, if we look at the share of construction phase to the cradle to gate emission when looking at the building as a product, the ratio is 15 per cent of the total embodied carbon in the building.

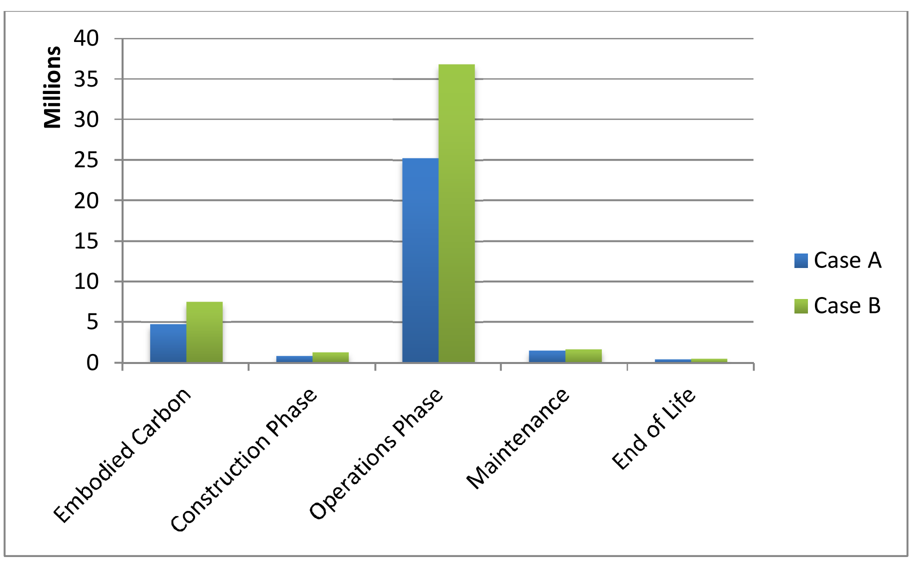

Figure 58 – Carbon emissions of different life-cycle phases (Kg CO_2)

6.4.3. Maintenance activities

The numbers presented in this paragraph are estimations based on scenarios derived from similar cases in Edinburgh of other older buildings, and cases from literature as discussed early in this thesis. The scenario excluded any major refurbishment for the purpose of modernization or architectural changes, and other modifications based on the change of building function.

The service life of materials and components is derived from manufacturer's data when available, and when it is not available other locally based data was used. The scenario used in this research study assumes that the material or the component will be completely replaced a number of times according to the ratio of the building life span to the component service life, and if the last time of replacement was very near to the building end of life (less than 5 years) it will be ignored. For example, if a component service life is 12 years this means that it will be completely replaced 4 times within the 50 year building life span, but the 4^{th} replacement will take place on year 48 which is less than 5 years of the building end of life, this means that the last replacement is not included within the calculations in the research within this thesis (Ashworth, 1996).

According to these assumptions and building information, maintenance of building A is estimated to emit 1492 tonnes of carbon most of which are related to interior works maintenance approximately 1126 tonnes of CO_2 followed by services maintenance then external envelope and structure, see Figure 59.

For building B a similar sequence of carbon emissions is estimated with higher figures due to the difference in area. However, maintenance of the interior of building B is not much higher than the first one as the most frequently replaced components in building A are not present at the same quantities in building B.

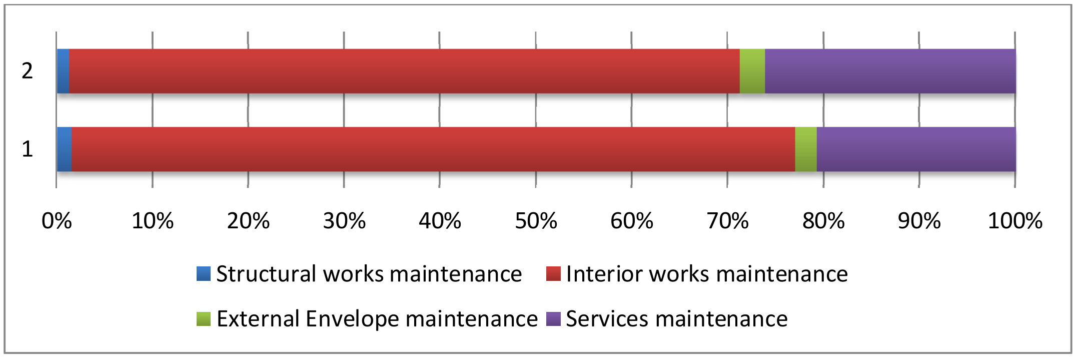

Figure 59 – Contribution of systems maintenance carbon emissions

6.4.4. End of life activities

In the context of physical construction, deconstruction is the selective dismantling of building components, specifically for re-use, recycling, and waste management. It differs from demolition where a site is cleared of its building by the most expedient means. The process of dismantling structures is an ancient activity that has been revived by the growing field of sustainable, green building. Buildings, like everything, have a life-cycle. Deconstruction focuses on giving the materials within a building a new life once the building as a whole can no longer continue.

When buildings reach the end of their useful life, they are typically demolished and hauled to landfills. Building implosions or 'wrecking-ball' style demolitions are relatively inexpensive and offer a quick method of clearing sites for new structures. On the other hand, these methods create substantial amounts of waste. Components within old buildings may still be valuable, sometimes more valuable than at the time the building was constructed. Deconstruction is a method of harvesting what is commonly considered "waste" and reclaiming it into useful building material.

As mentioned earlier in this thesis, building demolition is based on an assumed demolition and recycling scenario. A sum of 75 per cent of the materials will need transportation because they will not be used on site. Being possible to be recycled materials will not affect the embodied carbon of this building, but benefits will be gained by next building, and this is outside the study boundary. It is found that the demolition plant emissions and waste transportation will be responsible for 475 tonnes of CO_2 in building A and 520 tonnes for building B.

This estimate is based on data collected from site reports of UK buildings demolition energy consumption and carbon emissions. Each tonne of demolished materials consumes 15 kg CO_2 in general.

6.5. Conclusion

This chapter presents the results of the life-cycle assessment analysis for two new-build offices in Scotland, and forms an introduction for a further discussion within the next chapter.

Data verification and quality check analysis are presented in Chapter 7, in which discussions of the results and explanations of different "scenario analyses" based on "what if" principle are detailed. The results then are discussed in light of study limitations and further research recommendations are listed in chapter 8.

Chapter 7 - Results Discussion

7.1. Introduction

This research added two case studies to the growing literature of life-cycle assessment of buildings. Each case study could be used as a base case for further analysis. Some of these analyses are done and explained within this thesis, and others are listed as recommendations for further research.

A key task is to find the weak points in the process and identify the most polluting materials and component combinations. Addressing these will permit the development of ideas and the use of products which can contribute to the reduction of the whole building life cycle carbon dioxide emissions.

The case studies serve as a base case to perform sensitivity analyses, based on "what if" scenarios. For example, reducing the glazing ratio is found to cause a slight increase in the embodied carbon but a significant decrease in the operational carbon. Another example might highlight the importance of wall insulations to reduce the external envelope U values, which has significant effect on reducing operational carbon. Moreover changes in the types of HVAC systems and other related building technologies might reduce the total emissions of the building.

In most of these sensitivity analyses, the possibility of investing carbon is present, and an increase in the embodied carbon may result in huge savings in operational carbon emissions. This opens up a field for further research which can only be undertaken following definition of base case studies such as these for buildings in the UK.

Scenario analyses are done to present sets of results rather than one clear result. This makes the study more realistic and defines ranges for emissions depending on future predictions presented by the local authorities or responsible manufacturers and suppliers.

Against this background, this chapter discusses the results presented within this thesis, and attempts to interpret the findings. It discusses alternative possibilities, focusing on changes to materials, components, and processes, and opens up further research opportunities.

7.2. Data quality

The data used within this research is divided into two categories; building data, and inventory data. Building data is all that data related specifically to the building including materials, components, elements, systems, and building activities in terms of quantities, i.e. how many units of item is used within the building. Inventory data is all that data related to the environmental impact of these items, for example, how many kg of CO_2 is emitted by producing a kg of reinforced concrete.

The data assessment matrix which was used within this thesis is presented in chapter 4. Building and inventory data was checked against the criteria presented in Table 3. The data was checked for its reliability, completeness, its date of issue, its location, and technological applicability. The results of the data quality assessment are presented in Table 20.

Data Quality Maximum score = 1 Minimum score = 5	Acquisition method		Independence of data supplier		Representativeness		Data Age		Geographical correlation		Technological correlation	
Case building	A	B	A	B	A	B	A	B	A	B	A	B
Building materials	2	2	1	1	2	2	2	2	2	2	2	2
Construction	2	3	2	2	2	3	2	2	2	2	2	3
Heating service	2	2	2	2	1	1	1	1	1	1	1	1
Electrical service	2	2	2	2	1	1	1	1	1	1	1	1
Maintenance	2	2	2	2	3	3	2	2	2	2	3	3
Demolition	3	3	2	2	2	2	3	3	2	2	3	3

Table 20 – Summary of the data quality assessment

Most of the data used within the research presented in this thesis scores 2 or 1, the best two levels. The minority of data which scored 3 (13 out of 72 cells in Table 20) mainly deals with future predictions. This data is partly based on assumptions, and may slightly increase the uncertainty of the results, but as the contribution of these phases is not large, this small uncertainty level could be neglected, more details will be discussed within the scenario analysis paragraph.

The overall quality of the data used is mostly as targeted or even better. Overall, the data used has the following qualities:

- calculated data based on measurements,
- verified data from enterprises with an interest in the study,
- representative data from smaller number of sites but for adequate periods,
- less than 5 years difference between the data and the year of study,
- average data from larger geographical area in which the area under study is included,
- data from processes and materials under study but partly from different enterprises.

The studied system as mentioned in chapter 5 is an open system with positivistic orientation. This means that the researcher has no influence on the system. The researcher is an observer of facts, and has no influence on the results. But choosing the sources of data and the methods of calculations could affect the results significantly and this increases the uncertainty of the results. However, the data quality check process which was presented earlier is a key tool to minimize the uncertainty of the results. Much of the confusion concerning the relevance of LCA results is linked to the use of aggregated data during the impact assessment phase. Indeed, White et al. (1995) make the point that the practice of calculating global parameters for impact categories by aggregating data across the life cycle assumes a worst case scenario that could *"misguide improvement measures or policy-making"*.

Methods of calculations and sources of data are treated as alternatives when available, and the optimum was chosen according to data quality criteria. The choice of most accurate building and inventory data was cross-checked using literature data and other locally accepted sources. For example, the carbon dioxide emissions of concrete within building A are calculated using different data sets. The first set was based on design drawings and cross-checked with building observations and real measurements. The second set was based on the actual orders extracted from sub-contractors bills.

In both cases the units used against inventory data are different. For the first case a cubic meter of concrete is used as the base unit, and a kg of material was used for the second case. The use of kg of material breaks down the component which is a cubic meter of concrete into its materials and gives more explanation of the findings, however, it could prolong the analysis time and needs more work and it is limited to data of materials and components production, so the final decision about the units was based on data availability. This type of analysis was only done for the first case study embodied materials analysis as presented in Table 21

Activity	Actual orders	Design drawings and measurements
Underpinning	31,799	31,220
Excavating	125,542	122,423
Filling	4,196	4,238
Formwork	4,554	3,610
Concrete work	2,028,893	2,006,248
Waterproofing	11,943	10,636
Disposal systems	22,126	21,156
Reinforcement	704,501	697,120
Steel	140,647	141,661
Surface treatment	6,302	6,290
Waste Disposal	20,342	19,498
Dry lining	435,418	424,824
Flooring	230,260	233,824
Ceilings	187,421	184,360
Door sets & joinery	29,281	28,739
Metal works	21,190	22,630
Block works	43,200	42,800
Curtain walling	145,887	144,323
Cladding works	115,235	115,220
Roof works	37,935	38,600
Electrical and mechanical systems	240,532	244,523
Other	155,098	170,563
Total	**4742302**	**4714506**

Table 21 – Carbon dioxide inventory obtained from different calculation methods (kg CO_2)

There are slight differences in the calculations presented in Table 21. Most of the "actual orders" figures are higher. This is to be expected in most buildings when comparing design drawings and actual orders, as changes may occur within the construction stage. However, the comparison here is based on as-built drawings, thus there is no significant difference in calculations. Differences could be related to differences in construction activities and possible wastage on site. Backfilling is an example, where the concrete used for this purpose is connected with the excavation activity. If the excavation was larger than the designed volume then the concrete used for backfilling is more than the quantities derived from design drawings, and this could not be checked by as built measurements, because the components are hidden under the building when the study took place after building completion. In such a case actual orders were chosen to build data analysis on.

7.3. The functional unit

When selecting the functional unit it is necessary to evaluate the alternatives which may usefully be compared. Generally there is no simple answer to this as there is an unlimited number of relevant functions. The central function selected will determine the alternatives which can usefully be compared. For this study a start from the term “building emissions” as the central option, for example, may be useful when the choice of type of building is still completely open, and as a result the types could range from house to retail and offices. The addition "office" means that other types are no longer relevant and limits the type of buildings. The addition "carbon dioxide" rules out other environmental impacts from the alternatives. However there are still office buildings in different countries should be included. When the choice concerns "a Scottish" the functional unit becomes more determined (Fava, 1993).

Clear boundaries of study are key factors in determining the functional unit which should be used. In the research within this thesis the chosen functional unit is kg CO_2/m^2 gross floor area (GFA) of a new-build office building in Scotland. The selection of this functional unit is based on the possibility of comparing the results to previous case studies within the literature from other countries. The results of a life-cycle assessment are dependent on the clear determination of functional unit, and until now there is no agreed way of selection, or a unit for a specific product.

A study holder may be confused about what unit to choose, especially those who have changed their normal life thinking into a life-cycle assessment way of thinking. Many alternatives could be considered, and could lead to different life-cycle results. This depends on the aim of the study and boundaries and limitations. For example, a study which looks at different companies' environmental profiles will not utilise square meter of building area as a central unit, it will rather look at how many employees there are in the company, at their production ratios, at the effectiveness and quality of company products and their impact on the environment, and so on. The building itself will be only part of the study in this case, and the building related emissions will be part of the input of the studied system.

On the other hand, studying the carbon emissions of an office building will exclude most of these "out of boundaries" inputs. Additionally, a slight change in the functional unit may change the results significantly. Table 22 shows the effect of changing the unit from m^2 GFA into m^2 of office space area (Cordoba et al.) or other functional unit.

By looking at the totals in table 22, we notice a change in the first case study building carbon dioxide emissions results by approximately 36 per cent, while for the second case the change is approximately 57 per cent. This changes the results of any comparison analysis significantly. This shows the importance of giving clear attention to functional units when making comparison with other case studies.

Activities	**kg CO_2/m^2 GFA**		**kg CO_2/m^2 OSA**	
	A	**B**	**A**	**B**
Underpinning	2.66	0.00	3.62	0.00
Excavating	10.49	4.72	14.29	7.41
Filling	0.35	0.16	0.48	0.25
Formwork	0.38	0.84	0.52	1.32
Concrete work	169.47	111.22	230.98	174.74
Waterproofing	1.00	0.88	1.36	1.39
Disposal systems	1.85	0.84	2.52	1.32
Reinforcement	58.85	13.84	80.20	21.75
Steel	11.75	164.60	16.01	258.61
Surface treatment	0.53	0.50	0.72	0.79
Waste Disposal	1.70	2.57	2.32	4.04
Dry lining	36.37	20.80	49.57	32.67
Flooring	19.23	45.92	26.21	72.15
Ceilings	15.65	11.72	21.34	18.41
Door sets & joinery	2.45	0.89	3.33	1.40
Metal works	1.77	1.77	2.41	2.77
Block works	3.61	3.86	4.92	6.06
Curtain walling	12.19	16.16	16.61	25.39
Cladding works	9.63	9.31	13.12	14.63
Roof works	3.17	4.52	4.32	7.10
Electrical and mechanical systems	20.09	21.50	27.38	33.78
Other	12.96	12.39	17.66	19.46
Plant emissions	43.85	48.48	59.77	76.17
Accommodation	3.61	3.90	4.92	6.13
Formwork	3.55	3.81	4.84	5.99
Transport	16.25	14.80	22.15	23.25
Waste removal	4.25	5.38	5.79	8.46
Structural works maintenance	1.86	1.22	2.54	1.91
Interior works maintenance	94.08	67.96	128.23	106.77
External Envelope maintenance	2.81	2.55	3.83	4.00
Services maintenance	25.92	25.41	35.32	39.92
HVAC natural gas	222.67	265.99	303.48	417.91
HVAC electricity	568.41	667.81	774.71	1,049.24
Lights electricity	672.64	810.29	916.76	1,273.10
Equipment electricity	646.83	450.33	881.59	707.54
End of life	39.73	31.00	54.15	48.71
Total	**2,742.58**	**2,847.93**	**3,737.95**	**4,474.56**

Table 22 – Effects of changing the functional unit

7.4. Sensitivity analysis

The reliability of the environmental profiles or the inventory tables affects the certainty with which a conclusion can be drawn. The term sensitivity analysis is commonly used to refer to the determination of the influence of changes on the end results. The research within this thesis performed a sensitivity analysis to evaluate the effects of possible changes during the long service life, fifty years, of a new-build office building in Scotland.

As presented in chapter 4 and 5, sensitivity analysis can be in the form of what if scenarios and cornerstone scenarios. The "what if" scenarios are used to compare quantitatively different alternatives in the system or to test some specific changes within the system (Junilla, 2004). In the next section, scenarios are presented in five different themes – changes in the electricity generation fuel mix, changes to the glazing ratio, issues surrounding recycling of materials, the provision of car parking, and the frequency of major refurbishment.

7.5. Scenario analyses

7.5.1. Electricity mix

It is stated generally that life-cycle assessment can describe and calculate already completed processes more accurately than the future ones, as more assumptions and predictions are made in the latter. It is one of the main limitations of life assessment studies held at early stages of building process that the future activities are assumed to have the same emissions as those of today. For the research in this thesis, this is particularly related to running, maintenance, and end of life emissions.

For example, the calculations and estimations of carbon dioxide emissions within this study are based on the current local UK power profiles and inventory data provided by the supplier company. At present, to produce electricity the UK uses

28.9 per cent of coal, 44.2 per cent of natural gas, 17 per cent of nuclear power, 7.9 per cent of renewables, and 1.7 per cent of other sources (DECC, 2011). This makes the average carbon dioxide emission of electricity at demand point 450 g CO_2/kWh, as presented in Table 23 and Table 24.

Energy Source	**Per cent**
Coal	28.9
Natural Gas	44.2
Nuclear	17.3
Renewables	7.9
Other	1.7

Table 23 – United Kingdom fuel mix (DECC, 2011)

Energy Sources	**g/kWh**
Coal	910
Natural Gas	400
Nuclear	0
Renewables	0
Other	620

Table 24 – Carbon dioxide emissions of UK fuel mix (DECC, 2011)

The electricity mix and carbon profile used for carbon emissions estimations of building A are based on data provided by the building engineers which are close to UK averages. However, the electricity supplier may be changed at any point of the building life. By changing the electricity supplier, a significant increase or decrease of carbon dioxide emissions could occur.

Using the current carbon profiles of alternative electricity suppliers, quoted in DECC (2011), it is possible to estimate the total life-cycle emissions of building A when using electricity from different suppliers. This is shown in Figure 60 and ranges from 15295 tonnes of CO_2 by using Green Energy UK as a supplier, up to 49196 tonnes of CO_2 by using Scottish Power as a supplier. Of course, this may change in future, as different companies are applying different strategies to reduce their carbon footprint.

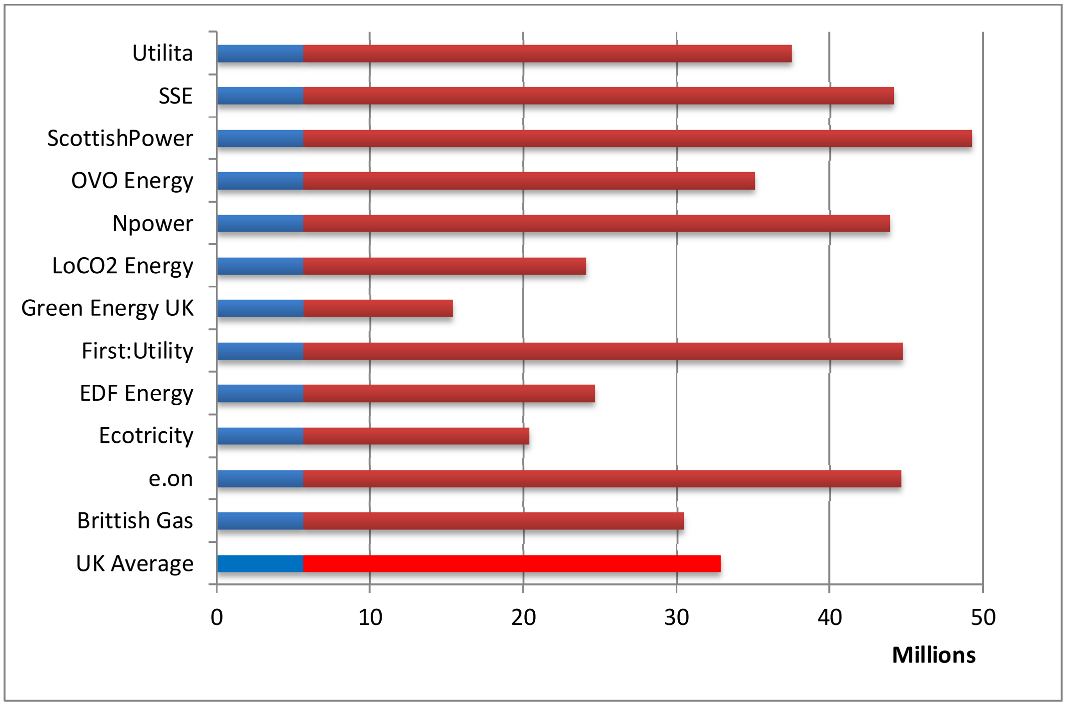

Figure 60 – Estimated carbon emissions using different electricity suppliers for building A

As discussed earlier within this thesis, the UK is working to achieve a goal of 80 per cent carbon reduction by 2050. The carbon profiles of power suppliers are changing over time according to their implemented policies and strategies to reduce their carbon footprint, to achieve the required goal.

The national grid operators have produced three scenarios of development for analysis, Slow Progression, Gone Green and Accelerated Growth, as a single forecast of energy demand does not give a sufficiently rich picture of possible future developments (Smith, 2012).

- In the Slow Progression scenario developments in renewable and low carbon energy are comparatively slow, and emissions and renewable targets for 2020 are not met until after 2025.

- In the Gone Green scenario the renewable target for 2020 and the emissions targets for 2020, 2030 and 2050 are all reached.

- The Accelerated Growth scenario uses the same view of energy demand as Gone Green but has faster development of offshore generation. All environmental targets are reached earlier than the required dates.

The assumptions behind the scenarios are described in some detail out to 2030 below, including:

- The economic background;
- Fuel prices;
- Developments in the heating market, with particular emphasis on heat pumps;
- Developments in transport, with particular emphasis on electric vehicles;
- Electricity demand, with discussion of high efficiency technologies, especially lighting, and the application of smart technology for demand side management.

Developments from 2030 to 2050 are not considered in the same level of detail, but a brief description of the main demand sectors is given, along with the implications for electricity generation and gas demand (Smith, 2012).

In the Slow Progression scenario, there is a slower build-up of lower carbon generation and a greater reliance on gas-fired plant. The scenario also assumes slower advances with regard to new technology, with carbon capture and storage (CCS) proving to be uneconomical for large scale coal plants (Smith, 2012). Slow progression scenario assumes that the currently set targets will be achieved 7 years later.

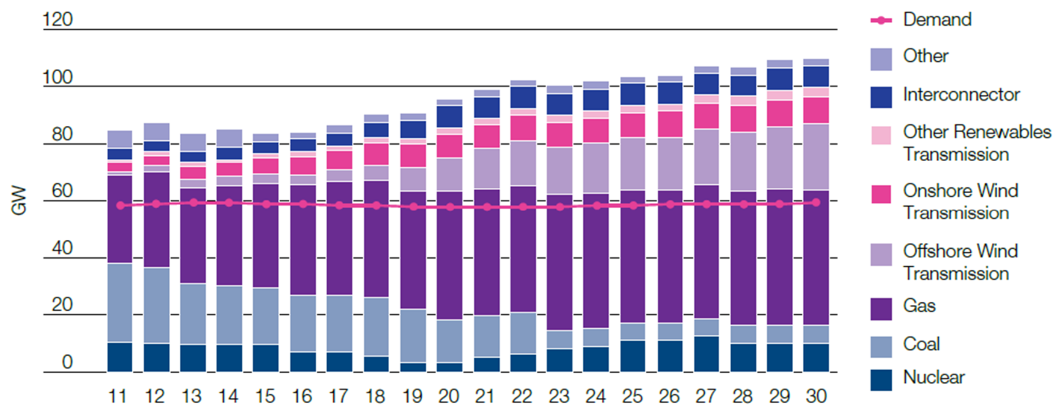

Figure 61 - Demand and generation background: Slow Progression

Gone Green is constructed in such a fashion that the renewable energy and carbon emissions targets are always achieved. It includes a more rapid build-up of wind generation, with the supply chain, and thus growth in offshore wind, maintained post 2020. Nuclear plant is assumed to receive an additional five years life extension when compared with the Slow Progression scenario, maintaining the level of nuclear capacity until the advent of new nuclear plant, and assisting in lowering the level of carbon emissions from the generation sector. CCS plant is envisaged at both coal and gas plants into the future, with thermal plant developed after 2023 which is required to have CCS technology. The increased lifespan of the Advanced Gas-cooled Reactor (AGR) plant results in existing Combined Cycle Gas Turbine (CCGT) plant closing earlier than in the other scenarios.

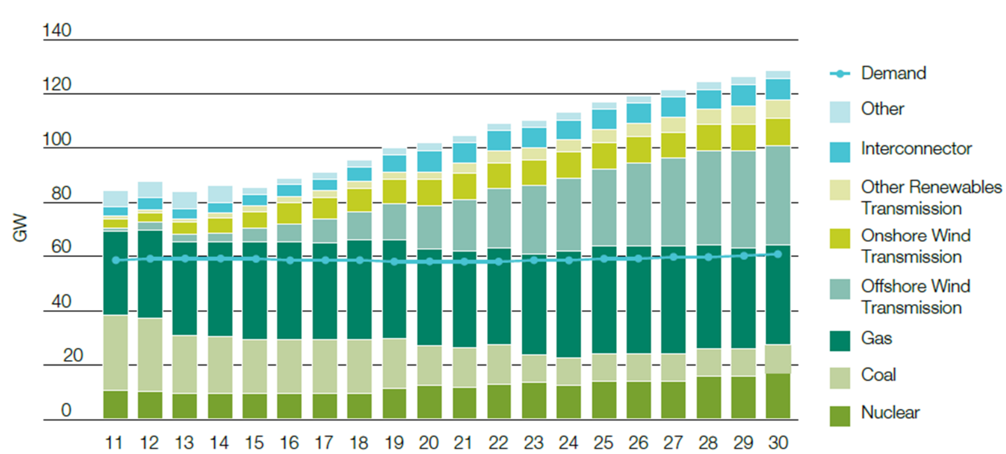

Figure 62 - Demand and generation background: Gone Green

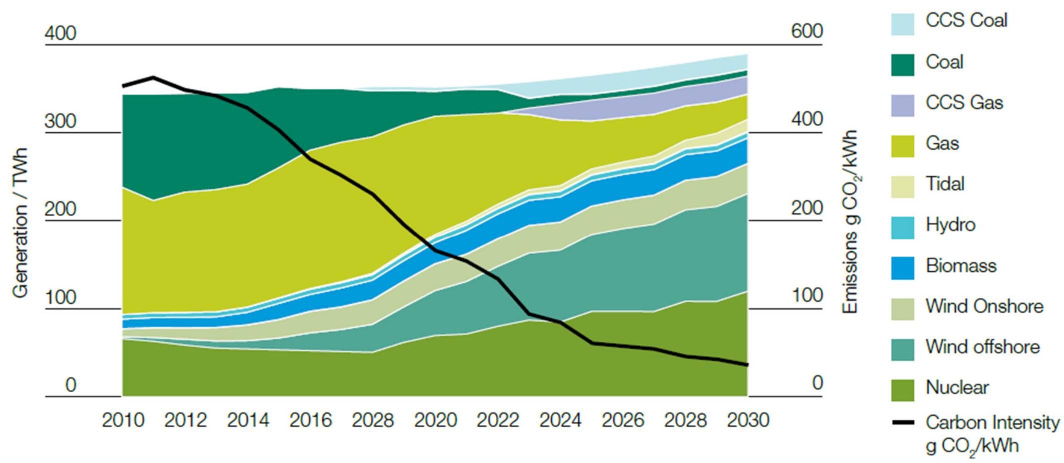

Figure 63 - Generation by fuel type and carbon intensity: Gone Green

The Accelerated Growth scenario uses the Gone Green onshore background as a base with the assumption that offshore generation builds up far more quickly due to a rapidly established supply chain, higher carbon prices and strong government stimulus. The key differences in the onshore background are that the AGR plant is consistent with the Slow Progression scenario (AGR nuclear plant receive five-year life extensions unless otherwise announced) and that existing gas plant remains open for longer to maintain the plant margin and act as a back-up for the significant amount of wind generation.

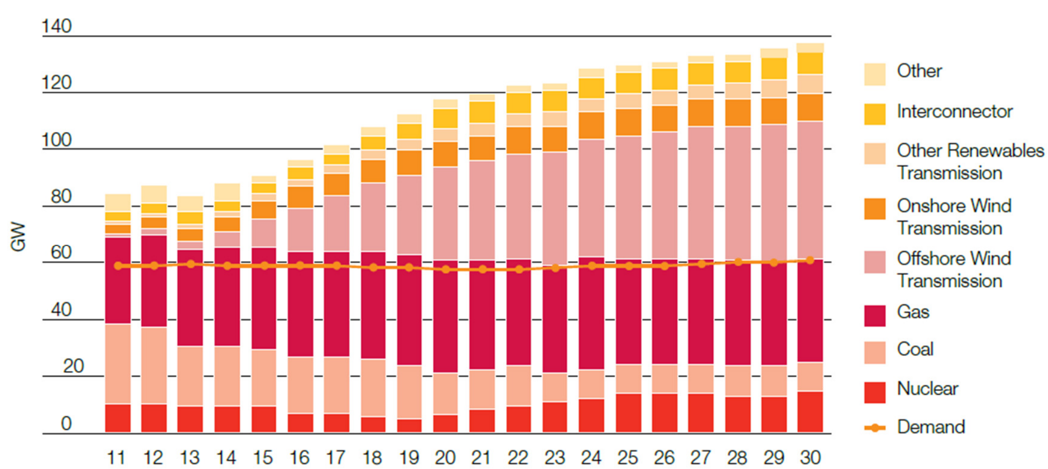

Figure 64 - Demand and generation background: Accelerated Growth

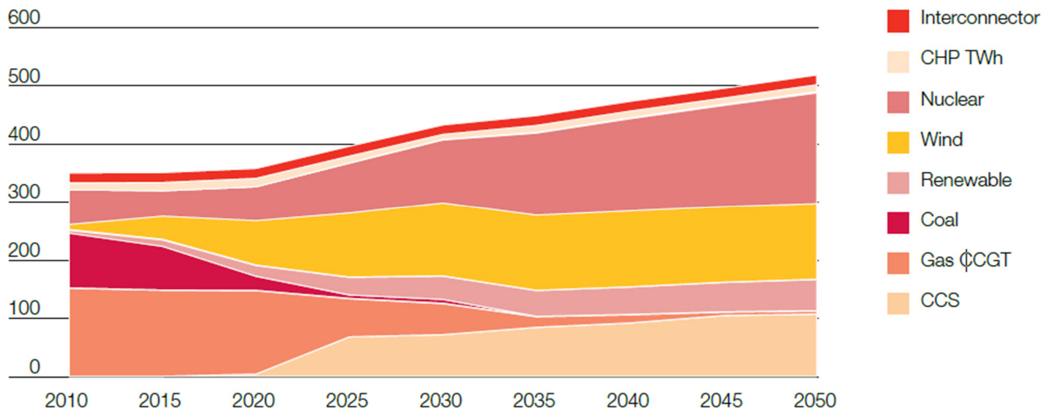

Figure 65 - Electricity generation by type, 2010 to 2050

Using the scenarios presented above, carbon emissions of the electricity fuel mix is estimated for the 50 year life span of case building A, as presented in Figure 66. For the Gone Green scenario, carbon emissions at demand point go down to 48 g/kWh in 2030 and could reach a value of 22 g/kWh by 2060. See Figure 66.

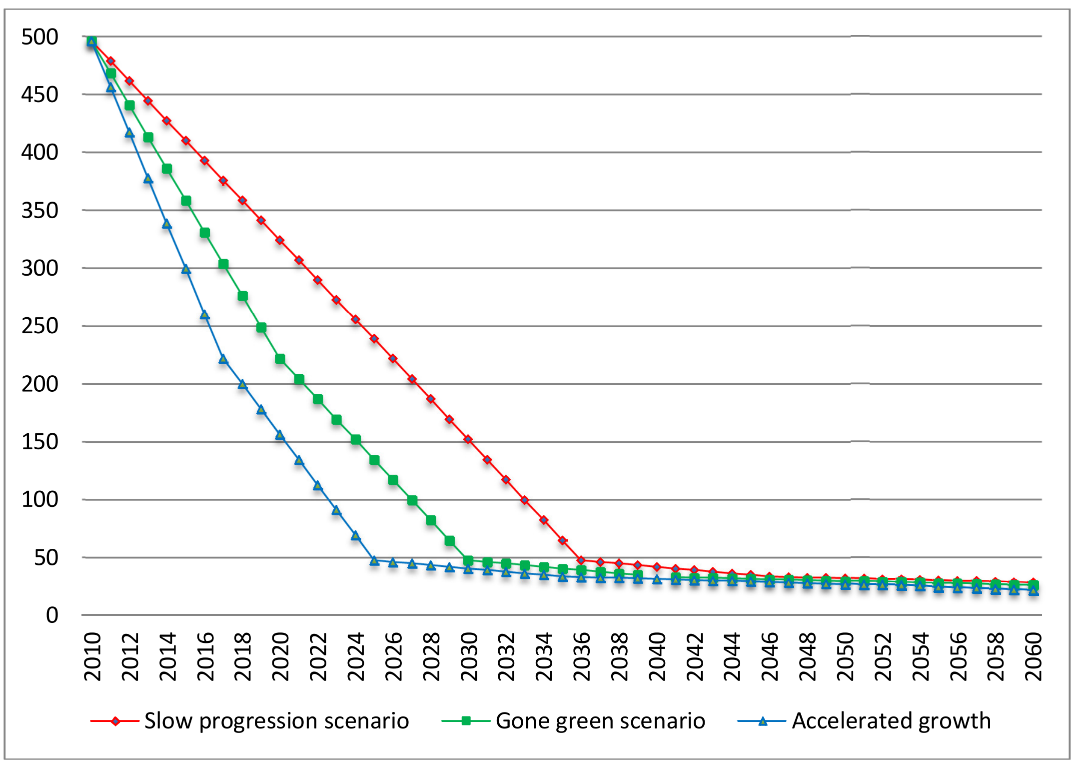

Figure 66 – Electricity carbon dioxide emissions scenarios (g CO_2/kwh)

These reductions in the emissions due to electricity reflect a significant reduction in the calculated whole life cycle carbon of case study building A as presented in Figure 67. The whole life carbon could be as low as 10832 tonnes of CO_2 which is approximately 34 per cent of the current estimations.

The effects of future reductions in the carbon profiles of electricity suppliers and manufacturing companies are applied only to future activities, the embodied carbon in the building materials and construction phase is not affected and the reduction of maintenance and end of life carbon dioxide emissions is estimated. The consequence is that the ratio of embodied carbon to total carbon increases from 17 per cent up to 52 per cent as presented in Figure 68.

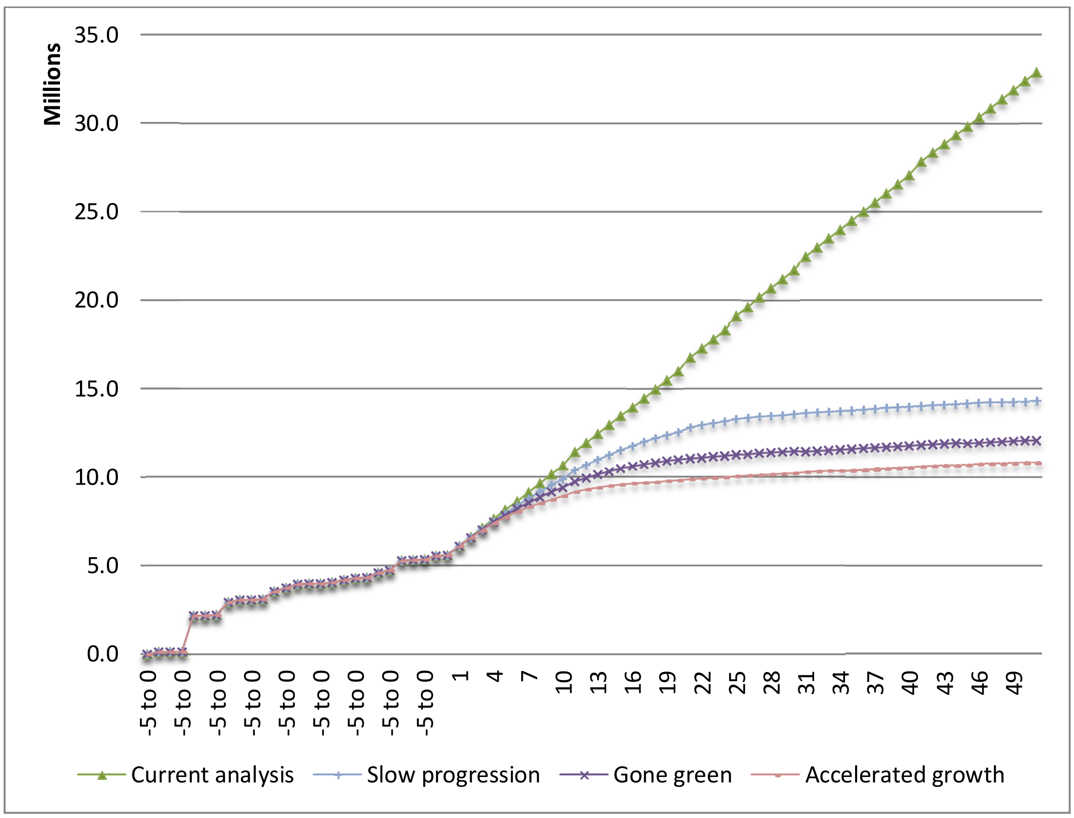

Figure 67 – Different scenarios building A carbon dioxide emissions kg CO_2

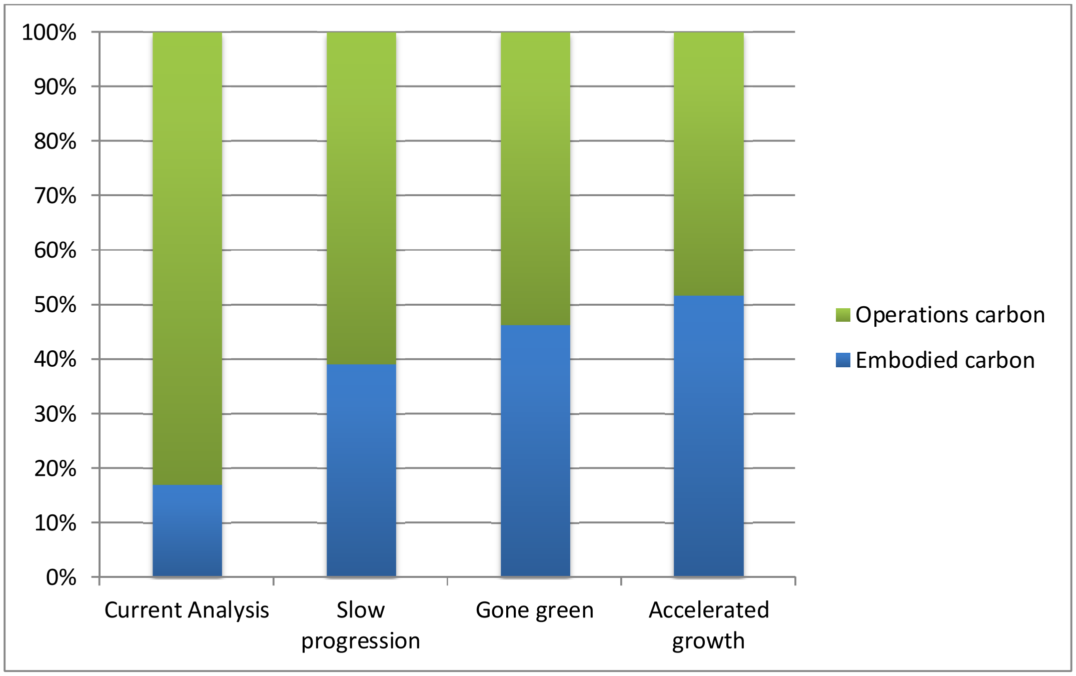

Figure 68 – Embodied carbon ratio, different electricity mix scenarios for building A

7.5.2. Glazing ratio

As discussed in chapter 3, one of the parameters which has a significant impact on building thermal behaviour is the size and orientation of glazing. The higher the glazing ratio the higher the gain from solar radiation, but the higher the heat transfer. This latter is principally due to the difference in U-values between glazing and external wall to the detriment of the glazing, and the conductivity gains/losses of the whole envelope are also increased.

Building on literature data presented earlier in this thesis, there are optimum ranges for glazing ratio which strike a balance among different parameters, mainly solar gain, heat loss, daylight, and glare. Studies proved that a range between 30 and 50 per cent of glazing ratio is optimum depending on the climate zone of the building location. Bokel (2007) concluded that an optimal window size is around 30 per cent of the façade area, while in the case of heating demand there is an optimum minimum around 50 per cent of window size. Steemers (2003) showed that there is an effect of building height on the optimum glazing ratio which should be reduced in the upper levels as shown in Figure 69.

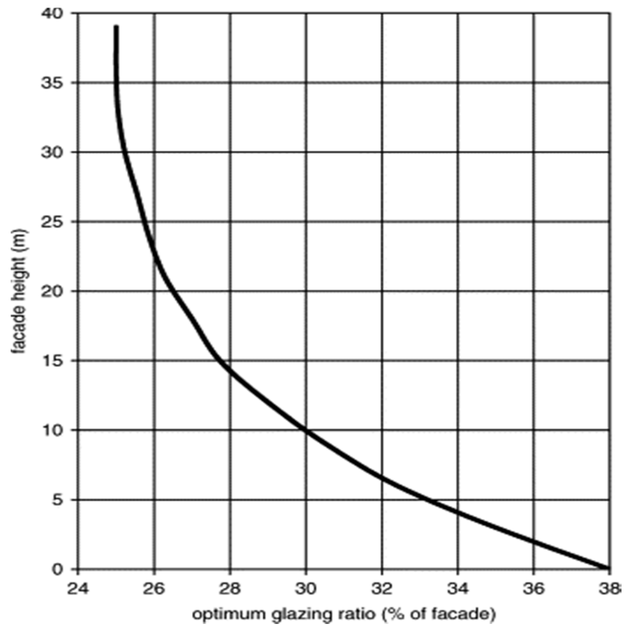

Figure 69 – Optimum glazing ratio for different building levels (Steemers, 2003)

The research within this thesis investigated the possible reductions in carbon dioxide emission by reducing the glazing ratio. Building A has 71 per cent of its external walls in the form of curtain walling. The other 29 per cent are mostly dominated by the sandstone façade. Embodied carbon is calculated for a square meter of façade including all components and materials involved. It was found that there is 53.73kg CO_2/m^2 embedded in the curtain walling system which has an average 1.86 U-value, and 104.76 kg CO_2/m^2 embedded in stone covered walls which have an average of 0.30 U-value. These values were obtained by summing all the materials and components over all the glazed areas and opaque areas, and then subdividing by their respective areas to give the embodied CO_2 per square metre. The stone walling is higher because it includes insulation, internal linings and finishes, which are not present in the curtain walling.

The operational carbon is dominated by HVAC accounting for approximately 189 tonnes of CO_2 per year, but lights have a significant share accounting for approximately 161 tonnes of CO_2 per year. Changing the glazing ratio decreased the HVAC carbon dioxide emissions, but caused a slight increase in the lighting emissions. On top of that the embodied energy increased by 79.7 tonnes of CO_2. Such a change increases the embodied carbon but decreases the operations emissions by approximately 5.8 per cent. This is caused by the total 20 per cent reduction of HVAC electricity carbon dioxide emissions, and 18 per cent reduction of natural gas CO_2 emissions, with a slight 5 per cent increase in lights emissions.

Figure 70 shows that investing 79.7 tonnes of embodied carbon by reducing the glazing ratio from 71 per cent to 30 per cent may reduce the total life-cycle carbon dioxide emissions by 931,892 tonnes. The payback period of the invested embodied energy is found to be 17 years of building life.

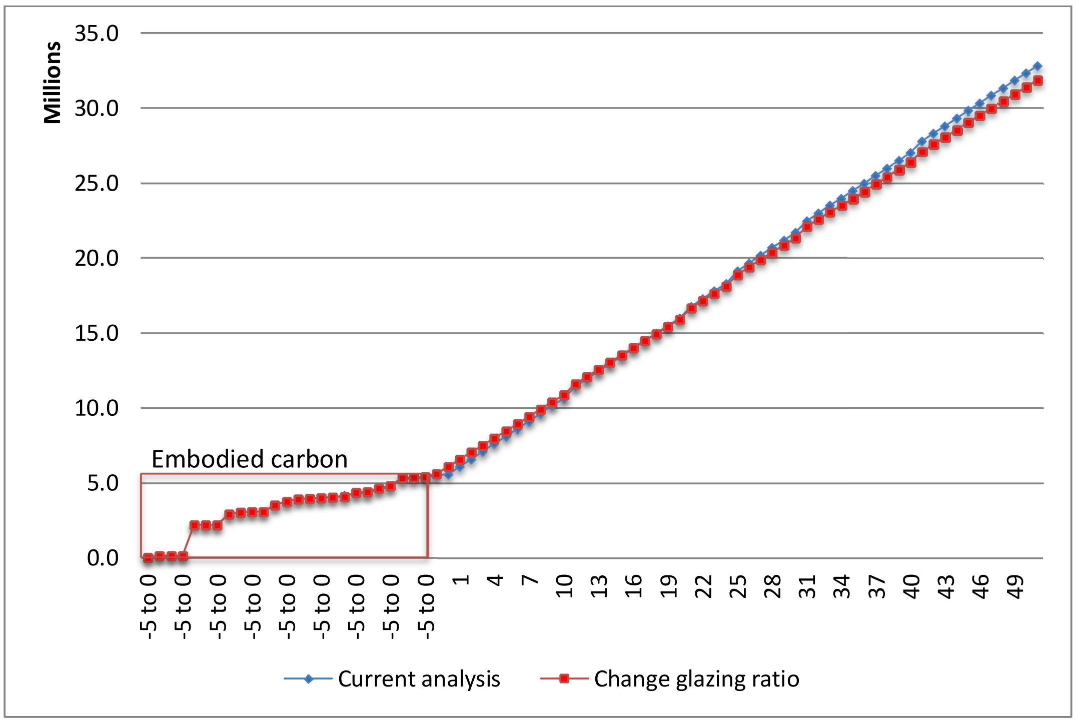

Figure 70 – Glazing ratio reduction scenario effects on carbon dioxide emissions

A closer look at the change of embodied carbon based on glazing ratio scenarios is presented in Figure 71.

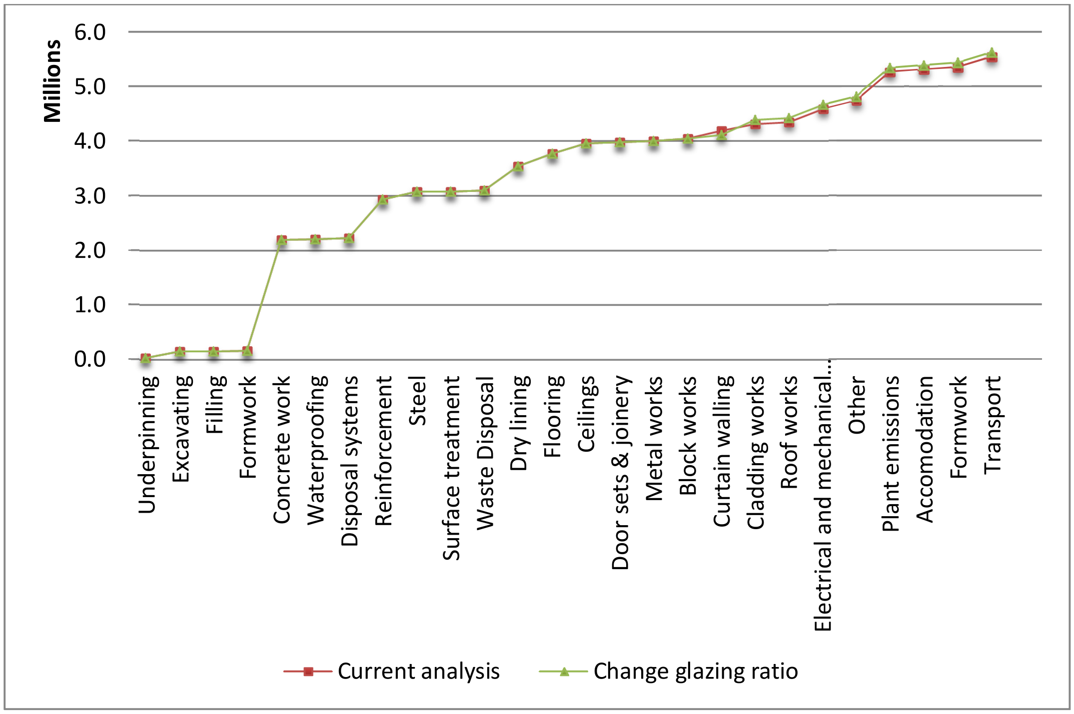

Figure 71 – Embodied carbon changes by changing glazing ratio

As previewed in chapter 4, older studies within the literature found a 23 per cent increase in energy consumption for a change of glazing ratio from 30 per cent to 60 per cent, and this goes up to 47 per cent when changing the ratio to 100 per cent (Johnson et al., 1984). The difference between this study and the research in this thesis could be attributed to the differences in U-values of the glazed area as modern advanced technologies have been developed.

Influence of orientation is significant in the case when facades are different in terms of window-to-wall ratio, or the building has one dominant façade. But changes in orientation is not possible in either case study building, as these are city centre buildings rather than out of city developments which have more open space and are more flexible with this particular parameter.

One of the other parameters which could affect the total carbon emissions of the building is wall insulation. This has a significant effect on the U-Value of the external wall, which may reduce the HVAC carbon dioxide emissions. It is found by studies as presented in literature that there is an optimum thickness of insulation. Adding more insulation has no effect on operational carbon, but only increases the embodied carbon of the building as presented in Figure 72. For building A, it was found that the insulation thickness is already optimized and no further developments could be done by changing it.

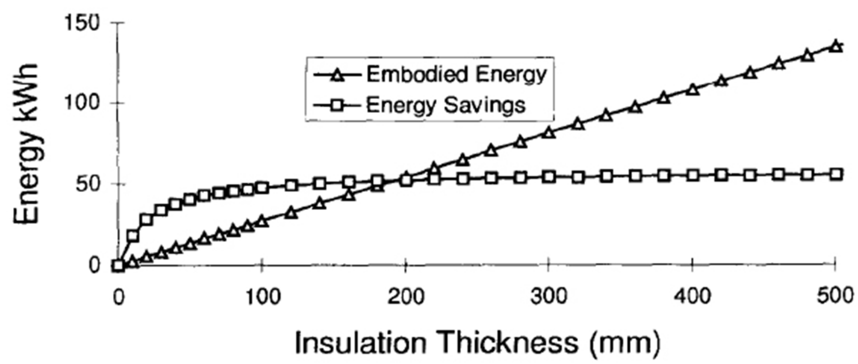

Figure 72 – Insulation optimum thickness for energy saving (Harris, 1999)

All this discussion shows that the issue of glazing ratio is complex, with conflicting effects of increased daylight/artificial lighting needing to be balanced against thermal insulation/heat loss. Building simulation software such as IES deals with this successfully but neglects embodied energy. This could be a topic for further research.

7.5.3. Recycled / recycling scenarios

There are many challenges to the life-cycle assessment researcher when dealing with recycling at different stages of the building life time. The boundaries and limitations of any study should be noted carefully as different assumptions and scenarios could lead to different results. In particular, the end of life scenario is critically important as it is built on assumptions rather than facts, and these scenarios are derived from real similar local cases presented in the literature.

There is much debate in the literature on the recycling potential and the use of recycled materials. Components or systems are in some cases as complex and unique as a building, and these systems may consume recycled materials and may create recycled materials at the end of its service time. The limitation of the study determines if the impact of recycling is considered at the current use within the case study building or the next building. This may cause confusion and mistakes by calculating the saving of carbon emissions twice in some cases. The input and output of these materials therefore require a well-rounded and robust methodology.

There are different methods and theories which allocate the recycling emissions savings. For example, the recycled content approach claims that without the system that uses the recycled materials recycling will not be beneficial, consequently this method allocates the savings to the consuming system. However, a substitution method allocates the savings to the producing system, and claims that without this system there will not be recycled materials. The third approach is a 50:50 approach which shares the benefits between two systems (Jones, 2009).

Looking from a different point of view, the recycled materials could be used at different stages of the building's life. A recycled material could mainly be used at the construction phase, then in a major refurbishment, or maintenance activities.

In the research within this thesis, the method used to benefit from recycling was the recycled content approach, and the possibility of getting benefit of building component and materials recycling at the end of life-cycle is considered to be outside of the boundaries of the study.

Different materials and components have different capability for being recycled, and this makes a significant difference when comparing concrete structured building with steel structured ones. In the research within this thesis, changing steel which has a 42 per cent recycled content into totally recycled steel will change the results of the study significantly, especially for building B as it is steel structured and steel is the main polluting material within the system as presented in Figure 73.

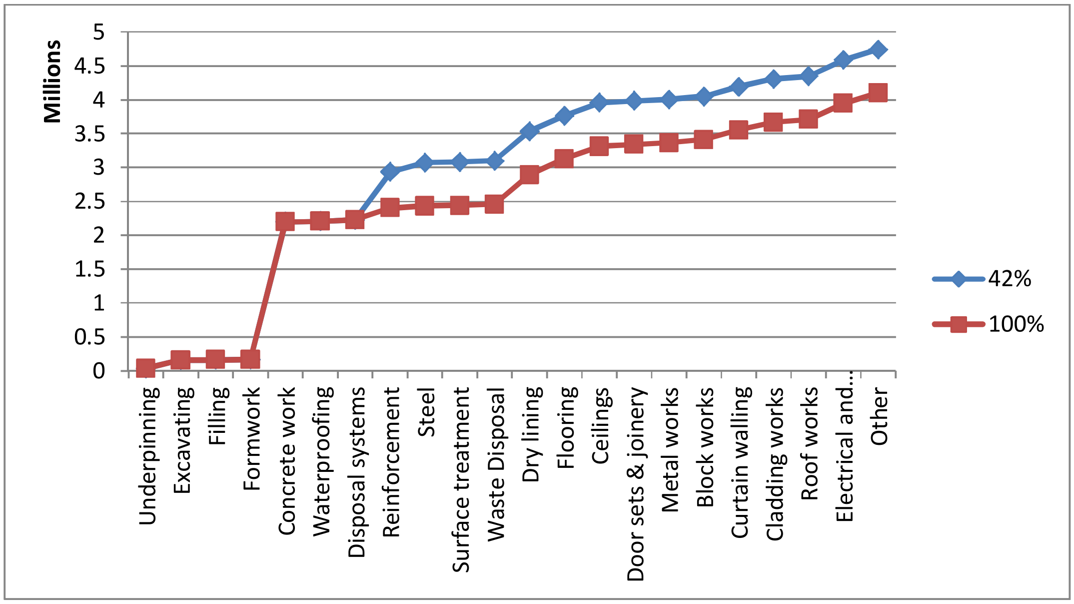

Figure 73 – Changing steel recycled content for Building A embodied carbon (kg CO_2)

Changing the steel content to 100 per cent recycled steel reduced the embodied carbon of building A by 639.8 tonnes of CO_2, while if the same scenario was applied to building B the change in carbon dioxide emissions is 2266.8 tonnes which is approximately 30 per cent of the building materials emissions. See Figure 74.

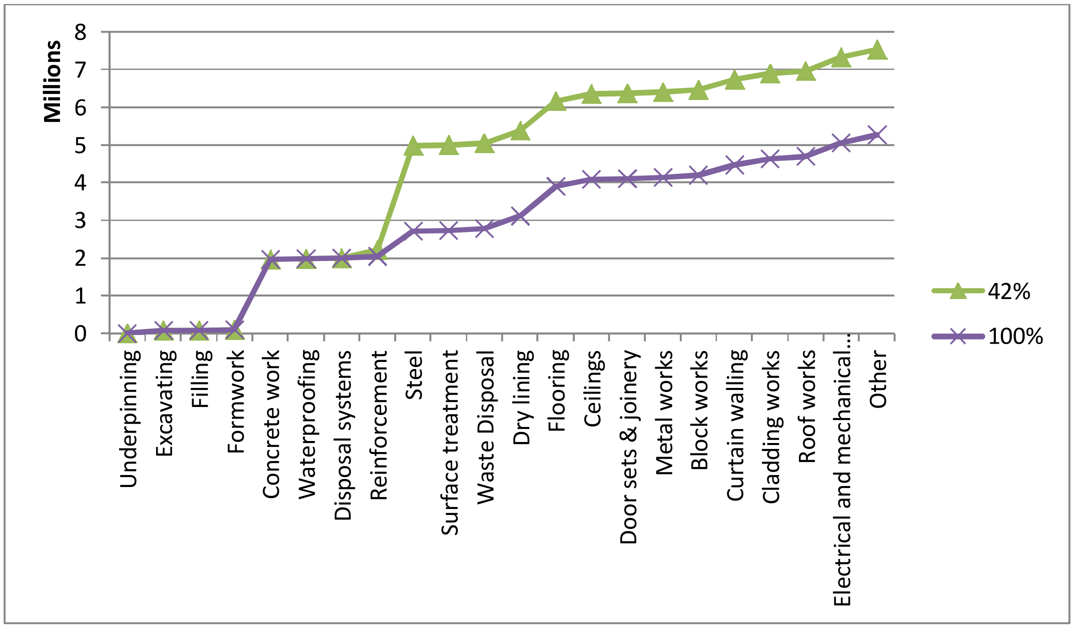

Figure 74 - Changing steel recycled content for Building B embodied carbon (kg CO_2)

It is well established that normally there are large environmental savings to be achieved through material recycling; this is particularly true for metals. However, some metals have high recycling profile, but they turn into unusable materials, for example aluminium is recycled into ingot which is not a usable product. Steel is a good example of materials which have high recycled content and make good saving in environmental impact, and this could bring benefits to the building process.

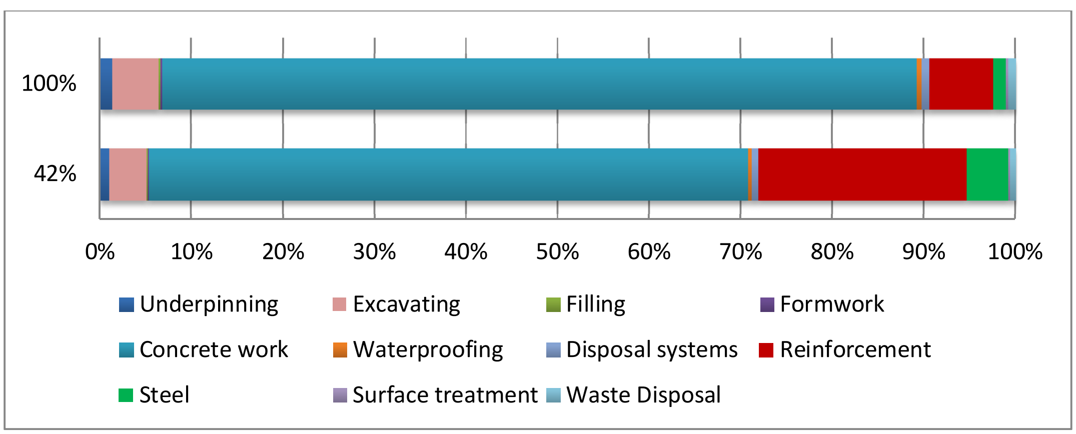

Figure 75 – Structural activities ratio of carbon emission for different steel recycling content for building A

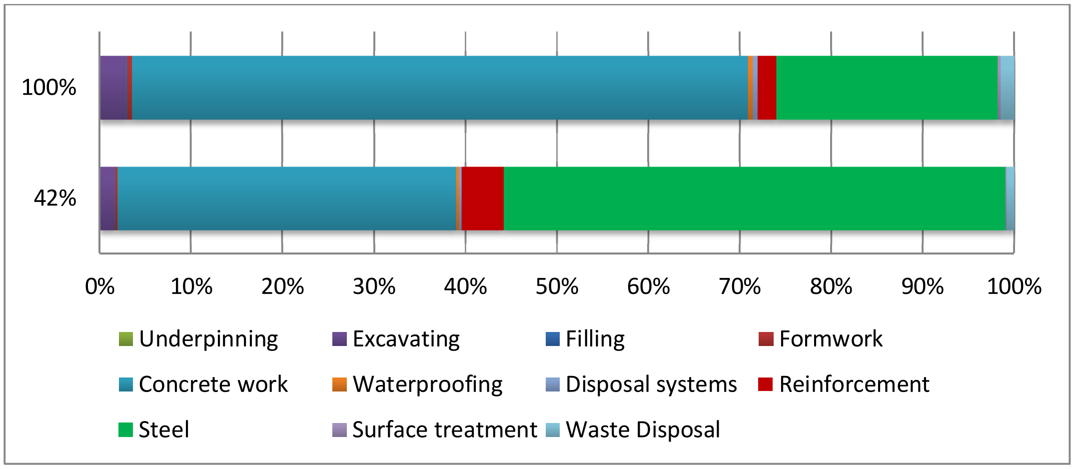

Figure 76 – Structural activities ratio of carbon emission for different steel recycling content for building B

7.5.4. Parking

Buildings A and B as described in chapter 6 have some common features and some different features which allow generalization from case studies. However, building B has different structure in terms of the main structural material and different parking area. Building B has a larger parking within the basement structure built under the whole plot with 2606 m^2 area, while building A has smaller parking with only 900 m^2 area built within the basement structure.

The retaining walls within the basement and the backfilling concrete with other relative activities mean the embodied carbon in the basement structure is much higher in building B than in building A, and has a significant share in the embodied carbon. Building B's basement structure is responsible for 28.8 per cent of the embodied carbon and this makes approximately 5.3 per cent of the total life-cycle carbon dioxide emissions, a figure that could be higher considering the other pre-mentioned scenarios. This is a contribution to the carbon emission which could be reduced significantly if alternatives were considered.

These results flag up the carbon embedded in basement structures, and may direct future research towards finding the efficiency of using the ground floor for parking rather than excavating a basement. This will make the building one storey higher (a possible problem if planning constraints imposes height restrictions) but may encounter huge savings in a commercial building's future carbon dioxide emissions. Questions that could be derived from these results and directed to the researchers and designers at the beginning of the design stages are.

- Does the building need such a lot of parking space?
- Is ground floor parking rather than basement an acceptable solution?
- What are the changes in operational carbon by increasing the building height by one floor?

7.5.5. Major refurbishment

It was stated within the methods chapter that a major refurbishment is not included within the maintenance activities, also it is generally accepted that most 1960s office buildings had at least one major refurbishment within their life time. A large amount of refurbishment is projected to occur in the coming years in the UK, and this is at least partially aimed at improving environmental performance. It is therefore important to understand when and why refurbishment is better than the alternative of demolishing and replacing the building.

The reason why this study did not consider a major refurbishment is the fact that in most cases the decision whether to make a major refurbishment or to knock down the building and replace it by a new one is made at refurbishment time and not at the beginning of building life-cycle. It is usually agreed that a new life-cycle assessment and life-cycle costing analysis will be held to support any future decision (Dunk, 2004).

Major refurbishment could be done for different reasons, mainly change of building function, improving environmental performance, modernization, and changes in fashion. And whatever the reason behind it, major refurbishment could cause an environmental improvement in building performance, as new technologies are used to reduce the operations carbon dioxide emissions of building's remaining life after refurbishment.

For the research in this thesis, life-cycle assessment is held at the beginning of building life, and in such case a major refurbishment is more prediction and assumptions rather than calculations. Moreover, all the pre-mentioned limitations of maintenance are applied to major refurbishment. For example, the carbon profiles of materials, components, and systems change significantly with time, as presented earlier in this chapter. However, major refurbishment causes a positive savings in building life.

7.6. Multiple scenarios

From the discussion presented in this chapter, there is a possibility to make multiple savings in the whole life-cycle carbon dioxide emissions by applying multiple optimistic scenarios based on the described scenario analysis. A choice of multiple scenarios based on 100 per cent recycled steel content, 30 per cent glazing ratio, and gone green scenario analysis for the first option of electricity mix at demand point and accelerated growth for the second option.

The whole life-cycle could go down from 32834 to 10411 tonnes of CO_2 and the embodied carbon life-cycle phase ratio goes up from 17.1 per cent of the whole life-cycle carbon in the current calculations to 44.9 per cent for multiple scenarios 1 and up to 48.3 per cent in the case of using accelerated growth scenario 2, as presented in Figure 77 and Figure 78. These are considerable changes.

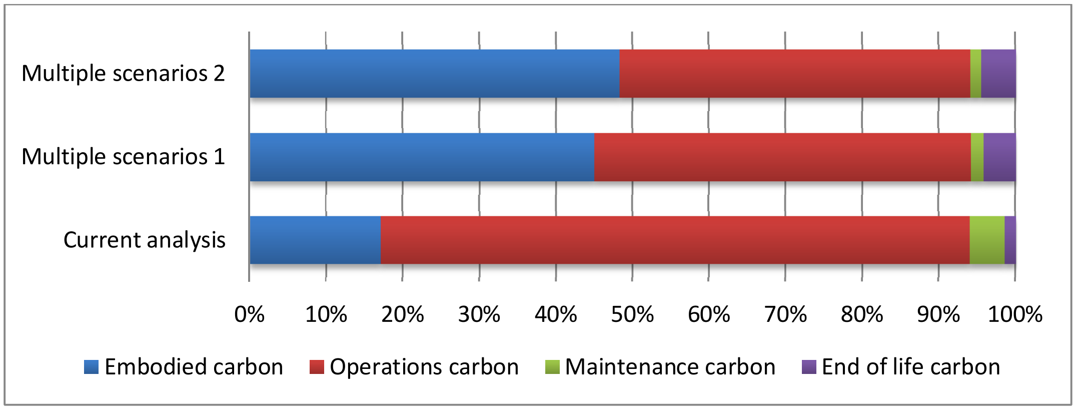

Figure 77 – Building A life phases using multiple scenarios 1 and 2

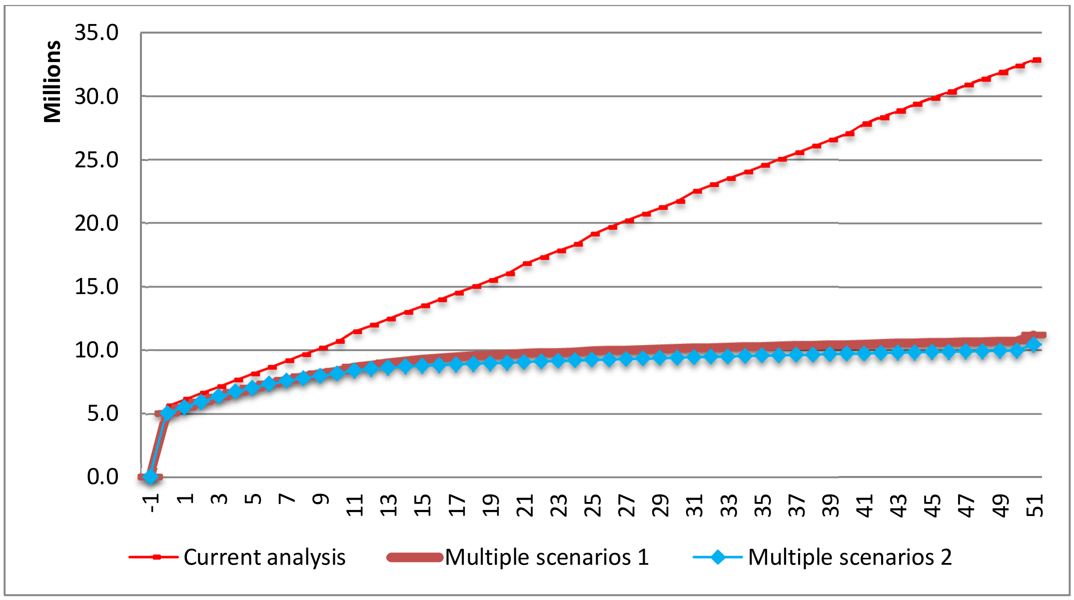

Figure 78 – Building A carbon dioxide emissions using multiple scenarios

Figure 78 shows that in the case of new-build offices there is significant carbon spike taking place at the start of building life. This spike is caused by the embodied energy which is very significant. The significance of the carbon spike increases by using multiple scenario analysis. This result is very similar to the results of a study by Saynajoki et al (2012). Their research indicates that new construction projects cause such a significant spike of carbon emissions in a short time that the benefits of improved energy efficiency only occur after several decades when compared to either renovating the old building stock or using existing residential areas built in the past, see Figure 79.

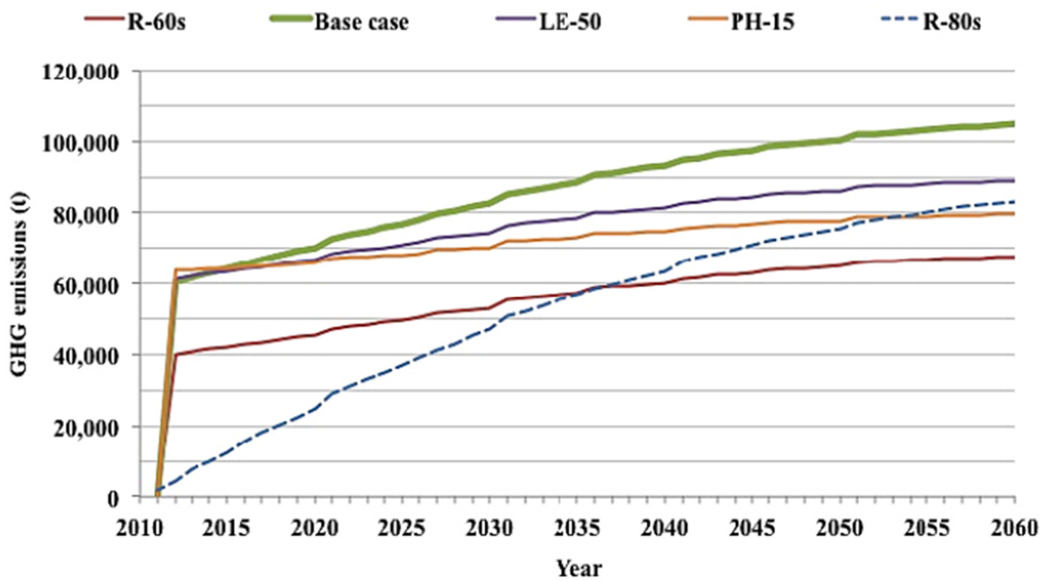

Figure 79 – GHG emissions over buildings life cycle, carbon spike.

7.7. Comparisons with literature

A fair comparison to literature is difficult to achieve because of the differences in studies boundaries and limitations, and differences in functional units, as discussed in chapter 3. A normalization analysis of results was carried out to make the results of literature studies at the same unit. The unit chosen for this purpose is (kg CO_2/m^2/year), as buildings analysis differ according to life span.

Table 25 presents, for different office buildings, the carbon dioxide emissions during their life time, and presents information which could play a role in their environmental impact including country, construction materials, area, life span, and year of study.

Case	Country	CM	Area m^2	Life span	Year	EC kg CO_2/m^2/year	WLC kg CO_2/m^2/year	Data source
A	**UK**	**Steel**	**11972**	**50**	**2012**	**9.35**	**54.85**	**This thesis**
B	**UK**	**RC**	**16780**	**50**	**2012**	**10.48**	**56.93**	**This thesis**
C	Finland	SRC	4400	50	2006	6.82	60.28	Junilla, (2006)
D	US	SRC	4400	50	2006	10.9	117.7	Junilla, (2006)
E	Japan	RC	1879	40	1998	15.5	81	Suzuki (1998)
F	Japan	RC	1404	40	1998	15	82	Suzuki (1998)
G	Japan	RC	1857	40	1998	14.5	63	Suzuki (1998)
H	Japan	RC	1340	40	1998	20.5	79	Suzuki (1998)
I	Japan	RC	1328	40	1998	21.5	94	Suzuki (1998)
J	Japan	RC	1253	40	1998	17.75	122	Suzuki (1998)
K	Japan	RC/S	1291	40	1998	23	92	Suzuki (1998)
L	Japan	RC/S	1358	40	1998	27.5	94	Suzuki (1998)
M	Japan	SRC	8458	40	1998	19.75	72	Suzuki (1998)
N	Japan	Steel	22982	40	1998	19.25	106	Suzuki (1998)
O	UK	S&T	1140	50	2010	18.46	63.35	Yolles (2010)
P	UK	RC	3411	50	2010	16.2	55	Yolles (2010)
Q	UK	Steel	2341	50	2010	10.76	36.9	Yolles (2010)
R	China	Steel	46,240	50	2008	6.29	47.72	Xing (2008)
S	China	RC	34,620	50	2008	12.12	48.18	Xing (2008)

Table 25 – Carbon emissions related to office buildings.
SRC: steel reinforced concrete; RC: reinforced concrete; RC/S: reinforced concrete/steel; EC embodied carbon; WLC: whole life carbon; CM: construction material

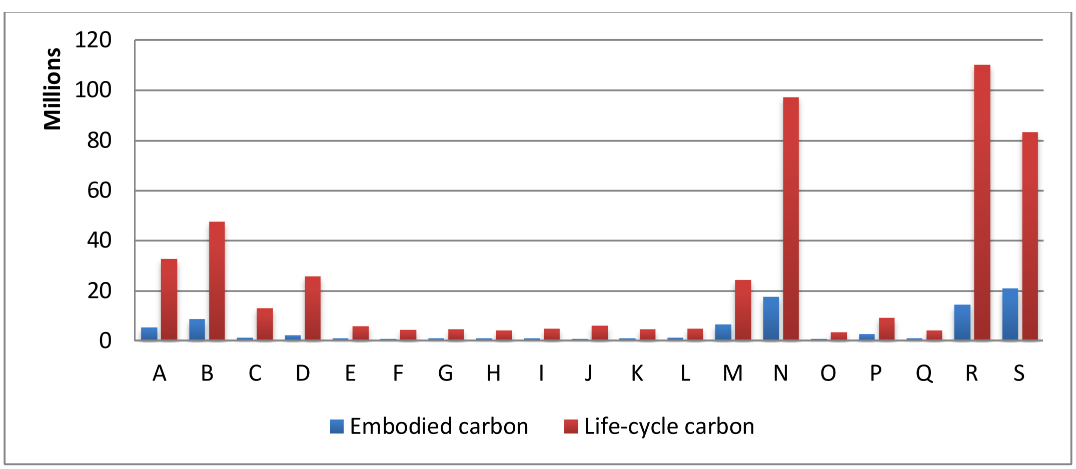

Figure 80 – Carbon emissions of different office buildings kg CO_2

Table 25 shows the total life-cycle carbon dioxide emissions of both case study buildings A and B compared to other cases derived from literature. Figure 80 shows that total carbon emissions are higher than most of the case studies because of the high floor area.

Normalization analyses show that the emissions of buildings A and B are relatively lower than the buildings presented as case studies within the literature, see Figure 81 and Figure 82. This could be related to different factors, mainly the age of the building and data inventories used to calculate the carbon emissions. Data inventory sets used in the past are different from the current data sets. The green movement has had an important effect on results, as manufacturing companies are trying to improve their carbon profiles, and be less harmful to environment.

Other studies in the literature have the similar finding with different ratios. A study of a university building in Michigan found that operational phase is responsible for 96.5 per cent of the whole life emissions over a 75-year life span (Scheuer et al., 2003). While another study of an office building in Europe stated that the operations share of carbon emissions is up to 86 per cent of the whole life cycle emissions (Junnila and Harvath, 2003).

A Canadian study held to compare three structures of office buildings in terms of life-cycle energy consumption found that the operational phase is responsible for up to 83 per cent of the total life-cycle energy consumption (Cole and Kernan, 1996).

Figure 81 and Figure 82 show that in general the lower the life-cycle carbon the higher the embodied carbon ratio.

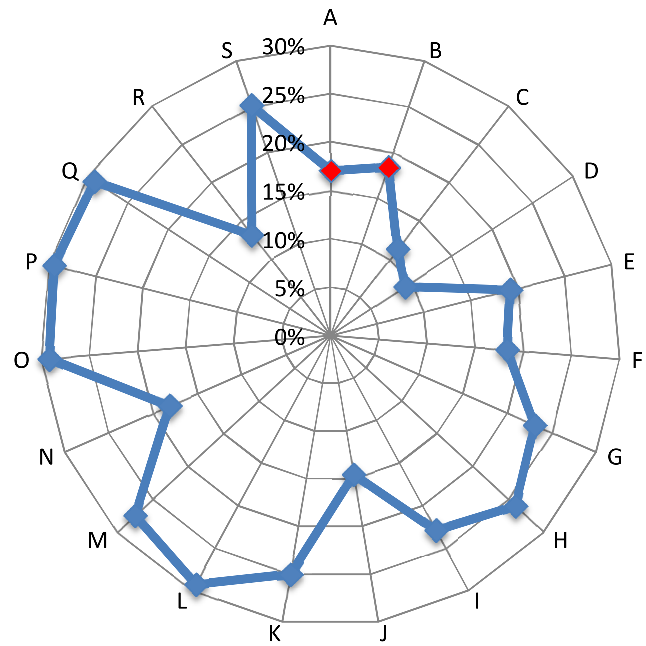

Figure 81 – Embodied carbon ratio of different office buildings

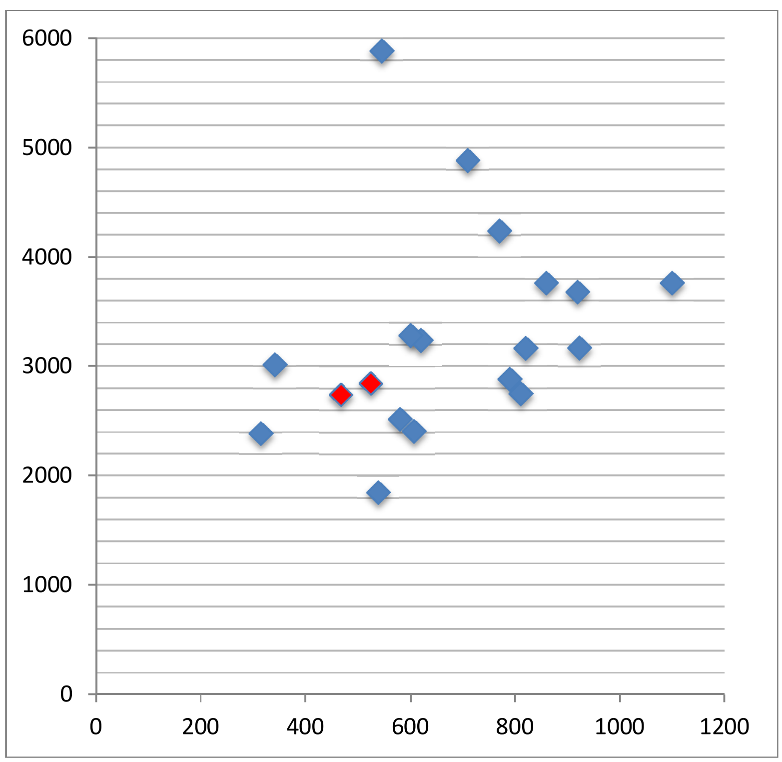

Figure 82 – Embodied versus life-cycle carbon emissions kg CO_2/m^2

7.8. Relevance to Professionals

This research has provided professionals with base case studies of new-build offices in Scotland, and introduced life-cycle assessment as a useful tool to be used within the decision making process at the early design stages. It opens the door to produce a tool which makes life cycle assessment easy and accessible to designers and decision makers.

The tool could be in the form of a website, in which the designer can enter building data and choose the most relevant specifications of the building materials, components, and processes. In the end, the tool will give an estimation of the carbon emissions during the building's life. The tool will use the most appropriate data which depends on real processes measurements, and calculations rather than predictions. Data accuracy, transparency, and quality are vital in such a tool, and will make it different from other tools available in the market. It is beyond the scope of this thesis to develop this tool, but this is a potential issue for further research.

Sturgis and Roberts (2010) developed a carbon profiling tool to aid design teams and contractors to define the best mix of specifications and technologies employed to create low carbon buildings. Their tool combines the operational and embodied emissions to produce a carbon profile for buildings. The study clarified that the tool depends on data provided by the University of Bath ICE (Inventory of Carbon and Energy), developed by Hammond Jones (2006). In the research described in this thesis, this data was used as backup data when manufacturer's data was not available.

The suggested website tool should depend on different data sets depending on the component location, production time, and specification. This would improve the quality of the data and the accuracy of the studies and could increase the comparability among case studies.

Manufacturers' data is not considered very reliable due to the lack of legislative enforcement. This could be solved if government regulations force manufacturers to issue carbon profiles for materials and components by consulting third party companies rather than calculating them in house. Another possible solution could be by the existence of quality assurance agencies which monitor the carbon profiling processes.

7.9. Conclusion

This chapter discussed the results of the life-cycle assessment analysis for two new-build offices in Scotland, and discovered the effects of changing parameters within the case studies. It proves that there could be a chance for carbon investment in terms of increasing embodied carbon by changing different sets of building parameters which may reduce the total life-cycle carbon dioxide emissions.

Data quality and verification was explained, and different scenarios were explained. The effects of changing electricity suppliers were detailed, and the possible changes in results due to electricity fuel mix improvements were explained. The chapter discussed the effect of changing glazing ratio of building A, and the possibility of reducing whole life-cycle carbon by changing the recycled content of materials and components. Possible effects of major refurbishment for different reasons were discussed, and the parking influence on results was explained.

Finally, this chapter compared the study results with other case study office buildings in the UK and overseas, and found that the emissions of Scotland office buildings are relatively lower than other offices in terms of both embodied and whole life-cycle carbon. The next chapter concludes the study and discusses the results in light of study limitations and illustrates those points where further research could be undertaken.

Chapter 8 - Conclusions

The purpose of this study was to quantify and compare the carbon dioxide emissions produced by office buildings during their lifetime. The study investigated the contribution of the different life- cycle phases and elements to life cycle emissions. Furthermore, the study performed a sensitivity assessment to evaluate the effects of possible changes over a service life of fifty years. The overall conclusion supports the original hypothesis that carbon dioxide emissions of new-build office buildings are relatively similar irrespective of their structure, materials and size. The carbon dioxide emissions of new-build offices in Scotland are somewhat less than the currently used benchmarks. This is the first time that such a study on Scottish office buildings has been reported.

The analysis of the case study buildings previously presented within the literature showed that the life cycle carbon dioxide emissions of office buildings is the sum of the operating (80–90%) and embodied (10–20%) carbon dioxide emissions. Normalised by floor area, the reported life-cycle carbon emissions of office buildings fall in the range of 40–122kg CO_2/m^2 per year. The new-build Scottish case studies gave carbon dioxide emissions results falling near the low end of the range. Building A's value of 54.85 kg CO_2/m^2 per year is slightly lower than building B's of 56.93 kg CO_2/m^2 per year. The life cycle carbon emissions can be reduced significantly by reducing the operating carbon through use of passive and active technologies even if their incorporation in the design leads to a slight increase in embodied carbon. However, an excessive use of passive and active features involving higher embodied carbon in a building may be counterproductive. Furthermore low energy buildings have a higher ratio of embodied carbon to total carbon than 'typical' buildings when considered over the whole life cycle.

Within the scenario analysis, the study found that life-cycle assessment is sensitive to even small changes in parameters. Many assumptions about the future must be made in a life-cycle assessment carried out at the beginning of the building's life and these can have a significant effect on the results, which in turn can influence the design decisions made. Overall, it is an important tool which can positively affect the decision making process. In this case, the results were most sensitive to those factors related to the assumptions about external conditions and obsolescence (electricity supply mix, rebuilding, energy mix, and refurbishment scenarios), but also quite sensitive to some input assumptions (energy consumption and recycling). The significant influence of the energy mix on the results is consistent with several previous studies that have already noted this. However, the effects of obsolescence have not yet been flagged as a significant cause of sensitivity in building life-cycle assessment.

The option of whether the building has (or does not have) a basement structure for parking and plant accommodation was discussed, and this issue is one for future research. The main difference in carbon dioxide emissions between buildings A and B could be attributed to the difference in the parking size. The parking within the basement structure of building B was found to be responsible for as much as 5.3 per cent of the total life-cycle emissions. Thus there is a real opportunity to investigate the differences in a building's emissions by considering different scenarios for the location of parking.

The data used for this research was checked against the quality criteria presented in chapter 8, and it was concluded that the data quality of this research is good. The same research protocol was used for both case study buildings which supports the reliability of the results. Unfortunately, lack of space means that not all the documents used to conduct the case studies could be included in the thesis. However, selected data sheets are attached within the appendices.

The outcome of the research described in this thesis, along with case studies derived from literature suggest that there are many possible ways to improve the carbon profile of buildings by reducing the carbon emissions of materials and components. This improvement does not mean only reducing the embodied carbon of materials and components, but also looking at the effects of considering alternatives on the whole life-cycle emissions. Environmentally conscious choice of materials should involve both lower embodied carbon and lower operational carbon, but it is still possible to achieve overall savings if embodied carbon is higher.

Some of the carbon reduction measures worth considering include:

- minimising the quantity and the variety of materials used;

- products with high recycled content, e.g. cement replacement materials such as GGBS (ground granulated blastfurnace slag) or PFA (pulverised fuel ash) in predominantly concrete buildings are typically the biggest quick wins on some projects;

- low carbon design details, e.g. exposed concrete ceilings; castellated steel beams; aerated blockwork; rotary piles; voided biaxial slabs; and

- low carbon alternatives to traditional building products.

This requires direct comparisons between potential options to establish the most carbon efficient solution.

It should, however, be noted that when trying to improve the carbon performance of a project, cradle-to-gate embodied carbon may sometimes have to be used in conjunction with other sustainability indicators, e.g. transportation of construction materials, use of renewable materials or operational energy consumption. The following are two examples of the typical carbon interlinks which require a multidisciplinary input:

- A product with very low cradle-to-gate embodied carbon produced overseas may actually have much higher overall life cycle carbon footprint than a locally sourced alternative due to the emissions associated with transportation. In this case carbon intensity of shipping should be considered as well.

- Adding high thermal mass materials, high in embodied carbon, may actually reduce the overall life cycle carbon footprint due to reducing the need for cooling over the building's life.

This research investigated the carbon emissions of new-build typical offices in Scotland. These case studies could provide a benchmark for comparison to unconventional designs in future, and it would be interesting to investigate the difference between typical and untypical office buildings in Scotland. Further research could also have a more action-oriented approach, so that the implementing of new knowledge in design processes with its potential beneficial effect on the environmental performance of buildings could be tested. Since office life is not confined to the performance of the building itself, it would be interesting to study other human-related activities within office buildings, for example comparing the carbon emissions of building to those of paper use and printing facilities during the building life. This would bring facilities management and business management together. Another wider example is the relationship between carbon emissions of the building and those associated with commuting and other business related transport.

Finally, carbon dioxide emission is only one of many indicators of environmentally conscious buildings. Even if it is currently accorded the greatest importance by many authorities, other indicators should be researched to produce a broader understanding of the relationship between building materials and components and the environment.

It is hoped that the results of this study could be used by designers, owners, specifiers, and facilities managers of office building at early design stages to share as a tool within the decision making process. The process could help them focus their attention on the areas which are environmentally sensitive. Conscious designers could benefit from this study as an example of the current trend of building in Scotland and make positive changes in design which could help meet the carbon dioxide emissions reduction goals of the country.

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Appendix A – Energy Performance Certificates

Building A

Energy Performance Certificate for buildings other than dwellings

Energy Performance Certificate

Building Energy Performance — **Scotland**

Calculated asset rating using IES <VE> 5.9.1 [ApacheSim]	Building type Office	**Current rating**

	Current rating
Carbon Neutral	**Excellent**
A (0 to 15)	
B (16 to 30)	**B**
C (31 to 45)	
D (46 to 60)	
E (61 to 80)	
F (81 to 100)	
G (100+)	**Very Poor**

Carbon Dioxide Emissions The number refers to the calculated carbon dioxide emissions in terms of kg per m² of floor area per year	**30**
Approximate current energy use per m² of floor area:	**75** kWh/m²

Main heating fuel: Grid Supplied Electricity **Building Services:** Air conditioning
Renewable energy source: **Electricity:** Grid supplied

Carbon Dioxide is a greenhouse gas which contributes to climate change.
Less Carbon Dioxide emissions from buildings helps the environment.

Benchmarks

A building of this type built to building regulations standards current at the date of issue of this certificate would have a rating:	32	**C+**
Where the accompanying recommendations for the cost effective improvement of energy performance are applied, this building would have a rating:	0	**Carbon Neutral**

Recommendations for the cost-effective improvement (lower cost measures) of the energy performance

Building B

Energy Performance Certificate for buildings other than dwellings

Energy Performance Certificate

Building Energy Performance — Scotland

Calculated asset rating using IES <VE> 5.9.0.1 [ApacheSim]	Building type Office	**Current rating**

Rating		Current rating
Carbon Neutral		**Excellent**
A	**(0 to 15)**	
B	**(16 to 30)**	
C	**(31 to 45)**	**C+**
D	**(46 to 60)**	
E	**(61 to 80)**	
F	**(81 to 100)**	
G	**(100+)**	**Very Poor**

Carbon Dioxide Emissions The number refers to the calculated carbon dioxide emissions in terms of kg per m^2 of floor area per year	**36**
Approximate current energy use per m^2 of floor area:	**159** kWh/m^2

Main heating fuel: Natural Gas
Building Services: Air conditioning
Renewable energy source:
Electricity: Grid supplied

Carbon Dioxide is a greenhouse gas which contributes to climate change.
Less Carbon Dioxide emissions from buildings helps the environment.

Benchmarks

A building of this type built to building regulations standards current at the date of issue of this certificate would have a rating:	**30**	**B**
Where the accompanying recommendations for the cost effective improvement of energy performance are applied, this building would have a rating:	**0**	**Carbon Neutral**

Recommendations for the cost-effective improvement (lower cost measures) of the energy performance

Appendix B – Carbon Inventory Example for Building A

Example spread sheets showing build-up of carbon data. Table B.1 is an example of the spread sheets used to calculate the total CO_2 attributable to the concrete works in building A. The same approach was followed for all the systems, items, and components of both buildings. As can be seen, the entries in the bills of quantities show amounts of each material in m^3, which was derived from manufacturers' data, Hammond & Jones (2010), Franklin (2010), and Environment Agency (2010). The total carbon inventory for concrete was obtained by summing all the entries (see the last line of Tables B.1). This table alonge with other spread sheets were used in tables and figures presented in chapter 7.

Table B.1 Embodied carbon in reinforced concrete

Number	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	E IN SITU CONCRETE / LARGE PRECAST CONCRETE					
	E10 MIXING / CASTING / CURING IN-SITU CONCRETE					
	Plain; spec E10/120					
	Beds					
4.2/1/A	50 thick blinding layer; sloping	81.00	m^2	85.60	432.21	36,997.07
	Plain; spec E10/120					
	Beds					
4.2/1/B	50 thick blinding layer	1,163.00	m^2			
	Plain; spec E10/120					
	Mass concrete fill					
4.2/1/C	to rock head	21.00	m^3			
	Reinforced; include for reinforcement					
	Ground beams; spec E10/105; reinforcement 250 kg/m^3					
4.2/2/D	generally	9.00	m^3	24.00	541.46	12,995.14

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	Ground beams to contiguous piles; spec E10/110; reinforcement 250 kg/m^3					
4.2/2/B	generally	15.00	m^3			
	Isolated foundations; pad foundations; spec E10/105; reinforcement 80 kg/m^3					
4.2/2/C	generally	281.00	m^3	321.70	425.30	136,820.30
	Isolated foundations; strip foundations; spec E10/105; reinforcement 80 kg/m^3					
4.2/2/D	generally	35.00	m^3			
	Beds					
4.2/2/E	300 thick; access ramp; spec E10/110; reinforcement 110 kg/m^3; sloping	127.00	m^2	38.70	432.43	16,735.12
4.2/2/F	150 thick; raised plant area level 77.185; spec E10/110; reinforcement 60 kg/m^3	38.00	m^2	5.81	422.68	2,457.45
4.2/2/G	200 thick; ground floor level 75.50 and 76.18; RC30; reinforcement 60 kg/m^3	782.00	m^2	159.40	422.68	67,374.75
4.2/2/H	300 thick; basement; spec E10/110; reinforcement 110 kg/m^3	1,163.00	m^2	355.80	432.43	153,859.31
	Thickenings to beds					
4.2/2/I	150 to 450 thick; spec E10/105; reinforcement 60 kg/m^3	9.00	m^3	9.00	422.68	3,804.09
4.2/2/J	over 450 thick; spec E10/105; reinforcement 110 kg/m^3	169.00	m^3	172.00	432.43	74,378.30
	Reinforced; include for formwork and reinforcement; drawing 19223:28:010 C, sections 7-7, 8-8 and 9-9					
	Walls					
4.2/3/A	facing to contiguous piled wall; spec E10/105; reinforcement 90 kg/m^3	119.00	m^2	36.30	418.84	15,203.75
	Reinforced; include for formwork and reinforcement; structural level 72.00 to 75.55					

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	Retaining walls; spec E10/105; reinforcement 125 kg/m^3			83.40	522.30	43,559.62
4.2/3/B	300 thick	273.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			10.68	541.46	5,782.84
4.2/3/E	250 thick; 1400 wide	7.00	m			
4.2/3/F	250 thick; 1000 wide	7.00	m			
	Rectangular columns integral with retaining wall; spec E10/115; reinforcement 250 kg/m^3					
4.2/3/G	600 x 600	18.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90kg/m^3			28.50	418.97	11,940.59
4.2/3/H	250 thick	112.00	m			
	Reinforced; include for formwork and reinforcement; structural level 72.80 to 75.55					
	Retaining walls; spec E10/105; reinforcement 125 kg/m^3			54.70	522.30	28,569.68
4.2/3/I	300 thick	95.00	m^2			
4.2/3/J	external angles	1.00	m			
	Retaining walls; spec E10/105; reinforcement 125 kg/m^3					
4.2/4/A	400 thick	63.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			7.48	541.46	4,050.15
4.2/4/B	250 thick; 1400 wide	8.00	m			
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/4/C	600 x 600	13.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3			6.25	428.08	2,675.48
4.2/4/D	250 thick	24.00	m			
	Reinforced; include for formwork and reinforcement; structural level 72.80 to 78.80					

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	Retaining walls; spec E10/105; reinforcement 125 kg/m^3			3.60	522.30	1,880.27
4.2/4/E	300 thick	12.00	m^2			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3			12.63	428.08	5,404.46
4.2/4/F	250 thick	25.00	m^2			
	Reinforced; include for formwork and reinforcement; structural level 75.55 to 79.25					
	External walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/4/G	250 thick	25.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			36.07	541.46	19,529.42
4.2/4/H	250 thick; 1400 wide	18.00	m			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3					
4.2/5/A	250 thick; 1000 wide	11.00	m			
4.2/5/B	250 thick; 800 wide	8.00	m			
	Rectangular columns integral with wall; spec E10/110; reinforcement 250 kg/m^3					
4.2/5/C	600 x 600	18.00	m			
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/5/D	600 x 600	15.00	m			
4.2/5/E	450 x 450	25.00	m			
	Circular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/5/F	300 diameter	29.00	m			
4.2/5/G	600 diameter	22.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3			102.60	428.08	43,920.60
4.2/5/H	250 thick	348.00	m^2			
4.2/5/I	extra for 1500 high section of wall being 400 thick	11.00	m			

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	Reinforced; include for formwork and reinforcement; structural level 79.25 to 82.95					
	External walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/5/J	250 thick	29.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			67.72	541.46	36,667.20
4.2/5/K	250 thick; 1400 wide	18.00	m			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3					
4.2/6/A	250 thick; 1000 wide	10.00	m			
4.2/6/B	250 thick; 800 wide	15.00	m			
4.2/6/C	250 thick; 500 wide	4.00	m			
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/6/D	450 x 450	52.00	m			
	Circular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/6/E	450 diameter	18.00	m			
4.2/6/F	600 diameter	37.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3			71.88	428.08	30,767.96
4.2/6/G	250 thick	275.00	m^2			
	Reinforced; include for formwork and reinforcement; structural level 82.95 to 86.65					
	External walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/6/H	250 thick	7.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			11.80	541.46	6,389.28
4.2/6/I	250 thick; 1400 wide	18.00	m			
4.2/6/J	250 thick; 1000 wide	10.00	m			
4.2/6/K	250 thick; 800 wide	15.00	m			

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/7/A	450 x 450	62.00	m	22.72	541.46	12,301.60
	Circular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/7/B	450 diameter	4.00	m			
4.2/7/C	600 diameter	33.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3			72.50	428.08	31,035.51
4.2/7/D	250 thick	278.00	m^2			
	Reinforced; include for formwork and reinforcement; structural level 86.65 to 90.35					
	External walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/7/E	250 thick	7.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			11.80	541.46	6,389.28
4.2/7/F	250 thick; 1400 wide	18.00	m			
4.2/7/G	250 thick; 1000 wide	10.00	m			
4.2/7/H	250 thick; 800 wide	15.00	m			
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3			22.44	541.46	12,148.58
4.2/7/I	450 x 450	62.00	m			
	Circular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/7/J	450 diameter	4.00	m			
4.2/7/K	600 diameter	32.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3					
4.2/8/A	250 thick	278.00	m^2	72.50	428.08	31,035.51
	Reinforced; include for formwork and reinforcement; structural level 90.35 to 94.05					

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	External walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/8/B	250 thick	7.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			10.05	541.46	5,441.71
4.2/8/C	250 thick; 1400 wide	18.00	m			
4.2/8/D	250 thick; 1000 wide	7.00	m			
4.2/8/E	250 thick; 800 wide	10.00	m			
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3			18.67	541.46	10,107.58
4.2/8/F	450 x 450	32.00	m			
	Circular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/8/G	300 diameter	22.00	m			
4.2/8/H	450 diameter	10.00	m			
4.2/8/I	600 diameter	32.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m3			71.88	428.08	30,767.96
4.2/8/J	250 thick	275.00	m^2			
	Reinforced; include for formwork and reinforcement; structural level 94.05 to 97.85					
	External walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/9/A	250 thick	7.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			10.80	541.46	5,847.81
4.2/9/B	250 thick; 1400 wide	19.00	m			
4.2/9/C	250 thick; 1000 wide	7.00	m			
4.2/9/D	250 thick; 800 wide	12.00	m			
	Rectangular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3			19.96	541.46	10,805.05
4.2/9/E	450 x 450	34.00	m			

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	Circular columns; including downstand at column head; spec E10/115; reinforcement 250 kg/m^3					
4.2/9/F	300 diameter	22.00	m			
4.2/9/G	450 diameter	12.00	m			
4.2/9/H	600 diameter	34.00	m			
	Stair and lift walls; spec E10/115; reinforcement 90 kg/m^3			131.50	428.08	56,291.99
4.2/9/I	250 thick	286.00	m^2			
	Reinforced; include for formwork and reinforcement; structural level 97.85 to roof; 3000 high excluding parapet					
	Walls; spec E10/110; reinforcement 90 kg/m^3					
4.2/9/J	250 thick	231.00	m^2			
	Blade columns; spec E10/115; reinforcement 250 kg/m^3			7.95	541.46	4,304.64
4.2/10/A	250 thick; 1400 wide	15.00	m			
4.2/10/B	250 thick; 1000 wide	6.00	m			
4.2/10/C	250 thick; 800 wide	6.00	m			
	Reinforced; include for formwork and reinforcement;					
	Sump pit; as drawing 19223:96:006 C; spec E10/105; reinforcement 110 kg/m^3					
	Upstands					
4.2/10/E	approximattely 200 thick and 200 high; spec E10/105; reinforcement 60 kg/m^3	76.00	m	3.08	422.68	1,301.85
	Upstands and projection; spec E10/105; reinforcement 110 kg/m^3					
4.2/10/F	approximattely 200 thick and 1000 high (varies); splayed soffit; drawing 19223:16:100 B section	26.00	m	5.20	432.43	2,248.65

	Item	Quantity		Sums m^3	Carbon value $kg\ CO_2$ / unit	Total carbon $kg\ CO_2$
	Contractor designed; reinforced; include for formwork, temporary propping, reinforcement, worked finishes/surface hardener, joints etc					
	Post tensioned slabs; structural level 75.55; measured over voids not exceeding 5 m^2					
4.2/10/G	300 thick	1,082.00	m^2	330.90	443.92	146,891.80
4.2/10/H	form void 4400 x 1300	1.00	nr			
4.2/10/I	form void 3500 x 1000	1.00	nr			
4.2/10/J	form void 3000 x 1300	1.00	nr			
4.2/10/K	form void 2100 x 1200	1.00	nr			
	Post tensioned slabs; structural level 75.55; measured over voids not exceeding 5 m^2					
	300 thick					
4.2/11/A	form void 2300 x 1200	1.00	nr			
4.2/11/B	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/11/C	form void 7000 x 3300; stair	1.00	nr			
4.2/11/D	perimeter	180.00	m			
	Post tensioned slabs; structural level 78.60; measured overall					
4.2/11/E	250 thick	15.00	m^2	7.75	446.56	3,460.81
4.2/11/F	400 thick upstand between level 78.60 and 79.25	10.00	m			
	Post tensioned slabs; structural level 79.25; measured over voids not exceeding 5 m^2					
4.2/11/G	250 thick	1,700.00	m^2	450.46	446.56	201,155.62
4.2/11/H	extra over for slab 350 thick	44.00	m^2			
4.2/11/HH	300X400 DOWNSTAND BEAM	13.00	m			
4.2/11/I	form void 4400 x 1300	1.00	nr			
4.2/11/J	form void 5000 x 800	2.00	nr			
4.2/11/K	form void 3500 x 1000	1.00	nr			
4.2/11/L	form void 3000 x 1300	1.00	nr			
4.2/11/M	form void 2100 x 1200	1.00	nr			
4.2/11/N	form void 2000 x 1800	1.00	nr			
4.2/11/O	form void 2400 x 1300	1.00	nr			

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
4.2/11/P	beam to support slab stair grid F/5	9.00	m	1.62	443.92	719.14
4.2/11/Q	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/11/R	form void 5500 x 3000; stair	1.00	nr			
	Post tensioned slabs; structural level 79.25; measured over voids not exceeding 5 m^2					
	250 thick					
4.2/12/A	form void 4500 x 3000; stair	2.00	nr			
4.2/12/B	perimeter	209.00	m			
4.2/12/C	75 x1500mm perimeter	31.00	m			
	Post tensioned slabs; structural level 82.95; measured over voids not exceeding 5 m^2					
4.2/12/D	250 thick	1,870.00	m^2	476.75	446.56	212,895.57
4.2/12/E	extra over for slab 350 thick	196.00	m^2	69.65	446.56	31,102.63
4.2/12/F	form void 4400 x 1300	1.00	nr			
4.2/12/G	form void 5000 x 800	2.00	nr			
4.2/12/H	form void 3500 x 1000	1.00	nr			
4.2/12/I	form void 1000 x 700	2.00	nr			
4.2/12/J	form void 3000 x 1300	1.00	nr			
4.2/12/K	form void 2100 x 1200	1.00	nr			
4.2/12/L	form void 2000 x 1800	1.00	nr			
4.2/12/M	form void 2400 x 1300	1.00	nr			
4.2/12/N	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/12/O	form void 5500 x 3000; stair	1.00	nr			
4.2/12/P	form void 4500 x 3000; stair	1.00	nr			
4.2/12/Q	perimeter	194.00	m			
4.2/12/R	75x1500 PERIMETER	82.00	m			
4.2/12/S	upstands 200 thick and 200 high	20.00	m			
4.2/12/T	upstands 200 thick and 400 high	20.00	m			
	Post tensioned slabs; structural level 86.65; measured over voids not exceeding $5m^2$					
4.2/13/A	250 thick	1,740.00	m^2	444.00	446.56	198,270.86

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
4.2/13/B	extra over for slab 350 thick	192.00	m^2	67.90	446.56	30,321.15
4.2/13/BB	300X400 DOWNSTAND BEAM	12.00	m	1.44	446.56	643.04
4.2/13/C	form void 4400 x 1300	1.00	nr			
4.2/13/D	form void 5000 x 800	2.00	nr			
4.2/13/E	form void 3500 x 1000	1.00	nr			
4.2/13/F	form void 3000 x 1300	1.00	nr			
4.2/13/G	form void 2100 x 1200	1.00	nr			
4.2/13/H	form void 2000 x 1800	1.00	nr			
4.2/13/I	form void 2400 x 1300	1.00	nr			
4.2/13/J	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/13/K	form void 5500 x 3000; stair	1.00	nr			
4.2/13/L	form void 4500 x 3000; stair	2.00	nr			
4.2/13/M	perimeter	208.00	m			
4.2/13/N	75X1500 PERIMETER	68.00	m			
4.2/13/O	upstands 200 thick and 200 high	16.00	m			
	Post tensioned slabs; structural level 90.35; measured over voids not exceeding $5m^2$					
4.2/13/P	250 thick	1,740.00	m^2	443.25	446.56	197,935.95
4.2/13/Q	extra over for slab 350 thick	192.00	m^2	68.25	446.56	30,477.45
4.2/13/QQ	300X400 DOWNSTAND BEAM	21.00	m	2.52	446.56	1,125.32
4.2/13/R	form void 4400 x 1300	1.00	nr			
4.2/13/S	form void 5000 x 800	2.00	nr			
4.2/13/T	form void 3500 x 1000	1.00	nr			
4.2/13/U	form void 3000 x 1300	1.00	nr			
	Post tensioned slabs; structural level 90.35; measured over voids not exceeding $5m^2$					
	250 thick					
4.2/14/A	form void 2100 x 1200	1.00	nr			
4.2/14/B	form void 2000 x 1800	1.00	nr			
4.2/14/C	form void 2400 x 1300	1.00	nr			
4.2/14/D	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/14/E	form void 5500 x 3000; stair	1.00	nr			

	Item	Quantity		Sums m^3	Carbon value $kg\ CO_2$ / unit	Total carbon $kg\ CO_2$
4.2/14/F	form void 4500 x 3000; stair	2.00	nr			
4.2/14/G	perimeter	207.00	m			
4.2/14/H	75X1500MM PERIMETER	69.00	m			
4.2/14/I	upstands 200 thick and 200 high	16.00	m			
	Post tensioned slabs; structural level 94.05; measured over voids not exceeding 5 m^2					
4.2/14/J	250 thick	1,734.00	m^2	442.00	446.56	197,377.75
4.2/14/K	extra over for slab 350 thick	197.00	m^2	70.00	446.56	31,258.92
4.2/14/KK	300X400 DOWNSTAND BEAM	30.00	m	3.60	446.56	1,607.60
4.2/14/L	form void 4400 x 1300	1.00	nr			
4.2/14/M	form void 5000 x 800	2.00	nr			
4.2/14/N	form void 3500 x 1000	1.00	nr			
4.2/14/O	form void 3000 x 1300	1.00	nr			
4.2/14/P	form void 2100 x 1200	1.00	nr			
4.2/14/Q	form void 2000 x 1800	1.00	nr			
4.2/14/R	form void 2400 x 1300	1.00	nr			
4.2/14/S	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/14/T	form void 5500 x 3000; stair	1.00	nr			
	Post tensioned slabs; structural level 94.05; measured over voids not exceeding 5 m^2					
	250 thick					
4.2/15/A	form void 4500 x 3000; stair	2.00	nr			
4.2/15/B	perimeter	209.00	m			
4.2/15/C	50X1500MM PERIMETER		m			
4.2/15/D	upstand 200 thick and 200 high	32.00	m			
4.2/15/E	upstand below saw tooth facade; 200 thick and 400 high	47.00	m			
	Post tensioned slabs; structural level 97.85; measured over voids not exceeding 5 m^2					
4.2/15/F	300 thick	1,686.00	m^2	515.40	446.56	230,154.96
4.2/15/F/1	375MM THICK	530.00	m^2	202.50	446.56	90,427.59

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
4.2/15/F/2	300x400 DOWNSTAND BEAM	13.00	m	1.56	446.56	696.63
4.2/15/G	form void 4400 x 1300	1.00	nr			
4.2/15/H	form void 5000 x 800	2.00	nr			
4.2/15/I	form void 3500 x 1000	1.00	nr			
4.2/15/J	form void 3000 x 1300	1.00	nr			
4.2/15/K	form void 2100 x 1200	1.00	nr			
4.2/15/L	form void 2000 x 1800	1.00	nr			
4.2/15/M	form void 2400 x 1300	1.00	nr			
4.2/15/N	beam to support slab stair grid F/5	8.00	m			
4.2/15/O	form void 7200 x 2300; lift shaft	1.00	nr			
4.2/15/P	form void 5500 x 3000; stair	1.00	nr			
4.2/15/Q	form void 4500 x 3000; stair	2.00	nr			
4.2/15/R	upstand below upper storey facade; 200 thick and 200 high	124.00	m			
4.2/15/S	slab edge	66.00	m			
	Post tensioned slabs; structural level 97.85; measured over voids not exceeding 5 m^2					
	300 thick					
4.2/16/A	upstand to terrace; saw tooth; 200 thick and 400 high	32.00	m	11.52	443.92	5,113.91
4.2/16/B	upstand to terrace; 200 thick and 400 high	110.00	m			
	Post tensioned slabs; generally					
4.2/16/C	upstand 200 thick and 200 high below glazing; (additional allowance)	180.00	m	7.32	432.43	3,165.40
	Landings.					
4.2/16/D	200 thick; 3000 x 1800	14.00	nr	15.12	432.43	6,538.37
	Post tensioned slabs; roof					
4.2/16/E	250 thick	206.00	m^2	51.00	443.92	22,639.72
4.2/16/F	parapet 1200 high	80.00	m	24.30	443.92	10,787.16
	Post tensioned slabs; suspended lift pit base noted on drawing 19223:28:011 C					
4.2/16/G	400 thick	24.00	m^2	9.60	434.94	4,175.42

	Item	Quantity		Sums m^3	Carbon value $kg\ CO_2$ / unit	Total carbon $kg\ CO_2$
	Reinforced; include for formwork and reinforcement; drawing 19223:16:100 B, section 1-1; spec E10/110; reinforcement 125 kg/m^3					
	Walls; 300 thick					
4.2/16/H	5900 long and 2300 high	1.00	Item	11.36	522.30	5,933.82
4.2/16/I	4200 long and 1800 high	1.00	Item			
4.2/16/J	8200 long and 1300 high	1.00	Item			
4.2/16/K	7600 long and 800 high	1.00	Item			
4.2/16/L	200 thick upstand to 300 thick wall; 1100 high	7.00	m	0.33	522.30	172.36
4.2/16/M	200 thick upstand to 300 thick wall; 1300 high	1.00	m	0.39	522.30	203.70
	Walls; 300 thick					
4.2/17/A	200 thick upstand to 300 thick wall; 600 to 1100 high	28.00	m	9.24	522.30	4,826.03
	Reinforced; include for formwork and reinforcement; drawing 19223:16:100 B, section 4-4; spec E10/110; reinforcement 125 kg/m^3					
	Walls; 200 thick					
4.2/17/B	800 high	59.00	m	95.89	522.30	50,081.81
	Reinforced; include for formwork and reinforcement; drawing 19223:16:100 B, section 5-5; spec E10/110; reinforcement 125 kg/m^3					
	Walls; 250 thick					
4.2/17/C	1200 high	19.00	m			
	Reinforced; include for formwork and reinforcement; drawing 19223:16:101 B, section 5-5; spec E10/110; reinforcement 125 kg/m^3					
	Walls; 300 thick					
4.2/17/D	215 thick parapet wall 1100 high to access ramp approximatley 25.5 m long	1.00	Item			
	Grouting					
	Stanchion bases					
4.2/17/F	generally	20.00	nr		3.40	68.00

	Item	Quantity		Sums m^3	Carbon value kg CO_2 / unit	Total carbon kg CO_2
	E40 DESIGN JOINTS FOR IN-SITU CONCRETE					
	Joints					
	Plain, formed , cut, isolation etc include for sealant - EXCLUDES JOINT SEALANTS					
4.2/18/J	to 300 thick basement bed approximatlely 1097 m^2 , perimeter 185 m	300.00	m		5.20	1,591.20
4.2/18/K	to 300 thick access ramp approximatlely 100 m^2	60.00	m		5.20	318.24
4.2/18/L	to 200 thick ground floor bed approximatlely 738 m^2 , perimeter 175 m	240.00	m		5.20	1,272.96
	E41 WORKED FINISHES /CUTTING TO IN-SITU CONCRETE					
	Worked finishes/surface hardener					
	basement bed					
4.2/19/A	generally	1,050.00	m^2		11.32	12,123.72
	access ramp					
4.2/19/B	sloping	100.00	m^2		11.32	1,154.64
	ground floor bed					
4.2/19/C	generally	720.00	m^2		11.32	8,313.41
	raised plant area bed					
4.2/19/D	generally	33.00	m^2		11.32	381.03
Total	**Embodied carbon**					**2,732,174.2**