Environmental Performance Evaluation of Heating and Cooling between Sustainable and Conventional Office Buildings

By

Elisavet Dimitrokali

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STUDENT DECLARATION FORM

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ABSTRACT

The aim of the study was to evaluate the long-term environmental performance effectiveness of heating and cooling systems between 'sustainable' and conventional office buildings. The key research question that this study tried to answer, is, 'To what extent do sustainable office buildings remain sustainable in the long run?'' On this basis, two hypotheses (HP) were tested:

- **HP1:** Sustainable buildings remain sustainable in the long run.
- **HP2**: Current indicators fulfill the role for determining long term sustainability.

From the sustainability point of view, this study focused only on the environmental aspect. The word 'sustainable' has been used for identifying office buildings where environmental aspects have been taken into consideration through sustainability approaches. In order to address the first hypothesis, initially this study used a case study comparison approach to compare 'sustainable' with conventional office buildings, by comparing building design and heating-cooling system characteristics. This helped to raise understanding of the environmental characteristics that classify an office building as sustainable. Two case studies were used:

- The first case study comparison consists of a new 'sustainable' BREEAM excellent certified office building from 2009 and a conventional office building from the 1960s that had no refurbishments.
- The second case study comparison consists of a refurbished 'sustainable' BREEAM excellent certified office building compared to a conventional office building from the 1950s that had an upgrade in the heating system.

The study then focused on assessing the current environmental performance of heating and cooling between the case study buildings. Therefore Post Occupancy Evaluation (POE) methods were used including site visits, interviews, recording of heating and cooling systems, collection of heating-cooling consumption data, conducting thermographic surveys, applying Heating Degree Data (HDD) Evaluation and undertaking Life Cycle Assessment (LCA).

LCA has played a key role in evaluating the long run environmental performance of heating and cooling systems. The LCA evaluated two performance indicators: a) energy consumption of heating and cooling for 2 years of operation and b) the raw-material consumption of heating and cooling system production. Further, hypothetical long run scenarios were developed to consider the consequences of the existing

operational and embodied raw-material emissions in the long run. Sensitivity LCA analysis was also used in order to evaluate the environmental impacts of alternative scenarios of different low/zero carbon technologies if they were installed in the case study buildings. Uncertainty analysis was used to assess the significance of uncertainty in the data evaluated.

The key outcome of this study was the need for developing a new Sustainability Indicator that can be used to support environment decision making in evaluating the long run environmental performance of heating and cooling systems in office buildings. The new indicator brings together all the research methods used in this study by developing further the existing energy indicator already integrated in existing SAMs and by developing a new indicator for raw-materials of heating and cooling systems. Suggestions for their integration on existing SAMs are also discussed. Finally the study ends with key conclusions and suggestions for further research.

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ABBREVIATIONS

FM	Facility Management
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
ISO	International Organization for Standardisation
POE	Post Occupancy Evaluation
h/c	heating/cooling
(t)	Temperature
(m)	Materials
OLRLCII	Overall Long Run Life Cycle Impact Indicator
ERMEI	Embodied raw-material emission indicator
Sustainable	Buildings built considering environmental and socio-economic aspects, certified by BREEAM assessment method.
SAMs	Sustainable Assessment Methods
Conventional	Building built from 1950 onwards without any sustainable measures
Embodied emissions	Environmental impacts occured during production-manufacturing stages of a building product or system.
Energy efficient	Used to describe low heat waste and low operational emissions
Eco-efficient	Used to describe low environmental impacts
Material efficiency	Used to describe low embodied raw-material emission
RM	Raw-materials
WP	Work package
LTHW	Low Temperature Hot Water
AHU	Air-handling unit
VRF	Variable Refrigerant Flow
VRV	Variable Refrigerent Volume
CHP	Combined Heat and Power
CHP (trigeneration(trigen)	Combined heat, Power and Cooling
CHW	Chilled Hot Water
DX	Direct expansion type of air conditioning

CHAPTER 1: INTRODUCTION

1.1 Background

Since the beginning of the twentieth century extreme global ecological issues such as climate change, ice-melting, temperature increase, sea level rising, and droughts have come to the fore, threatening human health, ecosystem quality and the environment. According to the United Nations Environment Program, buildings are responsible for more than one third of the total energy use and associated greenhouse gas emissions in society, both in developed and developing countries (United Nations Environment Programme Industry and Environment (UNEP) 2008). According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), *“Under a low-growth scenario, building-related CO_2 emissions and energy use could increase from 8.6 billion tons in 2004 to 11.4 billion tons in 2030. Under a high-growth scenario, it could increase to 15.6 billion by 2030”* (United Nations Environment Programme Industry and Environment (UNEP) 2008). The Intergovernmental Panel on Climate Change (IPCC), in its fourth assessment report based on the results of over 80 surveys worldwide, has concluded that, *“There is a global potential to reduce approximately 29% of the projected baseline emissions from residential and commercial buildings by 2020 and 31% from the projected baseline by 2030” (*United Nations Environment Programme Industry and Environment (UNEP) 2008b).

The Carbon Trust in the UK highlights the potential for energy saving by non-domestic buildings. The UK’s non-domestic building stock is about 1.8 million (Carbon Trust 2009a p. 4). Carbon emissions from the UK’s non-domestic buildings comprised of commercial offices, hotels, shops, schools, hospitals, factories and other buildings are responsible for around 18% of the total CO_2 emissions (figure 1.1) (Carbon Trust 2009a p. 4). These emissions will have to be reduced by at least 80% by 2050 (Carbon Trust 2009b). All new public sector buildings will have to be zero carbon from 2018 and private sector buildings by 2019 (HM Government-Department for Business 2010 p.5-13).

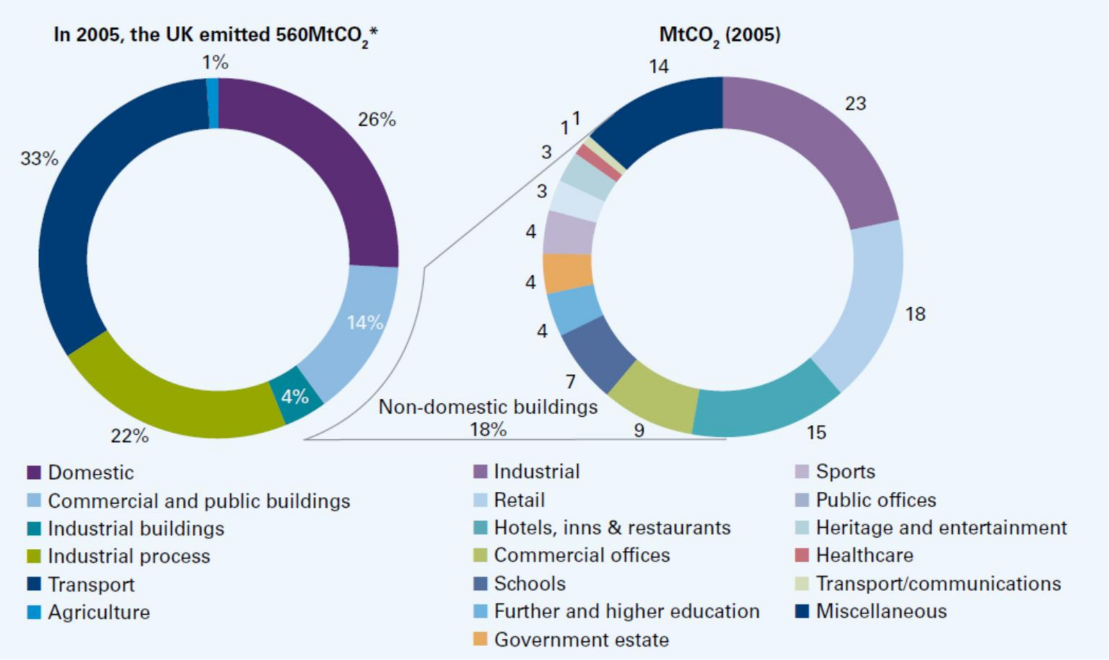

Figure 1.1: Breakdown of non-domestic buildings emissions by sector

Source: Carbon Trust (2009), p. 30

In order for the non-domestic sector to reduce its CO_2 emissions by 80% by 2050, all the available measures will have to be implemented (table 1.1), the electricity supply must be able to decarbonise carbon dioxide and all new and existing buildings will need to use less energy and low/zero carbon energy generation through better building design (figure 1.1) (Carbon Trust 2009a). According to Stafford, Gorce and Shao (2011) the initial focus of retrofitting strategies should be on the improvement of building performance. Other measures are available through micro-generation and low carbon technologies (Stafford et al. 2011). Understanding building behaviour and how people interact and use buildings and technologies is fundamental (Stafford, Gorce, & Shao 2011).

Table 1.1: Non-domestic building measures up to 2020 and beyond 2020

Up to 2020	Implement almost all cost-effective energy efficiency potential in non-domestic buildings. This will require the vast majority of buildings to undergo some level of improvement
By 2020	A 35% carbon reduction target is set through implementation of almost all of the cost-effective measures; reduction of annual emissions to 37MtCO2 from 106MtCO2 in 2005 and to 69MtCO2 in 2020 (around half of this reduction will come from expected decarbonisation of the grid). Presumably, this will create £4.5bn of net benefit to the UK (Carbon Trust 2009a p.16).
Beyond 2020	Implement currently expensive energy efficiency measures alongside low/ zero carbon energy generation, with a more integrated approach used at all stages in a building's development
Beyond 2020	Implement almost all technical carbon reduction potential, much of which is not currently cost-effective. This includes more costly energy efficiency and renewable technologies, requiring £50bn in capital investment by 2050
By 2050	a reduction from 106MtCO_2 p.a. to 21MtCO_2 or less
By 2050	Significant opportunities for reducing GHG emissions in the UK and saving energy costs, of 86MtCo2 and 13bn by 2050 through innovation.

(Carbon Trust 2009a p.2,17;Low Carbon Innovation Coordination Group 2012)

Innovation measures are split into four major technology areas (table 1.2) (Low Carbon Innovation Coordination Group 2012):

- Integrated design
- Build process
- Management and operation
- Materials and components

Table 1.2: Comparison of examples of existing commercial and illustrative innovative measures

	Existing commercial measures	Illustrative measures
Integrated design	•Simplified energy modelling used for new build • Dynamic modelling applied to selection of new build and refurbishment projects	•More advanced modelling • Measures to improve accuracy • Incorporating building performance data into design tools.
Build process	•Predominantly traditional construction • Sample details • Manual inspection	•Moves to off-site construction • Automated surveying and inspection tools • Improved process for commissioning and handover • Tools allowing correct sizing of building services
Management and operation	•Programmable thermostats • Reduce room temperature • Optimise start times • Thermostatic radiator values (TRVs) • Lighting – basic timers, turn off for 1 hour, presence detectors • Energy management monitors	• Targeted real time energy usage information • Greater use of hand-held devices for energy efficiency applets • New investment and leasing models that overcome split responsibility between designers, contractors and building occupants • Predictive controls
Materials and components	•Traditional insulation materials • Ventilation shafts and stacks • Light-pipes & sun-pipes • Triple glazing with coatings and insulating gases	•Optic fibre daylighting • ''Switchable'' glazing • Dynamic insulation and thin insulation products • Free cooling systems (e.g. groundwater)

Source: (Low Carbon Innovation Coordination Group 2012 p.6)

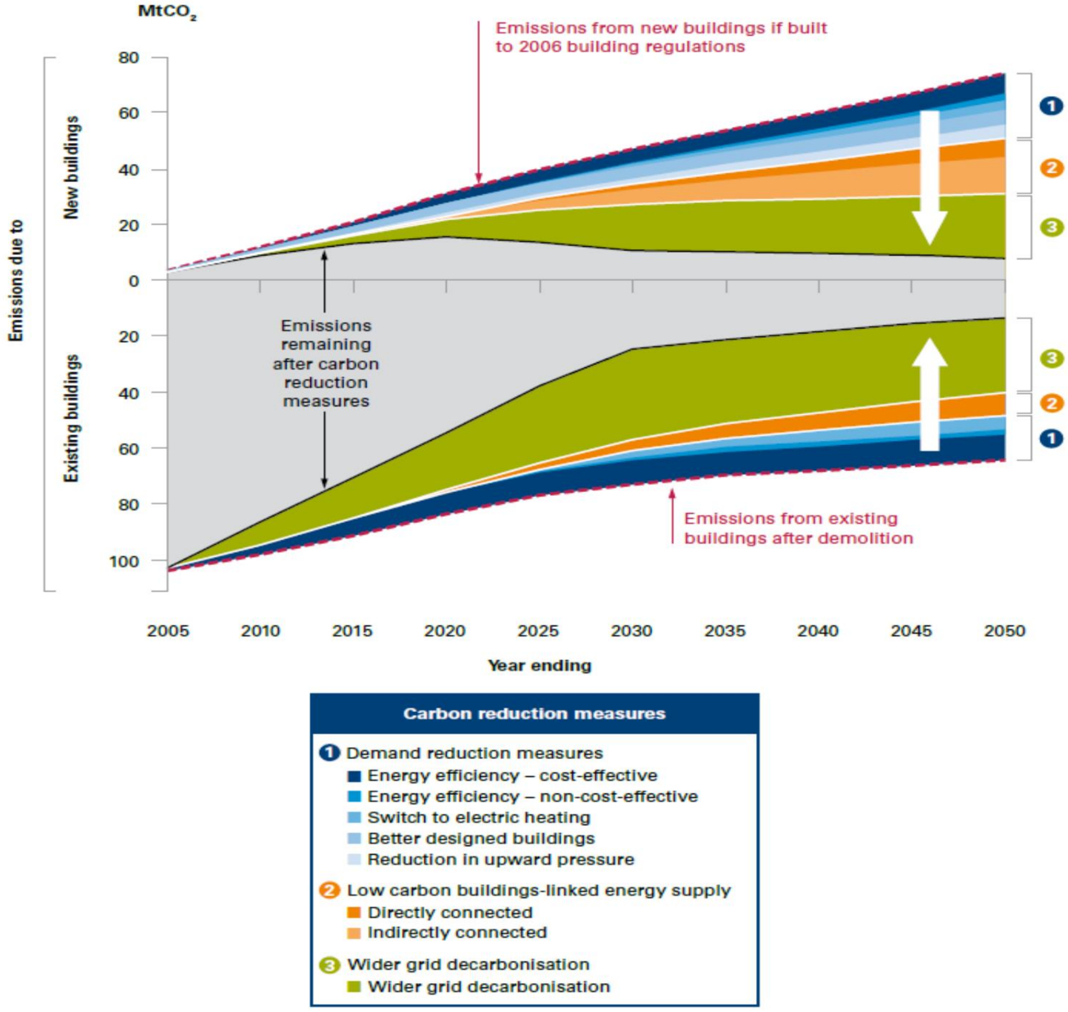

Figure 1.2: 'Wedge chart' showing how the emissions from new and existing buildings can be reduced (compared to a 'do nothing' scenario) through reduced demand from buildings, low/zero carbon energy generation linked to the building, and wider grid decarbonisation.

Source: Carbon Trust (2009), p. 8

Heating, cooling and ventilation are the largest end-use of energy in non-domestic buildings (HM Government-Department for Business 2010 p.24). Non-domestic buildings use around 300TWh of energy a year, (equivalent to the entire primary energy supply of Switzerland) to heat, ventilate and light the spaces (Figure 1.3) (Carbon Trust 2009a p.4).

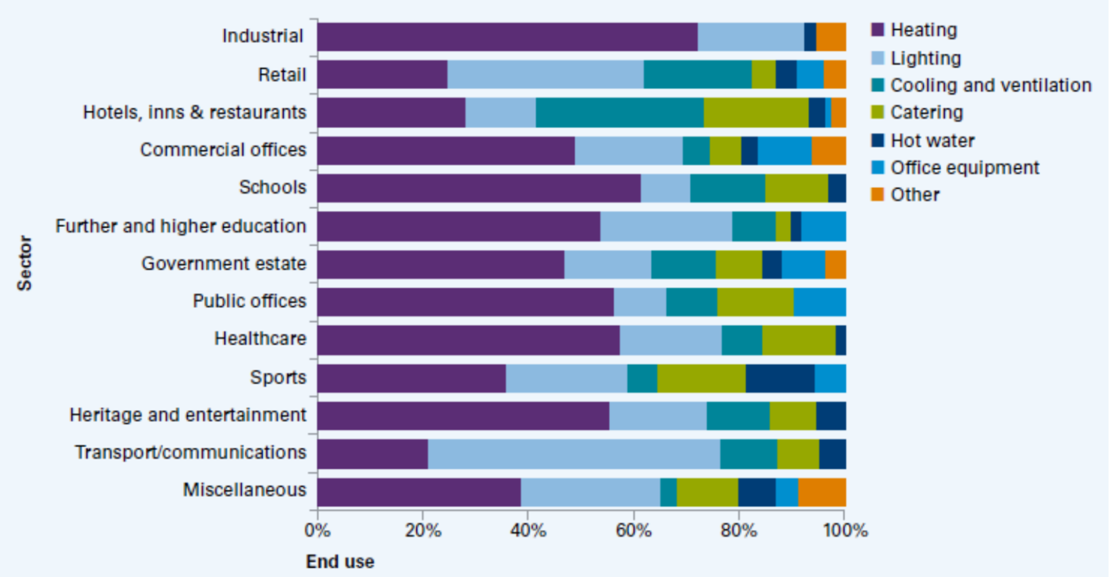

Figure 1.3: Breakdown of CO_2 emissions by end use in each sector (2005)

Source: Carbon Trust (2009), p. 31

Office buildings are the most tangible reflection of a profound change in employment patterns that has occurred over the last one hundred years (Conway 2009). Energy used by commercial and industrial buildings in the United States is responsible for about $200 billion in annual costs and creates nearly 50% of the national emissions of greenhouse gases (GHGs) that contribute to global climate change (EPA United States Environmental Protection Agency 2012). Energy represents 30% of the typical office building's costs and is a property's single largest operating expense (EPA United States Environmental Protection Agency 2012). In present-day America, northern Europe, and Japan, at least 50% of the working population is employed in office settings as compared to 5% of the population at the beginning of the 20th century (Conway 2009).

In the UK it has been assumed that all of the 3.6 million UK companies have at least one office, owned or rented (Pett and Ramsay 2003). In England three million companies occupy 288,000 offices covering in total 87.2 km^2 floor space (DTLR, 2000) (Pett & Ramsay 2003). The sector is dominated by London, which contains 47% of the property value but only 27% of the floor area (Pett & Ramsay 2003). A rare analysis of ownership by commercial property value comes from a report by Capital Economics for the Royal Institute of Chartered Surveyors (Capital Economics, 2002), and shows that owner-occupiers own 64% of commercial property. About 34% of London's commercial property is owned by non-UK sources (Pett & Ramsay 2003). Since 1973, energy use in the UK commercial sector has risen by almost 70%, and this increase is projected to continue (Pett and Ramsay 2003). Since the Prime Minister's announcement on 14 May 2010 for the greenest government ever, the government reduced its CO_2

emissions by 13.8% in 12 months (HM Government 2013). The target included 3000 central government office buildings from the Whitehall headquarters, to Jobcentre Plus Office and HM Courts. Over the 12 months to 13 May 2011, the government reduced carbon emissions from its office estate by 104,532 tons on the previous year (from a baseline of 764,141 tons CO_2) (HM Government 2013). The saving amounts to a reduction of nearly 238 million kilowatt hours in energy consumption, and will reduce the government's energy bills by £13 million in 2013 (HM Government 2013). A range of measures were implemented to reduce energy use, including (HM Government 2013):

- Facilities management improving controls over energy consumption, using building management systems to target excessive consumption, aligning operating temperatures for general office space and server rooms with best practice, shutting down buildings effectively over periods of low demand, etc
- Investing in energy efficient equipment such as voltage optimisation kit boiler upgrades, variable speed drives, software upgrades to building management systems and energy efficient lighting;
- Estate rationalisation efforts to concentrate accommodation in more energy-efficient buildings and reducing the m^2 of office space per staff member.

Figure 1.2 illustrates also that existing buildings need far more work to reduce their carbon emissions compared to new buildings. What is worth asking is whether it is better to renovate existing buildings or to build new since there is a huge amount of existing non-domestic building stock in the UK. The choice depends on several factors, on advantages and disadvantages. Davis Langston, an AECOM company explains some of the advantages in table 1.3 (Davis Langdon 2012). However it also mentions that not all the existing office building stock is suitable for refurbishment (see disadvantages in table 1.3).

Table 1.3: Advantages and disadvantages of existing office building refurbishment

New built office buildings	Refurbishment of the existing office building: advantages	Refurbishment of the existing office building: disadvantages
Contemporary design that accommodates the latest technology in infrastructure and sustainability	A better balance of risk and return	The building orientation and most importantly if the building is east-west facing
Commands higher rent	Reuse of existing assets	The quality of the external building elevation in terms of its thermal performance which involves heat losses and air-leakages
	A better balance of risk and return	Replacement of the existing glazing
	Quick delivery back to market	Introduction of secondary glazing
	Maximise the value of the existing asset	The level of service infrastructure and plant space in the base building that is available for use. Included in this is the availability of existing riser space to accommodate 21st century technology into a 19th or 20th century building

New built office buildings	Refurbishment of the existing office building: advantages	Refurbishment of the existing office building: disadvantages
	More affordable by avoiding reconstruction of large major structural elements (see also article by (Dimitrokali et al. 2011b)	Existing vertical circulation and the impact on this resulting from an increase in occupational density
	Support new way of working	The base building provides the fundamental constraints to the level and nature of the refurbishment.
	Potentially reduce the building carbon footprint	There is a risk that the base building could contain deleterious material and asbestos. This would need to be addressed as part of the refurbishment process as would the achieving of an adequate floor loading capacity. Additionally, the capacity of the existing structure may limit the potential to add area through additional floors
	BREEAM excellent increases the marketability of the existing asset	

Source: (Davis Langdon 2012)

Another constraint to the refurbishment or to the construction of new buildings is the fact that various stakeholders take part in different life cycle stages of a building from investment, development to design and construction, operation, maintenance until the end of life (figure 1.4) (Pett & Ramsay 2003). Also there is little policy activity targeting the commercial sector (Pett & Ramsay 2003) and the most current benchmark levels for energy and CO_2 emissions date back to 2003 (Action Energy 2003). The main problem begins at the design stage. Before the 2006 UK Building Standards, (Part L) clients did not often demand energy efficient buildings and architects only occasionally forced it on to the agenda (Pett & Ramsay 2003). Therefore environmental engineers designed building services to overcome the effects of inappropriate building design (Pett & Ramsay 2003).

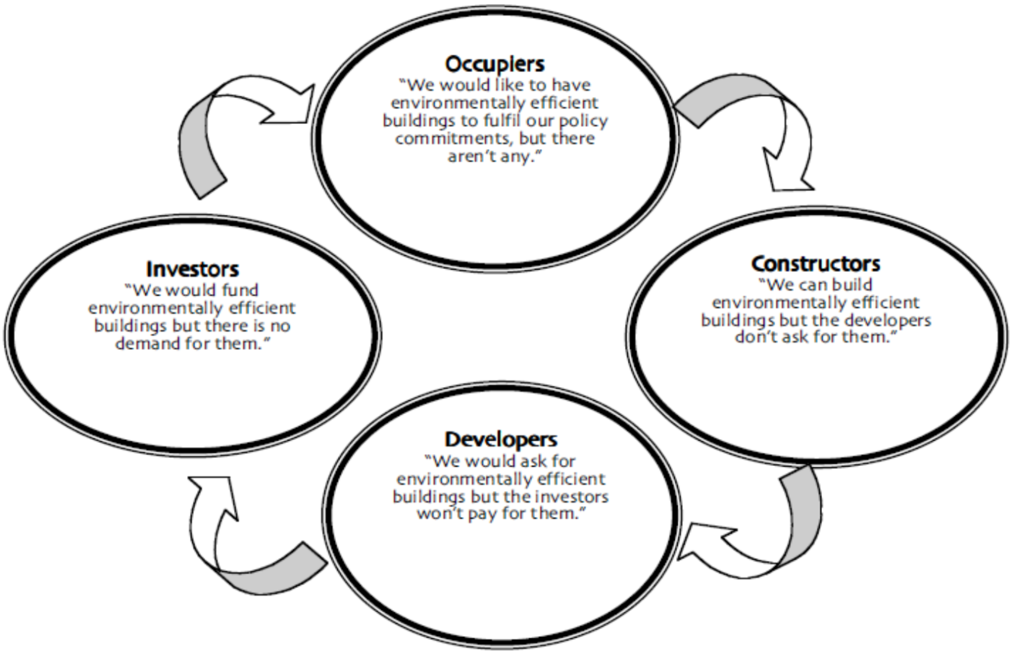

Figure 1.4: The commercial building "Vicious Circle of Blame".

Source: Pett and Ramsey (2003), p. 732

Sustainable assessment methods (SAMs) and tools play a crucial role in achieving individual building emission targets. The government has pointed out that the generally agreed way of assessing environmental impacts is to *''look at the whole life cycle of the building (construction, operation and end of life) and seek to optimise that by adjusting the design and product mix, rather than trying to optimise every individual product and then see how the building works'' (HM Government-Department for Business 2010 p.34).*

Currently in the UK, the most commonly used SAMs for non-domestic buildings are (BREEAM Research Establishment Limited), EPC (Environmental Performance Certificate), DEC (Display Energy Certificate), SBEM (Simplified Building Energy Model) and Code for Sustainable Homes, also considered in non-domestic buildings.

In order for the Government Intervention Strategy to better communicate the target emissions trajectory between different stakeholders, it has been deploying Display Energy Certificates (DECs) and Energy Performance Certificates (EPCs) to all buildings (Carbon Trust 2009a p.2). DECs and EPCs further assist in:

- Cutting emissions through better end user behaviours measured by DEC rating.
- Improving the quality of the buildings (creating better buildings) by EPC rating with the impacts of improvements on actual emissions being seen in the DEC rating.
- Improving benchmarks.

DECs record the actual CO_2 emissions from a building over the course of a year, and benchmarks them against buildings of similar use (Carbon Trust 2009a p.2). An Energy Performance Certificate (EPC), or asset rating, models the theoretical, as designed, energy efficiency of a particular building, based on the performance potential of the building itself (the fabric) and its services (such as heating, ventilation and lighting), compared to a benchmark (Carbon Trust 2009a p.2). For example, two offices can have the same DEC but different EPC ratings because one building is inefficient but used well by its occupants and the other is efficient but used badly by its occupants. This is key information for understanding the difference between well-used and badly-used sustainable and conventional office buildings. By 2015 all buildings are obliged to have an EPC (figure 1.5) (Carbon Trust 2009a p.14). DECs and EPCs for old conventional buildings are not yet available so that energy performance comparisons can be made. This is a problem as most of the existing non-domestic stock is old. For instance, buildings constructed during the 1960-1970 period make up around 15% of London city offices (London Climate Change Partnership 2009). Approximately 40% of office buildings in the City of London area were built during the 1980-90s. This period of building stock also makes up approximately 15% of the West End and mid-town buildings (London Climate Change Partnership 2009). It is significant to investigate the data limitations of old office buildings and to find ways to overcome these limitations so that DECs and EPCs can be applied.

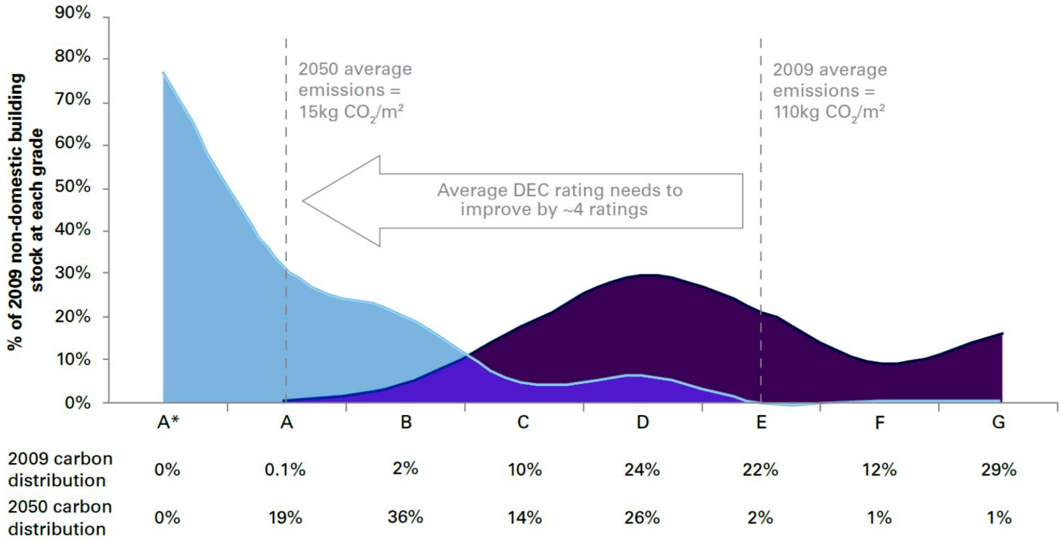

Figure 1.5: Shift in DEC distribution from 2009-2050 required to meet an 80% reduction in CO_2 emissions

Source: Carbon Trust (2009), p. 3

Although BREEAM is the most common SAM used at European Level, the word ‘sustainable’ or ‘sustainability’ is still a vague term in determining a building as sustainable, therefore BREEAM:

- sets standards for best practice and it gives assurance that the best environmental practice is incorporated in the building (BREEAM 2010).
- classifies a building as ‘sustainable’ by giving credits to a building scheme about its sustainability achievements with an outcome classification of ‘very good’, ‘excellent’ or ‘outstanding’ practice (BREEAM 2010).
- enables market recognition for low environmental impact buildings
- helps to identify a benchmark practice.
- under the BRE (Building Research Establishment)’s environmental assessment methods umbrella, life cycle assessment has been used as a foundation for assessing building construction products.

New and refurbished non-domestic buildings need to have a BREEAM certification in order to be able to withstand in the competitive environmental market (BREEAM 2010) However there are some key constraints attached to the effectiveness of BREEAM in ensuring operational and long run sustainable performance. Current BREEAM certified office buildings are assessed during the construction stage and the in-use stage (BREEAM 2013). However, BREEAM certified office buildings assessed before 2009 were assessed only during the design and the pre-construction stage. This raises concerns about whether these buildings built before 2009 actually perform as they were designed to perform (GSA 2012;Low Carbon Innovation Coordination Group

2012). A ‘performance gap’ appears between predicted and real energy performance, both in new build and in retrofit (Stafford, Gorce, & Shao 2011). This means that the in-use phase will have to be evaluated and that perhaps more energy-efficient technologies will have to be installed to replace existing technology. This is what happened with the new BREEAM very good Palestra office building in London (Lazell 2008) and with the refurbished BREEAM very good 100 Hagley Road office building in Birmingham (Calthope Estates 2013) (the cases are further explained in chapters 2 and 4). Therefore the building design and the building use are two highly important assessment criteria for low carbon buildings.

Another significant environmental concern that is raised is the fact that the high demand of new energy efficient technology to be installed in new, existing and refurbished buildings increases day after day, without considering the embodied emissions[1] caused by producing these technologies (Buro Happold 2013; Gielen et al. 2008; Institution of Mechanical Engineers 2013; United States Environmental Protection Agency 2009). Reducing emissions that contribute to one environmental problem often leads to higher emissions contributing to another environmental problem (Hermann et al. 2007). New EU Construction Product Regulations (CPR), require a large number of building products to be assessed with Life Cycle Assessment in order to be sold in the EU (Buro Happold 2013).

Over the last 20 years enormous steps have been taken in research on the environmental impacts of buildings. However there is a gap on actual figures or benchmarks against which the performance of buildings can be rendered as 'sustainable' through improved design (Roaf et al. 2013). There is a need of global new sustainability indicators to evaluate the general environmental performances of buildings (Pulselli et al. 2007). Future research must concentrate on improving understanding about the real, in-situ performance and performance distribution of retrofit measures together with the installation process and their impact on the environment (Stafford, Gorce, & Shao 2011).

Summing up from the above, in the UK, the existing SAMs focus mainly on energy performance evaluation and on assessing the environmental impacts of building construction materials without considering the environmental impacts resulting from low/zero carbon technologies installed in office buildings. The focus of future SAMs should be on assessing in parallel energy and raw-material emissions of heating and cooling on office buildings (the largest end-use of energy of non-domestic buildings in

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[1] According to the definition provided by HM Government’s Department for Business, embodied emission is the emission consumed in the extraction or manufacture of the materials-products-systems (HM Government-Department for Business 2010 p.21).

the UK) as this integration does not exist in current SAMs. This is certainly not enough to determine an office building as ‘sustainable’ although it is a good starting point for ensuring that environmental emissions do not shift from one life cycle phase to the other, increasing the overall emissions, embodied and operational, of an office building, throughout the full life cycle.

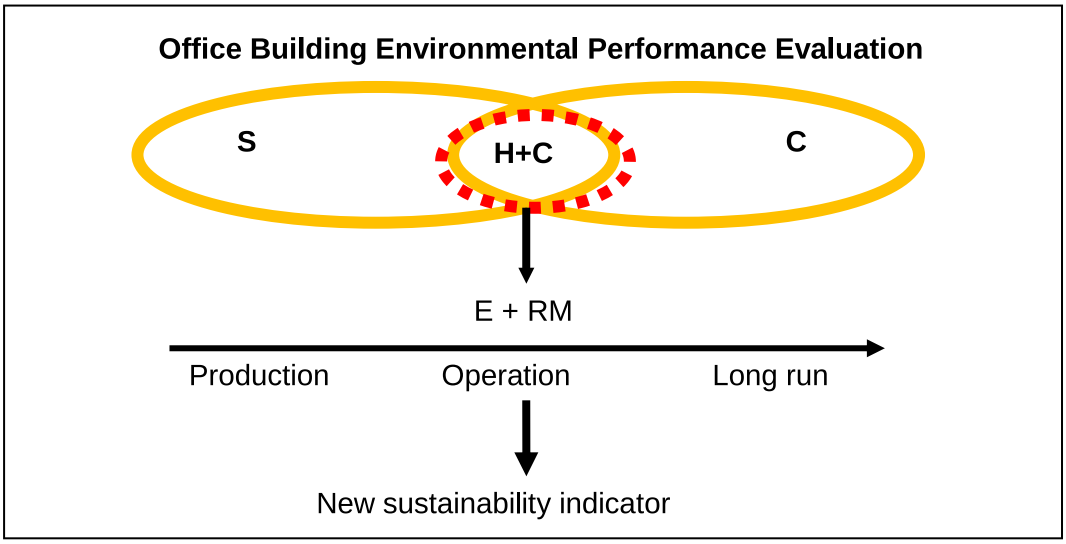


Figure1.6: Illustration of research relationships (S=sustainable office building, C=conventional office building, H=heating, C=cooling, E=energy, RM=raw-material)

1.2 Research questions

Within the background of this study, the core research questions are:

I. How effective is BREEAM certification of office buildings at indicating the perceived energy and raw-material improvements on conventional buildings?

II. How efficient is the long term environmental performance of BREEAM certified buildings?

III. What measures are required for old conventional office buildings to become BREEAM excellent or outstanding buildings in the future?

IV. Is there a performance gap between building design and real use of new or refurbished office buildings?

V. What is the influence of the heating/cooling systems design on energy efficiency and its role on raw-material environmental impacts?

VI. What are the existing barriers for doing research on the environmental performance evaluation of existing old office buildings? What methods can be used to overcome limitations?

VII. How suitable are sustainability indicators to address energy and embodied raw-material emissions of heating and cooling in office buildings?

VIII. How can a holistic approach through a new indicator evaluate the environmental performance of office buildings?

IX. How effective are current environmental performance indicators to determine whether historic and current office buildings are better than the current BREEAM office buildings?

1.3 Aims and Objectives

The aim of this study is to examine the relationship illustrated in figure 1.6. Specifically this study aims to investigate the long run effectiveness of current sustainable office buildings and the suitability of existing environmental performance indicators to assess the long run environmental performance of office buildings. Based on this broad aim the research objectives were to:

1. Demonstrate the key differences between BREEAM office buildings and conventional office buildings (chapter 6).
2. Identify and present the current heating and cooling (h/c) technology characteristics on BREEAM office buildings and on conventional office buildings and explain what are the key limitations and benefits of the different h/c types identified (chapter 6).
3. Explain the key sustainable influential parameters and factors that play a significant role in the environmental performance of office buildings, in terms of building design, energy and raw-material consumption (chapter 6).
4. Evaluate the energy and the related building fabric performance of office buildings (chapter 7).
5. Apply LCA comparison analysis to identify and to evaluate heating and cooling systems on sustainable and on conventional office buildings (chapter 8)
6. Develop long-run hypothetical scenarios about the energy efficiency and the material efficiency of h/c both for the sustainable and the conventional office buildings (chapter 8).
7. Use sensitivity analysis to assess alternative low carbon and zero carbon technology, to support decision making (chapter 8).
8. Develop a new sustainability indicator that can be used as guidance or as a conceptual tool by different stakeholders and policy makers for potential long run improvements of their office buildings (chapter 9).
9. Provide recommendations for upgrading existing sustainable BREEAM office buildings and for transforming old conventional office buildings to

higher BREEAM levels from the current new or refurbished BREEAM office buildings (chapter 9).

10. Explain what the data limitations are and further, explain ways to overcome them and to validate them (chapters 4, 9).

1.4. Contribution to knowledge

The key contribution to knowledge of this study is the examination of the relationship between heating and cooling systems energy and raw-material environmental impact indicators, between sustainable and conventional office buildings, considering their long term consequences, which can be applied under the development of a new sustainability indicator upon which a selection of environmental influential parameters and factors can be considered and further examined. Its integration on the existing SAM could play a fundamental role for ensuring a balanced reduction of environmental impacts caused by the examination of different environmental indicators in the long run.

1.5 Thesis structure

This PhD thesis consists of 9 chapters presented in a flow chart in figure 1.7. **Chapter 1** explains the research problem and presents the key research questions, the aims and the objectives, followed by a section on the key contribution to knowledge and the thesis structure. **Chapter 2** presents the literature review to shape the problem, explaining the key research gaps that need further exploration and those upon which this thesis has focused. **Chapter 3** provides a clear definition of the goal and scope of this study prior to research design. **Chapter 4** is on the research design presenting the rationale behind selecting the case study buildings and the key methods and research models used to collect and analyse data. **Chapter 5** presents the key characteristics of the case study buildings in terms of building structure and design and and heating and cooling systems. **Chapter 6** is on energy and building fabric performance evaluation, presenting the outcomes of post-occupancy evaluation methods used. **Chapter 7** looks at Life Cycle assessment on heating and cooling systems, using a comparison approach and developing long run hypothetical scenarios. It also presents the sensitivity analysis of LCA on the scenario of alternative low/zero carbon technology upgrades and the uncertainly LCA evaluation of the results. **Chapter 8** is the key contribution to knowledge showing how the new sustainability indicator has been developed, suggesting also ways for its integration into the current SAMs. Finally **chapter 9** concludes with key outcomes of the research, closing with suggestions for further research after the PhD.

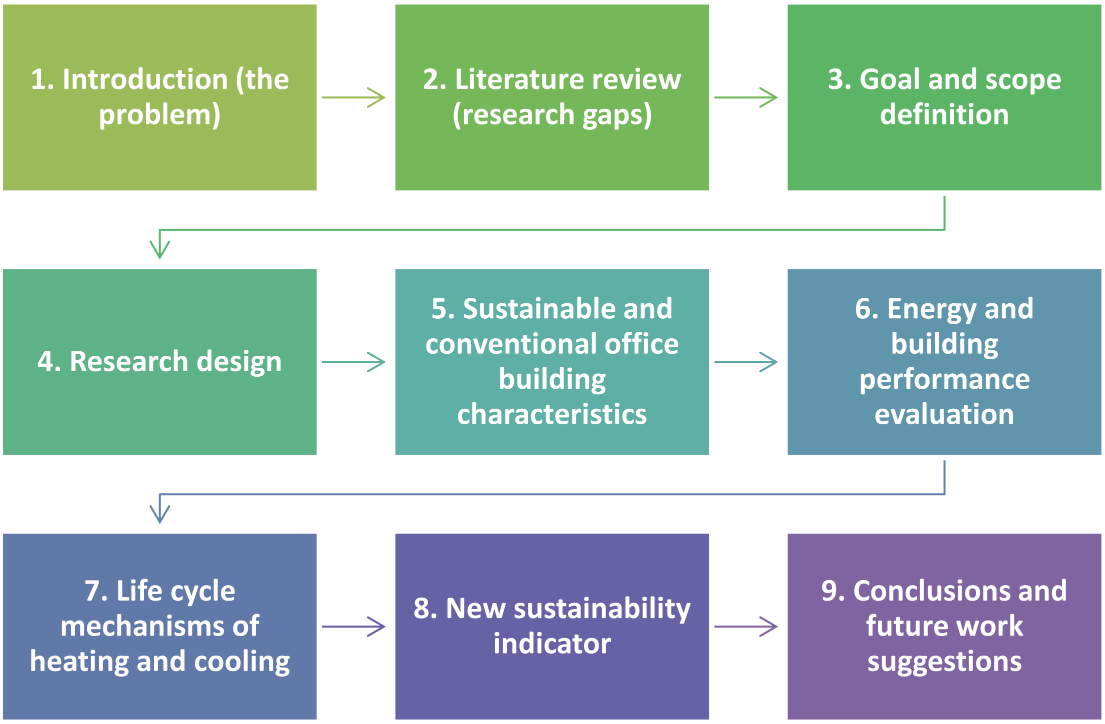


Figure 1.7: Flow chart of the thesis chapters

1.6 Summary

This chapter introduces the foundation and motivation (research problem) for this PhD research, as well as the aim and objectives of the research. In addition, the structure of the thesis is outlined. In the next chapter, the discussion of the broader research gap will be provided in more detail.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to present the literature review context of the research problem mentioned in chapter 1. This chapter provides further context to the key research gaps, unfolding key sustainable criteria upon which the research design has been developed and the case study buildings have been selected. Figure 2.1 below shows the key literature themes reviewed which are on office buildings, on heating and cooling systems, on energy and raw-material emissions, followed by a review of existing SAM's focus. The chapter ends justifying the selection of the key performance criteria with a summary section.

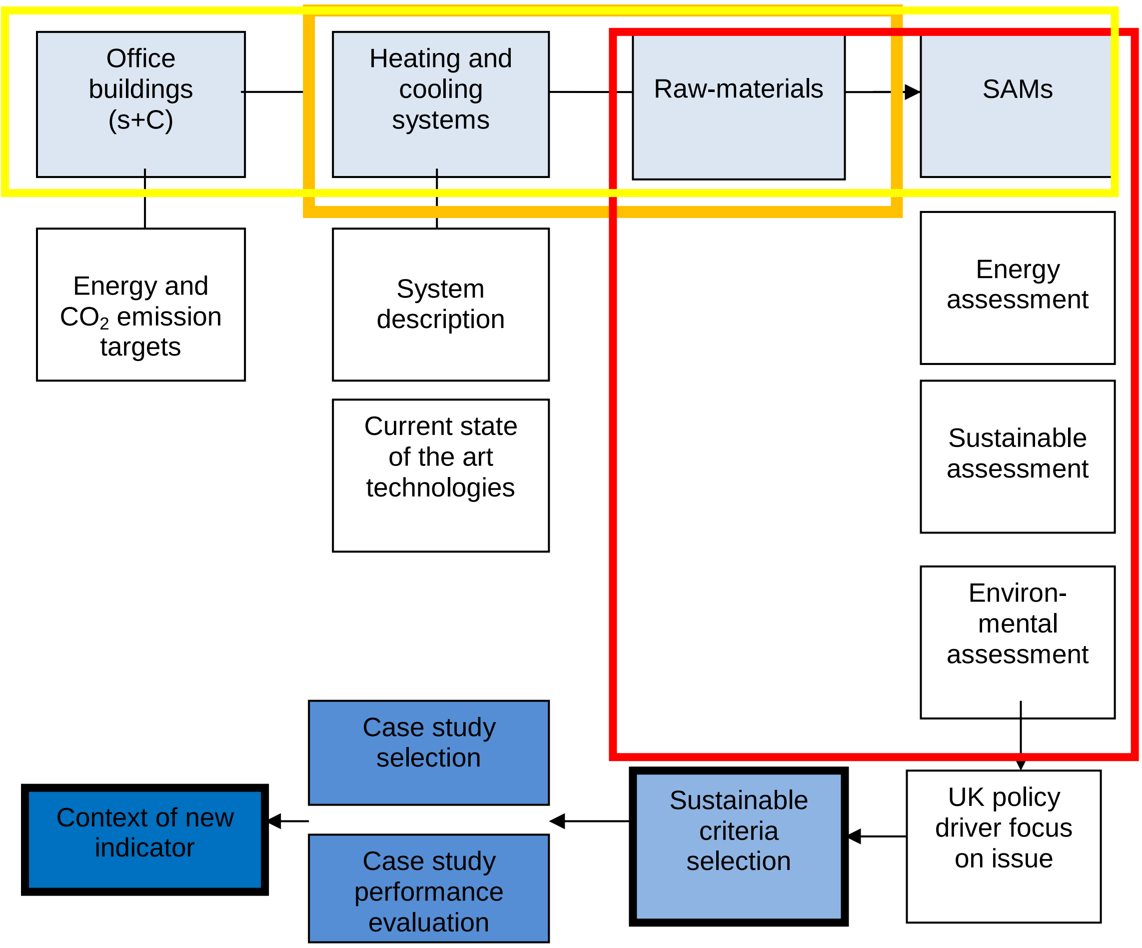


Figure 2.1: Key literature themes reviewed

After reviewing the literature on office buildings, it was found that insufficient literature was written and published on post-occupancy evaluation of buildings to get a better understanding of the effectiveness of new sustainable office buildings. Equally, insufficient literature existed explaining in a robust way the current state of the office building stock in the UK, in terms of building characteristics and energy and emission reduction targets specific to office buildings. Therefore the literature has explored broader themes around the issues discussed in chapter 1.

2.2 Office buildings: challenges for energy and emission reductions

2.2.1 Definition of office buildings

According to a European Commission report on office buildings, an office building is defined as:

> *"a building which contains administrative, financial, technical and bureaucratic activities as core representative activities. The office area must make up a vast majority of the total building´s gross area dedicated to purpose providing a service to other companies or to individuals. Therefore, it could have associated other type of spaces, like meeting rooms, training classes, staff facilities, technical rooms, etc" (Raya et al. 2011 p.8).*

However, office buildings are much more complex than defined, with various sizes, multi-cultural environments with different patterns of occupancy, with mixed-ownerships and with different facilities provided including retail areas, conference areas, accommodation areas, public spaces, etc. No standardised definition was found according to the current state of the office building sector.

2.2.2 Existing office building stock in the UK

The UK office building stock is about 106 million m^2/number of buildings and 1.7 million stock per 1000 inhabitants (table 2.1) (Raya, Isasa, & Gazulla 2011). The UK office building construction indicators being studied are shown in table 2.2. London is expected to have the largest amount of city office jobs in the UK, between 2010 and 2015, an approximate 2.6% increase (Raya, Isasa, & Gazulla 2011 p.29).

Table 2.3: Stock of the UK office buildings by age, size and location (million m^2)

		Non-residential <1000m^2	Non-residential >1000m^2	Total
Moderate Cimatic Zone	1975-1990	249.5	554.1	803.6
	1991-2002	232.5	543.5	776
	Total	1339.8	3042.4	4382.2

Source: Raya et al. 2011, p.14, 15

Table 2.4: Structural indicators of the UK construction sector

Enterprises	240,401
Turnover (in millions of €)	283412.2
Gross Value-Added (GVA) (as percentage of total value-added of the economy)	5.9
Persons employed	1,430,515
Apparent productivity(1,000€) (interpreted as a measure of efficiency: the higher the value, the higher the production per person in the building sector)	75.5
Investment	8.7%

Source: Raya et al. 2011, p.22, 23

The office building sector and existing stock of office buildings in the UK is tending to increase, while the European Commission report on office buildings reports that the maximum lifespan of an office building is 100 years, after which period the building will be knocked down (Raya, Isasa, & Gazulla 2011 p.39). After 50 years the external structures of the office building will require renovation, while a periodic renovation of replaceable structural parts such as windows and toilets would happen every 25 years and other temporary structures such as internal partitions would be renovated every 10 years (Raya, Isasa, & Gazulla 2011 p.39). Obviously, all the existing office building stock over 50 years of age must be fully renovated and existing new offices will need some renovation and maintenance services in the next 25 years, depending on Building Regulations and on policy change in the next 25 to 50 years. The most significant end-use sectors for reducing UK energy consumption are shown in figure 2.2.

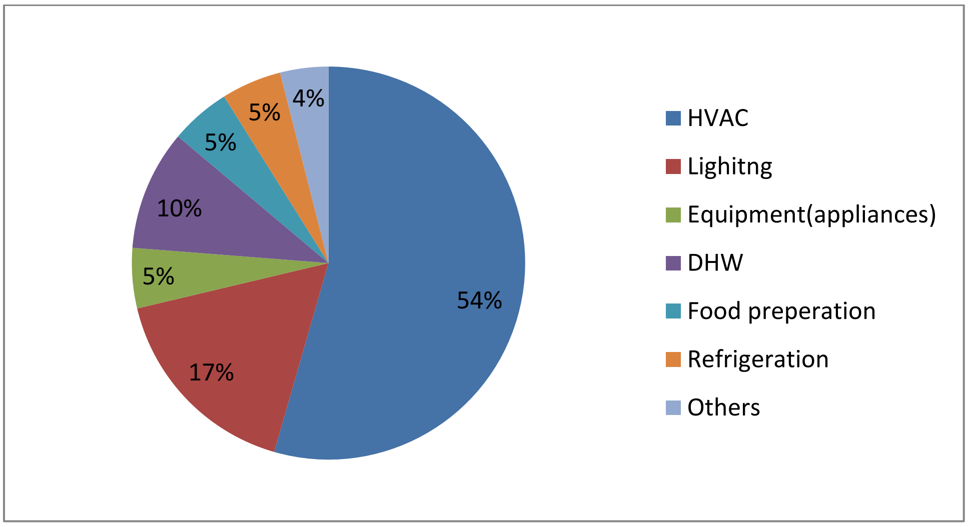


Figure 2.2: Energy end-use in office buildings

Source: (Raya, Isasa, & Gazulla 2011 p.34)

2.2.3 Benchmarking of the existing-new office building stock not updated since 2003

An interesting finding from the literature was that the new office building stock was compared to benchmark levels from 2003, as there were no updates in the available guides on office building stock since 2003; The Energy Consumption Guide (ECG) 19 mentioned four different types of office buildings in the UK, presented in table 2.3.

Table 2.5: The four different benchmark types of office buildings in the UK

Types of Office Buildings	CO_2 Emissions $KgCO_2/m^2/annum$
1. Naturally ventilated with cellular offices between 100-3000 m^2. These offices are usually smaller, technologically straightforward; they use daylight with simple control systems for artificial lighting and with limited common spaces and catering areas.	56.8 typical 32.2 lowest quartile
2. Naturally ventilated with some cellular offices and conference rooms, between 500-4000 m^2. This office type is characterized by open plan, higher light levels, use of office equipment and vending machines and usually artificial lighting is switched on in wide areas.	72.9 typical 43.1 lowest quartile
3. Air-conditioned standard office type, usually built for speculative reasons, with deeper floor areas, between 2000-8000 m^2.	151.3 typical 85.0 lowest quartile
4. Prestigious air-conditioned, are built for a purpose and can be as head or regional offices, with staff restaurants, centre computer suite, extensive IT capability with a wide range of equipment, between 4,000-20,000 m^2.	226.1 typical 143.4 lowest quartile

Source: ECG 19 guide, p.7

The prestigious headquarter offices, for instance, consume up to 600 w/m^2. A good practice, where well-proven energy efficient features have been used, consumes about 400w/m^2 and a typical office type, like the naturally ventilated, consumes about 150-250w/m^2 (Dye and McEvoy 2008). Energy consumption increases rapidly in all office types, while the prestigious offices use additional energy because occupants tend to have longer working hours and more service areas such as kitchen and restaurant. Furthermore, the air-conditioned types use extra electricity to run fans, pumps and controls for their handling systems as well as for lighting, office equipment, telecommunications and lifts. Consequently, the electricity in air-conditioned offices accounts for between 80%-90% of the total energy and CO_2 (Dye & McEvoy 2008). The performance of the mechanical systems though, depends on a few factors such as orientation of the building, form of the plan, detailed design of eternal envelope and on internal heat gains generated within the building (Dye & McEvoy 2008).

In terms of costing, in the UK, fuels from gas or oil typically account for £1.80/m^2 in all office types. Based on the annual costs showing benchmarks for different office types, (ECG19), it can be seen that good practices use half or less than half energy, where most of it is spent on electricity in air-conditioned offices, which accounts for approximately 80%-90% of the total energy costs and CO_2. A comprehensive survey of energy use in UK office buildings at the beginning of 1990s by the ECG19 produced a statistical analysis based on investigation of 200 office buildings. It showed that, generally, in all office types (figure 2.3), energy use is higher in typical examples (medium to high energy consumption):

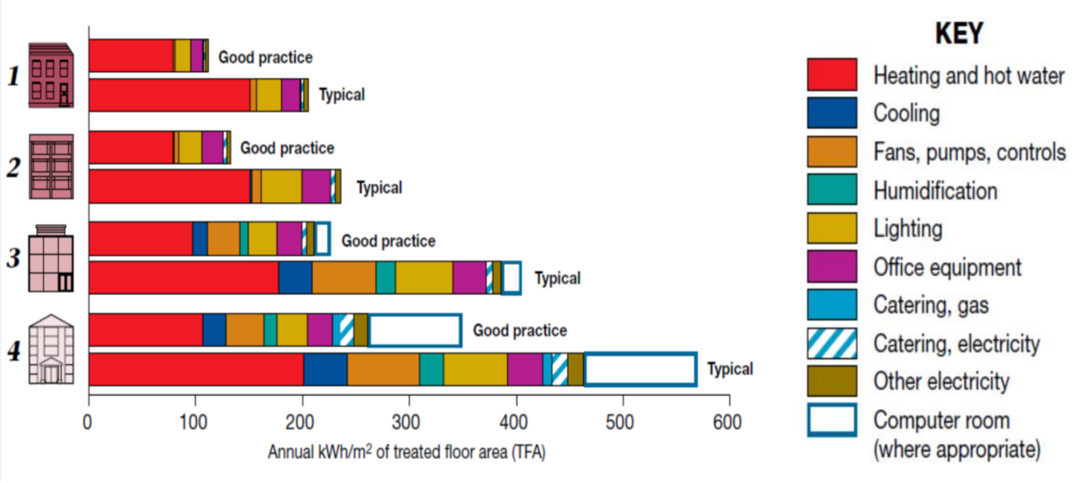


Figure 2.3: Energy use for typical and good practices in the four office types

Source: ECG 19, p. 10

Figure 2.4 shows that in the naturally ventilated cellular building types, good practices consume energy first for heating hot water and then for office equipment, lighting, fans, pumps and control systems, whereas the typical examples use energy more or less for the same services but in higher amounts. In the naturally ventilated type (second type, table 2.3), energy is used more for heating and then for lighting, office equipment, catering facilities, and less for cooling. For the air-conditioned standard types, good practices consume more energy for heating, fans, pumps, control systems, lighting, office equipment, catering, and less for humidification and computer room facilities. However, the typical examples use higher amounts of energy for heating and fans, pumps and control systems and they use about the same amounts of energy for lighting, cooling and office equipment, and less for humidification, computer facilities and catering. On the other hand, the prestigious office types consume more energy for heating followed by computer rooms, lighting and office equipment, fans, pumps and cooling, and less for catering and humidification. Figure 15 illustrates the energy costs per m^2. In the naturally ventilated cellular type, the heating costs of good practices are similar to the costs of lighting and office equipment and less is spent for fans, catering and other electricity being used. Energy costs for the typical practices are approximately the same for heating and lighting and less for office equipment, fans and catering. In general, energy costs are higher in typical buildings.

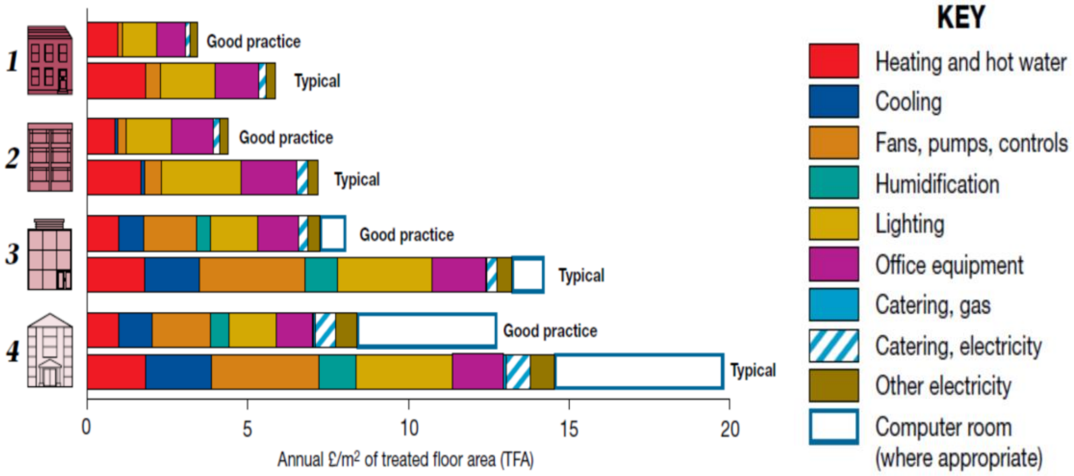


Figure 2.4: Energy costs for typical and good practices of the four office building types

Source: ECG 19, p.10

Costs for energy use in the naturally ventilated good types are higher for fans and office equipment and less for heating and other electricity. The energy costs of building services and other equipment in typical buildings is higher than in good practices and most of it is spent for fans, pumps, office equipment and heating. Moreover, in the air-conditioned standard types, costs for good types are roughly the same for fans, pumps, lighting and office equipment and less is spent for heating, cooling, computer room and humidification. In the typical office types, costs for the same services appeared to have increased. Finally, the air-conditioned prestige office types seem to be costly. Most costs in good practices are spent for computer rooms, fans, pumps and lighting and less for heating, office equipment, cooling and other electricity, whereas as shown before, the costs in typical building types are increased. Figure 2.5 presents the figures of annual carbon dioxide emissions per m^2 for office buildings. Generally, in the typical and later buildings, energy consumption is high and carbon emissions are higher than the good practices. Carbon emissions for computer rooms, heating, fans, lighting and cooling are higher than the emissions created by office equipment, humidity and catering services. Summarizing the above statistics, typical office buildings use a higher amount of energy than good practices, more is spent on energy usage and higher amounts of carbon are emitted. Larger buildings with big office areas use more building service systems and office equipment than smaller offices, which means that they use more energy for more hours and consequently this increases the costs and the carbon emissions.

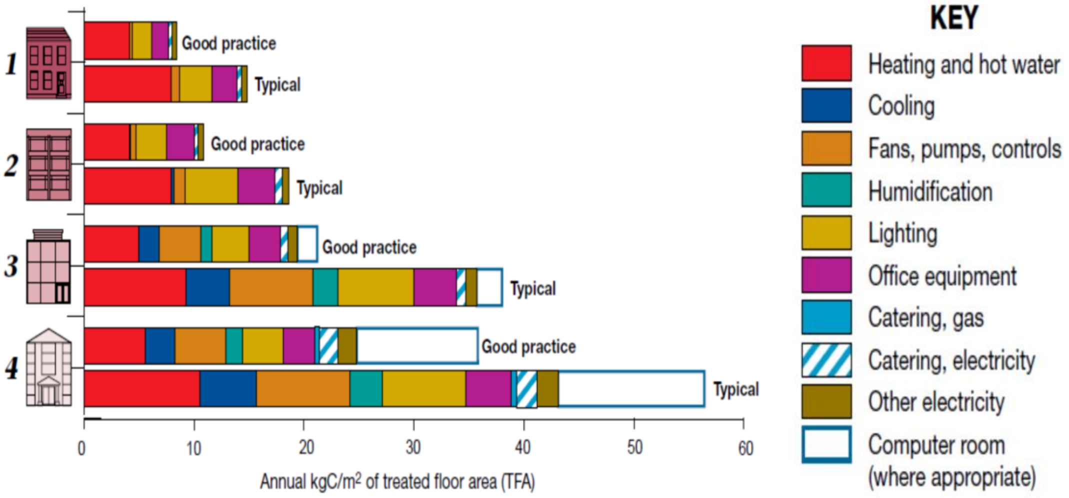


Figure 2.5: Annual C0$_2$ emissions for typical and good practices of the four office types (kgC/m^2)

Source: ECG 19, p.10

The main differences are that higher amounts of energy are consumed first by the operation of building services and then by office equipment, clearly depending on the type of office building, where costs are higher in smaller and typical buildings with natural ventilation but in larger buildings costs for office equipment and computer rooms are also increased. On the one hand, the naturally ventilated buildings generate more carbon emissions for energy needed to perform heating and lighting and then for computer rooms with office equipment, whereas the larger air-conditioned offices generate more emissions to perform office equipment than to perform building services. Evidently, in order to reduce energy consumption, particular focus should be paid firstly to the operation of office building services and then to office equipment in typical practices from the standard air-conditioned to prestigious air-conditioned types. However the report of Pett J. et al mentions that some commentators have suggested that the four different office types do not represent the current office building stock in the UK (Pett et al. 2004).

Apart from the operational energy, embodied energy is also an issue of the overall energy consumption of office buildings which has not been highly considered. According to Trealor et.al, embodied energy is the energy consumed in all activities necessary to support a process and comprises a direct and indirect component, where direct energy includes building assembly and indirect includes the energy embodied in building materials and products (Treolar et al. 2001).

Furthermore, Tim Battle, in his report on embodied energy, mentions that efficient use of materials, transport of construction products, waste recycling and prefabrication also have an impact on the environment but there have been arguments about whether the energy used in the construction of the building is related to the energy use when the building is operated. As regards conventional buildings the case could be that the operating energy is higher because of the high amount of energy being used. However recent studies have shown that embodied CO_2 can increase if basic assumptions about life span and energy efficiency of the building process are considered (Battle 1996). Several studies show that there are different factors which are important to take in mind for the use of embodied energy, like local climate, number of storeys, building heights, construction system, volume ratio, building shape and architectural style (Treolar, Fay, Llozor, & Love 2001) as well as age, layout, staffing and security levels, hours of operation and standards of maintenance and management (Jones Lang LaSalle 2007).

A study by Aye, L et.al (Aye et al. 1999) has shown that there was a correlation between embodied energy and height in low rise commercial buildings. The embodied energy was high in single storey buildings because of the poor surface area to volume ratio but when the floors started to increase and the surface area improved, the embodied energy decreased and as the storeys increased the embodied energy started to increase (Aye, Bamford, Charters, & Robinson 1999). Following this study, Treolar et.al mentioned that there was a need to evaluate the embodied energy in elemental terms. Similarly, the Environmental Assessment Method for Buildings (BREEAM), through implementing guidelines, supports the idea that greater efficiency of the building will reduce the operational energy but increase the initial cost. For instance, for a 10,000 m^2 office building with $30W/m^2$ for power, $20W/m^2$ for lighting and 20±1c design temperature for air-conditioning, the initial costs will increase by 3% but it will then reach valuable cost reductions during operations (Dye & McEvoy 2008).

2.3 Heating and Cooling Systems in Office Buildings

2.3.1 Energy and CO_2 Emissions Issue

From a study report by DECC published in March 2011, it was clear that while energy-efficiency of heating and cooling tended to improve technologically, their efficiency itself was not sufficient for an office building to remain energy-efficient and attain a high BREEAM scoring and high EPCs and DECs.

Further, the report explained that in 2010 instead of a reduction in emissions, there was an increase of 2.8% (DECC 2011c). In 2010 UK emissions covered by the Kyoto Protocol were provisionally estimated to be 582.4 Mt (Million tons) $CO_{2,}$ 2.8% higher than the $566.3MtCO_2$ in 2009 (DECC 2011c p.1). This problem occurred mainly because of switching from nuclear power and using gas and oil fuels instead: *''changes in the efficiency in electricity generation and switching from coal to less carbon intensive fuels such as gas''* (DECC 2011c p.4). The emissions were mainly related to the electricity generated by power stations and then from the electricity used by buildings (DECC 2011c p.1). It can be assumed that the office building sector can have a significant contribution to the latter, considering the existing amount of the office building stock and the slow progress being made to make these buildings energy efficient to current standards. As with the entire building sector, the office buildings must reduce their CO_2 emissions by 80% by 2040.

2.3.2 Methods of Heating-Cooling in Office Buildings

Generally commercial office buildings are heated and cooled in two different ways, passively and mechanically, explained as follows:

1. **Passive**

Passive design is highly recommended but its design must avoid overheating in warm weather and over cooling in cold weather (Prek 2004c). In order to achieve that, building elements must be designed in such a way as to optimise solar collection. For instance, sunlight in domestic buildings can be pleasant but in commercial spaces like an office building, it can cause overheating because of the occupants and the heat emanating from equipment and appliances. Also it can create glare directly through windows or as reflections from computer screens. This increases the use of artificial lighting as well as the consumption of electricity (Prek 2004c). There are different heating systems with different characteristics and solar abilities, for collecting, transmitting, absorbing, storing and distributing solar energy (Nicholls 2008). According to Richard Nicholls (2008), the availability of solar energy depends on the time of the year and the atmospheric conditions. The total amount of energy falling on a surface depends also on (Nicholls 2008):

- the number of hours of sunlight
- the solar intensity
- the surface orientation. For instance, over the summer the solar intensity is higher on horizontal surfaces.

2. Mechanical

Mechanical heating/cooling requires fuel to convert energy into heating or cooling. Its operation depends on the insulation and airtight standard of the building envelope (Prek 2004c).

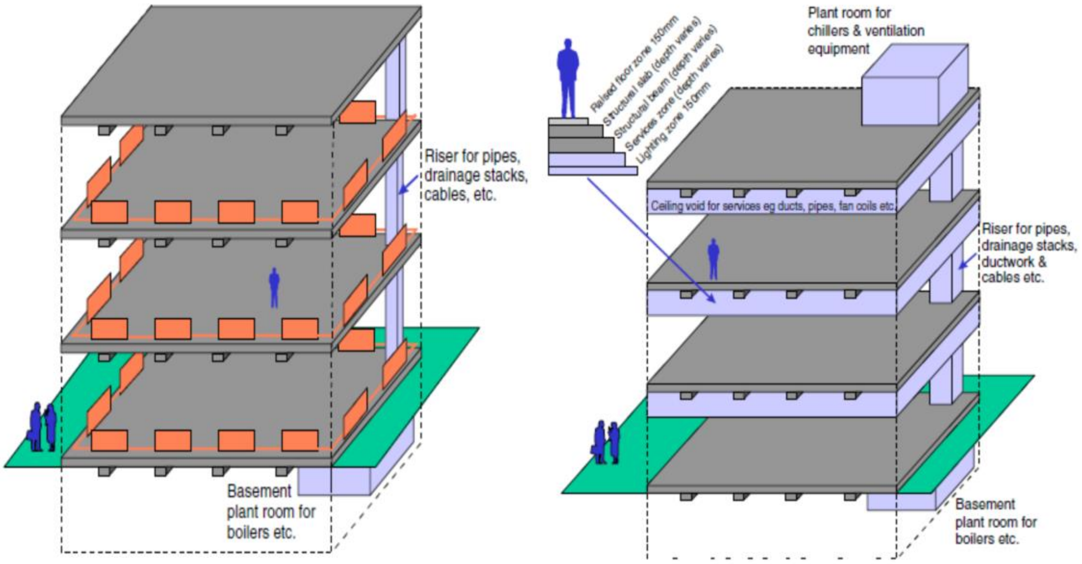


Figure 2.6: Example of a simple heating system distribution Layout and of an air-conditioned building showing the additional plant and distribution place that is required

Source:(Saulles 2002a p.2)

Building services can account for around 30% of the capital cost and 50% of the operating cost of a typical office. It is therefore important to ensure that building service systems will operate efficiently (Saulles 2002b). In large commercial spaces heating systems require a lot of space (figure 2.6), for instance the space taken up by the services in a conventional office will be in the order of 6-10% while for a high-tech building it will be around 15-30% (Saulles 2002b). This is an important consideration for realising the size and amount of equipment needed in a high-tech building as well as the raw-material used (for further information see section 2.5).

2.3.3 Heating and cooling system types

There are different heating systems with different characteristics which cannot be used in all building types. Some types provide both heating/cooling service and some provide separate heating/cooling service (tables 2.4, 2.5, 2.6).

Table 2.6: Cooling system types in office buildings

Cooling systems		
Type	**Characteristics**	**Components**
Central system	HVAC systems which use chilled water as a cooling medium. This category includes systems with air-cooled chillers as well as systems with cooling towers for heat rejection. Heating in these systems is often generated in a boiler and is distributed in hot water or steam piping	The system is broken down into three major subsystems: the air-handling unit, the chilled water plant, and the boiler plant
Packaged system	These are systems which do not used chilled water as an intermediate cooling medium. The cooling is delivered directly to the supply air in a refrigerant evaporator coil.	Packaged systems include both unitary systems such as rooftop units, and split systems. It includes cooling-only units as well as heat pumps.
Individual Room Air Conditioning		Includes window AC units, packaged terminal air-conditioners (PTAC's), packaged terminal heat pumps (PTHP's), and water-loop heat pumps (WLHP's).
Central Chiller	"Water-cooled" chillers use water to transport away the heat rejected in their condensers. The water (called "condenser water") is cooled in a cooling tower. "Air-cooled" chillers have condensers which are cooled with ambient air.	Centrally located and that produces chilled water in order to cool air. The chilled water is then distributed throughout the building by use of pipes.
District Chilled Water	Water chilled outside of a building in a central plant and piped into the building as an energy source for cooling (see CHP section 2.4.1.2)	

Source: (Westphalen and Koszalinski 2001)

Table 2.7: Heating system types in office buildings

Heating systems		
Type	**Characteristics**	**Components**
Central heating	Steam or hot water produced inside of a building in a central plant	
District heating``	Steam or hot water produced outside of a building in a central plant and piped into the building as an energy source for space heating or another end use (see CHP section 2.4.1.2).	The heating water system indicated in Figure 3-1 includes a boiler and a pump for circulating the heating water. The heating water may serve preheat coils in air-handling units, reheat coils, and local radiators
Baseboard	Baseboard heating distribution equipment relies on passive convection to distribute heated air in the space.	A type of heating distribution equipment in which either electric resistance coils or finned tubes carrying steam or hot water are mounted behind shallow panels along the bottom of a wall.
Furnace	A type of space-heating equipment with an enclosed chamber where fuel is burned or electrical resistance is used to heat air directly without steam or hot water. The heated air is then distributed throughout a building, typically by air ducts	
Boiler	Heat produced from the combustion of such fuels as natural gas, fuel oil, or coal is used to generate hot water or steam	A type of space-heating equipment consisting of a vessel or tank

Source: (Westphalen & Koszalinski 2001)

Table 2.8: Heating and cooling systems in office buildings

Heating and cooling systems		
Type	Characteristics	Components
Fan-Coil Unit	Fan-coil units have thermostatically controlled built-in fans that draw air from a room and then carry the air across finned tubes containing hot water, steam, or chilled water	A type of heating and/or cooling unit consisting of a heating or cooling coil and a fan for air circulation.
Heat pump	Draws heat into a building from outside and, during the cooling season, ejects heat from the building to the outside. Heat pumps are vapor-compression refrigeration systems whose indoor/outdoor coils are used reversibly as condensers or evaporators, depending on the need for heating or cooling	Different categories of heat pumps include Single-Package, Split-System, Packaged Terminal Heat Pumps, and Water Loop Heat Pumps

Source: (Westphalen & Koszalinski 2001)

2.3.4 Renewable systems

Renewable technology plays a crucial role in lowering GHG emissions to zero during their operation in a building development. Some renewable technologies are included in table 2.7.

Table 2.9: Renewable technologies for heating, cooling and power

Renewable technology		
Type	**Characteristics**	**Functionality**
Absorption cooling	Requires no mechanical vapour compression activated by external heat source.	Uses waste heat from CHP source used to provide cooling source for air conditioning
chp	Generates both electricity and heat and cooling using fossil or renewable fuels like biogas.	Requires predictable and constant loads for best performance
Ground source heat pumps	Takes up heat from ground and releases it at higher temperatures.	It can also be run in cooling mode.
Photovoltaic (PV)	Converts sunlight directly to electrical power	Requires careful positioning for optimum performance
Windturbine	Converts wind energy to electrical power	Requires open, non-urban locations. It can also be integrated into a building

Source: (Pennycook 2008)

Renewable technology is highly desirable but its effectiveness depends on several demanding factors in design, installation, management and maintenance. The starting point should be to reduce heating loads starting from improving the building fabric and then to upgrade existing low-energy efficient systems as shown in Nunes et al (2013) study. This is an important consideration for the development of a new indicator. Through a new indicator the environmental evaluation must show the issues on building fabric and of existing in-use energy equipment, then current and long run recommendations must be provided which could include further improvement and upgrade of ratings through renewable technology. A comparison environmental performance evaluation could help to see what has been achieved and what needs to be achieved if conventional buildings are compared with low/carbon buildings.

2.3.5 Current state-of-the-art system for heating and cooling in office buildings

Figure 1.2 (p.18) illustrates how CO_2 emissions can be reduced by existing and new non-domestic buildings showing that this can happen with low/zero carbon energy generation through low carbon buildings and wider grid decarbonisation. This can be enhanced with the use of Combined Heat and Power (CHP) technology. CHP can be seen as an alternative to the conventional power and energy distribution where power, heat and cooling are locally produced and provided to district buildings, working as a local mini power station, avoiding transmission and distribution losses and utilizing the waste heat locally, leading to higher fuel efficiency and lower carbon emissions (DECC 2011a). CHP cogeneration (heat and power or co-gen) and tri-generation (heat, cooling and power or tri-gen) have been highly recommended by DECC as an alternative to conventional technology from small scale to large scale developments.

Since the Directive of the European Parliament and of the Council of the European Union (L52) on the promotion of cogenerations (European Parliament. and European Council. 2004) came into force in 2004, an increased amount of data has been gathered on a European level to meet the scope of the Directive. The Department of Energy and Climate Change In the UK has gathered data on a number of schemes (DECC 2011a). The number of schemes increases each year (figure 2.7) and natural gas is the most common fuel type used (figure 2.8). CHP technology is presented as the current state-of-the-art for educational-office buildings in the UK. Educational buildings and mostly universities have been taking actions to mitigate CO_2 emissions by adopting measures to reduce energy consumption and increase energy efficiencies. This can be seen from the investments put forward to enhance research in sustainable development, energy and carbon accounting and the investments for retrofitting and for applying sustainable-renewable technologies in university campuses. CHP technology demand increases year after year in UK universities. Some of the examples of universities using CHP unit in UK are: University of Central Lancashire (UCLan) (figure 2.9), University of Warwick, University of Nottingham, University of Bradford and Edinburgh University (figure 2.10).

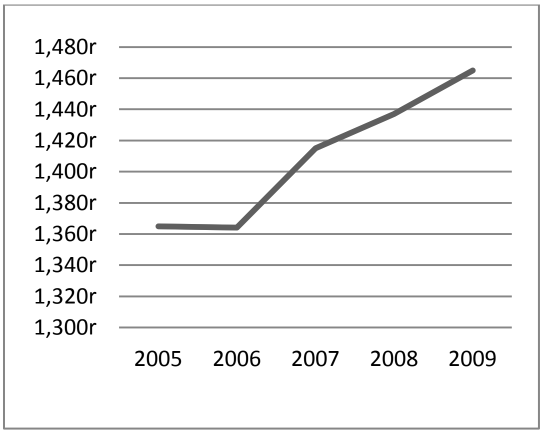


Figure 2.7: Number of CHP schemes in UK in GWh

Source: (DECC 2011b)

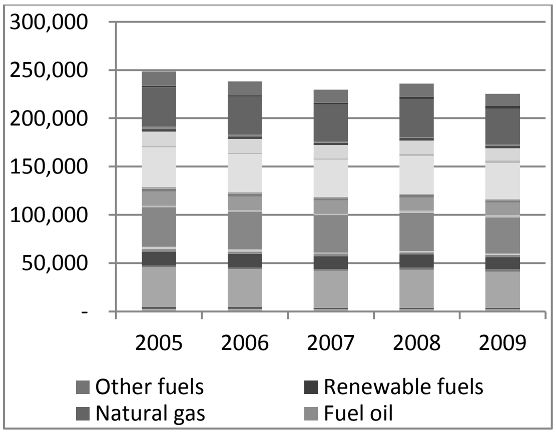


Figure 2.8: Different fuel types used in CHP for heating

Source: (DECC 2011b)

Figure 2.9: Micro-CHP in the University of Central Lancashire, plantroom

Source: Site visit

Figure 2.10: CHP tri-generation, University of Edinburgh

Source: Site visit

By looking at the executive summary that was produced to respond to the European Directive claims, the analysis section explains that in 2005 there were 1.502 CHP units with total electricity capacity of 5.440 MWe, generating 27TWh of electricity and 51 TWh of heat (AEA Energy & Environment. et al. 2007 p.II). Past projections showed that by the end of 2010 there would be 350TWh of electricity supply with a projected contribution from CHP of 36 TWh. Table 2.8 shows that according to the projections for energy and economic potential by 2015, the amount of CHPs will increase (AEA Energy & Environment., BRE., & PB Power. 2007 p.II). Thus it becomes even more important to consider the environmental impacts not only of the CHP but also of whole heating or cooling systems (AEA Energy & Environment., BRE., & PB Power. 2007 p.II).

Table 2.10: The energy of economic potentials for CHP technology (Projections)

Year	Delivered Energy (TWh)		Capacities (MW)		Energy saving (TWh)
	Heat	Electricity	Heat	Electricity	
2010	76	61	10.361	8.188	44
2015	94	81	12.529	10.567	57

Source: (AEA Energy & Environment., BRE., & PB Power. 2007 p.II)

As the number of CHP applications is expanding, several studies have been conducted to draw up the benefits, potentials and the barriers of this technology, as the EU Directive (L52) emphasised in article 6, p.54 (European Parliament. & European Council 2004). Some of these studies are based on reviews of the benefits and characteristics of CHPs (Wu and Wang 2006), other studies are more specific, examining the use of renewable fuels to replace fossil fuels (oil and natural gas) with biomass for instance and examining potentials of existing markets where CHP can be applied (Brown and Mann 2008). Other studies have investigated the environmental impacts related to this technology (Canova et al. 2008;Mancarella and Chicco 2008).

Methodologies adopted in this study include break-even analysis to develop indicators and scenario analysis to examine the possibility of emission reduction in the future from different types of CHPs (Mancarella & Chicco 2008 p.418). Other methods include models of local and global emissions using emission balance approaches and overview on characterisation of emissions (Canova, Chicco, Genon, & Mancarella 2008 p.2900). The most current state of the art approach has been to use the environmental tool life cycle assessment (LCA). A study by Pehnt (2008) investigates the environmental impacts of micro-cogeneration (small CHP units) by carrying out a detailed LCA and an analysis of local air quality impacts of micro-cogeneration systems (Pehnt 2008). Research to enhance potential developments for cogeneration technology has increased although most of these CHPs have been studied at micro-level for small scale developments.

There is a need for more LCA studies in larger scale CHPs in larger developments. It is important also to show how energy efficient CHP is according to its building context and which influential internal and external parameters play an important role in influencing its energy efficiency. This will give a better idea of the actual operational emissions caused by the low/carbon claimed CHP technology.

2.4 Raw-material consumption in the UK

The previous section on heating and cooling system types gives an idea about the size and the space that they take to cover a large volume of open plan spaces in office buildings. Therefore it can be considered that the size and the design of the building reflects the demand for heating and cooling space/size which then reflects the amount of raw materials consumed to manufacture heating and cooling systems.

Post-World War II, a new generation of energy technologies evolved; renewable, geothermal, and nuclear testing, the question of energy balance and of less environmental emissions (Horne et al. 2009). The utilisation of these technologies nowadays is more significant than before as environmental concerns have increased. The UK 80% greenhouse emission reduction by 2050 will require an enormous amount of current and emerging technologies to be installed in existing and new buildings and in urban sites, which means ongoing mass production of equipment which impacts energy and raw-material consumption.

The building sector in the UK has a range of impacts on the environment through the high consumption of resources; around 30-40% of all raw-materials consumed in the UK and other developed economies are used in buildings, leading to related energy and pollution impacts. Also, buildings in the UK use 16% of global water withdrawals and 25% of the annual global wood harvest is used for construction, whilst during the 20th century, chemically based and treated materials became widespread in the building industry, affecting the health of people, flora and fauna (Thirdwave 2008). About 72 million tons of construction demolition waste are generated by building projects. The property and construction sectors account for a very large proportion of resource use and environmental damage (The City of Edinburgh Council 2009). In the UK each year, 260 million tons of minerals are extracted (The City of Edinburgh Council 2009). The UK is an important producer of a range of minerals that are consumed in many sectors of the economy, and some 211.3 million tonnes of minerals were extracted from the UK landmass for sale in 2009. These can be broken down into four categories (figure 2.11) (Centre for Sustainable Development 2011a):

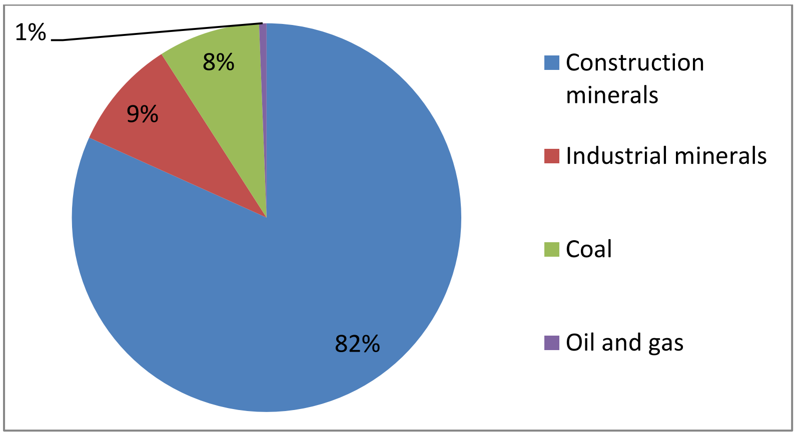


Figure 2.11: 172.9 million tons of construction minerals, 19.4 million tons of industrial minerals, 17.9 million tons of coal, 1.3 million tons of oil and gas (oil equivalent).

Source: Centre for Sustainable Development 2011a

A further 137.7 million tons, consisting mainly of oil and gas (oil equivalent), but also marine–dredged sand and gravel, were extracted from the UK Continental Shelf (Centre for sustainable Development 2011b). Britain is a major consumer of all the major metals which are essential for the manufacturing industries in steelwork construction and for mechanical appliances and equipment. It has been a world scale producer of metalliferous minerals, extracted primarily and mined in the UK. Such metals are gold, silver, iron, manganese, copper, lead, zinc, tin, tungsten, and arsenic. Now only one small gold mine exists producing 100 tons of lead, about 65% per year. Ferrous and non-ferrous metals are smelted in the UK from imported ore or partly refined, including iron, aluminium, lead and nickel. The dominant primary production of metal in the UK is of pig iron from imported iron ore and coking coal (British Geological Survey 2010 p.1).

Table 2.11: Metal production in the UK

Metals	Metal Production 2008	Metal Consumption 2008
Pig iron	10136800	-
Lead	139000	222123
Nickel	38700	-
Aluminium	325000	741643
Iron-steel	-	11852000
Copper	-	42920
Zinc	-	151500

Source: (British Geological Survey 2010 p.3,5)

The UK accounts for 45 % of Europe's annual global trade in recycled metals and exports 60% of its recovered metal production. It recovers 15 million tons of metal, distributing an estimated 5 billion to the UK's economy. Construction is the most important UK market for steel followed by engineering, consuming between 28-65% of lead and aluminium (British Geological Survey 2010 p.3). About 40% of steel and aluminium used in the UK is recycled production of secondary metals, requiring less energy than extraction, smelting and refining ore. Secondary production of metal cuts CO_2 by 99% compared to primary which means less air pollution and disposal in landfills (British Geological Survey 2010 p.6). There is a growing concern in the EU for long term security of supply of mineral raw materials, ensuring EU access to raw-materials from international markets, fostering sustainable mineral supply from and within the EU, increasing resource efficiency and recycling. The concern for limitations of critical raw-material supply is for the use of minerals over technology metals, fundamental to various new and rapidly expanding applications employed in information and communication technologies as well as in pollution control and in climate change mitigation such as in wind turbine technologies.

Raw-material emissions is a significant indicator that has to be integrated within existing sustainability and environmental assessments of buildings, considering the building design and the design of the heating and cooling systems installed in conventional and new office buildings. A comparison study on raw-material emissions between sustainable and conventional office buildings is necessary to get a better understanding of the embodied raw-material emissions, according to the building context.

2.5 Energy efficiency and emission policy drivers

At the Kyoto Summit held in 1997 several countries committed to changing the way they use and supply energy (International Energy Agency 2012; The Renewable Energy Ccentre 2013). In 2002 the European Union of 15 states ratified the Kyoto Protocol to reduce GHG by 20% by 2020, to source 20% energy from renewable sources by 2020 and to reduce the use of primary energy by 20% by 2020 (International Energy Agency 2012; The Renewable Energy Centre 2013). The UK committed to reducing GHG by 12.5% between 2008 and 2012 and to source 15% of all energy from renewable sources by 2020 (The Renewable Energy Centre 2013). In 2008 the Climate Change Act was introduced in the UK by the government, binding the UK to commit 34% reduction in GHG emissions by 2020 and 80% by 2050 (Department of Energy and Climate Change 2008). The government has introduced a number of measures for the commercial sector, with grants and incentives to help support energy efficiency and low carbon technology (The Renewable Energy Centre 2013). A list of the UK Directives implemented alongside the Kyoto Protocol to fight climate change is provided in table 2.10.

Table 2.12: List of the implemented UK Directives alongside Kyoto Protocol

1997	**Kyoto Summit**	Meeting to agree a set of actions to reduce greenhouse gas emissions and climate change.
2000	**UK Finance Act**	Is a first legislative tool to reduce energy consumption in buildings. It is chargeable for lighting, heating and power by commercial consumers.
2001	**Climate Change Levy**	The Climate Change Levy is a tax on commercial businesses which supply electricity, natural gas, petroleum and hydrocarbon gas in liquid state, coal and lignite, coke and semi-coke or coal or lignite and petroleum coke. Currently oil, road fuel gas, heat, steam, low value solid fuel and specific waste materials are not included in the levy.
2002	**Ratification of Kyoto Protocol**	The UK committed to a 12.5% reduction in emissions below 1990 levels between 2008-2012.
2002	**Renewable Obligation (RO)**	The RO was established to ensure that energy suppliers would increasingly source power from renewable sources. The 2002 obligation was 3% renewable energy supply which is steadily rising to 15.4% by 2015.
2005	**EU Emissions Trading Scheme (ETS)**	A cap is set on the amount of emissions an installation can produce. Those which fall under can trade the excess to those who exceed the limit. The ETS now covers 45% of EU emissions with over 12,000 installations involved. Sectors include: -Electricity Generation -Iron and Steel -Mineral Processing -Pulp and Paper Processing
2008	**Climate Change Act**	The UK created a legally binding target to: -Reduce greenhouse gas emissions by 34% below 1990 levels by 2020 -Reduce greenhouse gas emissions by 80% below 1990 levels by 2050
2010	**Carbon Reduction Commitment**	Now called the CRC Energy Efficiency Scheme and is for larger businesses and organisations to reduce energy

		consumption. Businesses using over 6000Mwh of electricity per year.
2010	**Energy Bill**	This bill has been created by the coalition government to support and increase energy saving measures across the UK in all areas and encourage the use and implementation of renewable energy.
2010	**Feed In Tariff (FIT)**	This is an incentive scheme to reward those who generate their own electricity through the use of low carbon technology or renewable energy. As long as the amount of power generated is less than 5MW per year the scheme offers a rate of payback to the generator for the power which is used and any excess which is exported back to the grid (Energy Saving Trust 2013).
2010-11	**Renewable Heat Incentive (RHI)**	A UK Government scheme set up to encourage uptake of renewable heat technologies in households, communities and businesses through the provision of financial incentives. The UK Government expects a significant contribution towards 2020 ambition of having 12% of heating coming from renewable sources (Energy saving trust, 2013). The types of heating covered: biomass, heat pumps, geothermal, solar thermal collectors, biomethane and biogas
2013	**Non-Domestic Scheme Early Tariff Review consultation**	The consultation sets out how the Government proposes to respond to the low up take of some technologies to ensure that renewable heat can make an effective contribution to our 2020 renewable energy targets, support the UK renewable heat industry and achieve decarbonisation of heat supply by 2050.

Source: (DECC 2013;energy saving trust 2013;Pank et al. 2002;The Renewable Energy Centre 2013)

The above Directives have played a key instrumental and influential role for energy efficient changes to non-domestic buildings, however most of these schemes are related to new buildings as there has been a slow related progress in the existing office building stock and none of the above directives aims at reducing raw-material emissions of HVAC systems used in office buildings.

2.6 UK non-domestic Building Standards

The UK building regulations (updated 2010) PART L2A (new) and L2B (existing) on the conservation of fuel and power in buildings other than dwellings, issued by the Secretary of State, provides practical guidance on ways of complying with the energy efficiency requirements and regulations (HM Government 2010a;HM Government 2010b). From part L2A, the most significant requirements for new buildings are (HM Government 2010a):

1. BER (building CO_2 emissions rate $kgCO_2/(m^2.year)$) and the TER (Target CO_2 emission rate $kgCO_2/(m^2.year)$). BER must be no greater or worse than TER.
2. Zone control must correspond to each area of the building that has different solar pressure, pattern-type of use, independent timing and temperature, respond to the requirements of the space.
3. U-values must be achieved as shown in table 2.11
4. Limit solar gains to reduce the need for air-conditioner operation, to reduce the installed capacity.
5. Insulation to be reasonably continuous.

Table 2.13: Limiting fabric parameters in $W/m^2.K$

Roof	0.25
Wall	0.35
Floor	0.25
Windows, roof windows, rooflights, curtain walling, pedestrian doors	2.2
Vehicle access and similar large doors	1.5
High-usage entrance doors	3.5
Roof ventilators	3.5
Air permeability	10.0 $m^3/h.m^2$ at 50Pa

Source: Part L2A, Building Regulations

From part L2B, the most significant requirements for existing buildings are (HM Government 2010b):

1. Ensure continuity of insulation and air-tightness.
2. New thermal elements where U-values are worse than the threshold U-values (table 2.12).
3. To reduce heating capacity with upgrade of thermal elements and replacement of windows and doors with U-values worse than 3.3 $W/m^2.K$. To reduce cooling capacity with upgrade of thermal elements and replacement of windows with

over 40% of the facade area, rooflights over 20% of the roof area and with design solar load that exceeds 25w/m^2.

Table 2.14: Upgrading retained thermal elements in W/m^2.K

	Threshold	**Improved**
Wall-cavity wall insulation	0.70	0.55
Wall-external or internal insulation	0.70	0.30
Floors	0.70	0.25
Pitched roof-insulation at ceiling level	0.35	0.16
Pitched roof-insulation at rafter level	0.35	0.18
Flat roof or roof with integral insulation	0.35	0.18

Source: Part L2A, Building Regulations

In contrast the Scottish Building Regulations (2008, number 309) on Energy Performance of Buildings (Scotland) also mentions the need for energy performance certificates:

> *‘’Where a building is to be sold or let the owner must make a copy of a valid energy performance certificate for the building available free of charge to a prospective buyer or prospective tenant (paragraph 5)”*
>
> *‘’An energy performance certificate for a building is valid for a period of 10 years from the date on which it was issued (paragraph 6)”*
>
> *‘’A methodology of calculation of the energy performance of buildings, including methods for calculating asset ratings of buildings, based on the general framework set out in the Annex to Directive 2002/91/EC of the European Parliament and of the Council (paragraph 7)’’*
>
> *‘’The owner or, where the owner is not the occupier, the occupier, of a public building must ensure that an energy performance certificate for that building is displayed within the building in a prominent place clearly visible to visiting members of the public (paragraph 9)”*

A mandatory standard for energy (section 6.0.4) (Scottish Government, Technical Handbook, 2006):

> *‘’In calculation thermal bridging may be disregarded where the difference in thermal resistance between bridging and bridged material is less than 0.1m^2 K/W’’*

Table 2.15: U-values

Roof	0.16 pitched/0.25 flat
Wall	0.30
Floor	0.25
Windows, roof windows, rooflights, curtain walling, pedestrian doors	5.7
Vehicle access and similar large doors	1.5

Source: Technical Handbook, section 6.1.4, p.428

Table 2.16: HVAC System Efficiencies

HVAC	Cooling SSEER (system seasonal energy efficiency ratio)	ScoP (seasonal co-efficient of performance)
Heating only	n/a	0.73
Air-conditioning	1.67	0.83
Mechanical Ventilation	n/a	n/a

Source: Technical Handbook, section 6.1.5, p.430

The above building regulations play a key role in decision-making on the building design and on the services to be installed in buildings in order for energy efficiency to be achieved to the appropriate standards, which therefore reflects on the intention of the existing sustainable assessment methods.

2.7 Sustainable Assessment Methods (SAMs) used in Office Buildings

2.7.1 Energy Performance Certification (EPCs)

EPCs set out the energy efficiency grade of a commercial building. They are required when a building is over 50 m^2, sold or rented. Under the EPS requirements there are two grades of office buildings, which refer to the complexity of the building being assessed (Communities and Local Government 2008):

- A simple building is one having “frequently occurring characteristics" such as simple heating systems, simple natural ventilation and small comfort cooling systems”, ie, those which are very similar to domestic premises in terms of fabric and services, such as a block of shops with flats above them. These buildings are commonly assessed by Level 3 assessors using SBEM but they can also be assessed by Level 4 assessors using SBEM or even a Level 5 assessor using DSM (Communities and Local Government 2008).
- A complex building has both fabric and services installations that are not found in domestic buildings. The asset rating is best measured using dynamic

simulation. These buildings are assessed by Level 4 or 5 assessors (Communities and Local Government 2008).

EPCs are not required in buildings operated for less than two years, when the building is sold or let with vacant positions and when the building is suitable for demolition and, on reasonable grounds, that a prospective buyer or tenant intends to demolish the building (on evidence of an application for planning permission) (Communities and Local Government 2008). The EPCs include information on energy efficiency rating, on the environmental impacts CO_2 rating, on estimated energy and CO_2 and fuel costs, and a summary of energy performance related features and recommended measures to improve building energy performance (Department for Communities and Local Government 2013). The EPC also shows current and potential rating. This is important information for comparing the energy performance of buildings; however it would be better if for a refurbished building, previous current and potential ratings were shown. This could help in getting a better understanding on the improvements made. Also, in the case that recommendations are not implemented for potential rating upgrade, the certificate could explain the long run consequences of not doing that. This is important information for developing a new indicator.

2.7.2 Display energy certificates (DECs)

DECs are required in buildings where public authorities and institutions provide public spaces for a building that is occupied by more than 1000 m^2. DECs are displayed at all times and they provide information on the actual energy used by the buildings as opposed to an EPC which conveys asset rating showing the intrinsic performance of the buildings. If a building has an EPC the asset rating is provided on the DEC (Communities and Local Government 2008). Using the analysis of the 45,000 DEC records lodged in the Central Register database by mid-February 2010 (figure 2.12), the distribution of A to G grades for the 17 of the 29 categories of building which had significant representation in the data set. The TM 46 benchmarks were intended to be median values at the D-to-E boundary, as indeed they are for offices and schools (Bruhns et al. 2011 p.5). More DECS for the office buildings fall into D category followed by a large number in category E and C. Buildings that fall into C category are conventional existing office buildings.

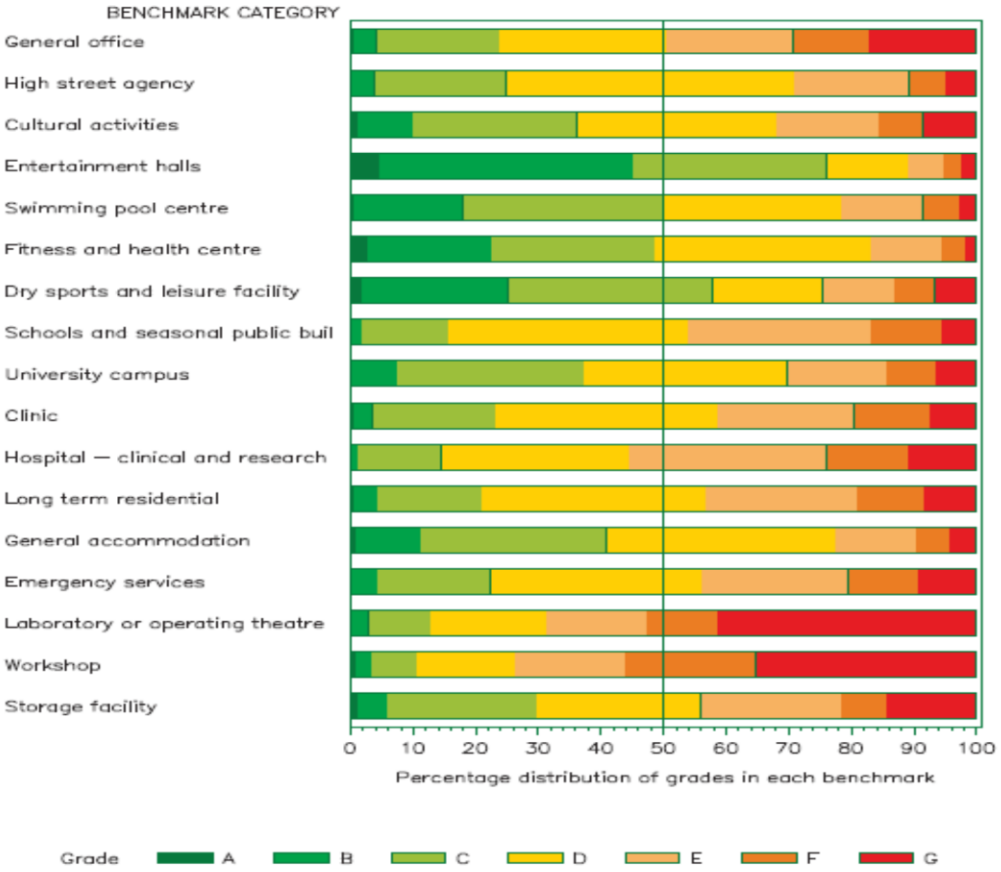


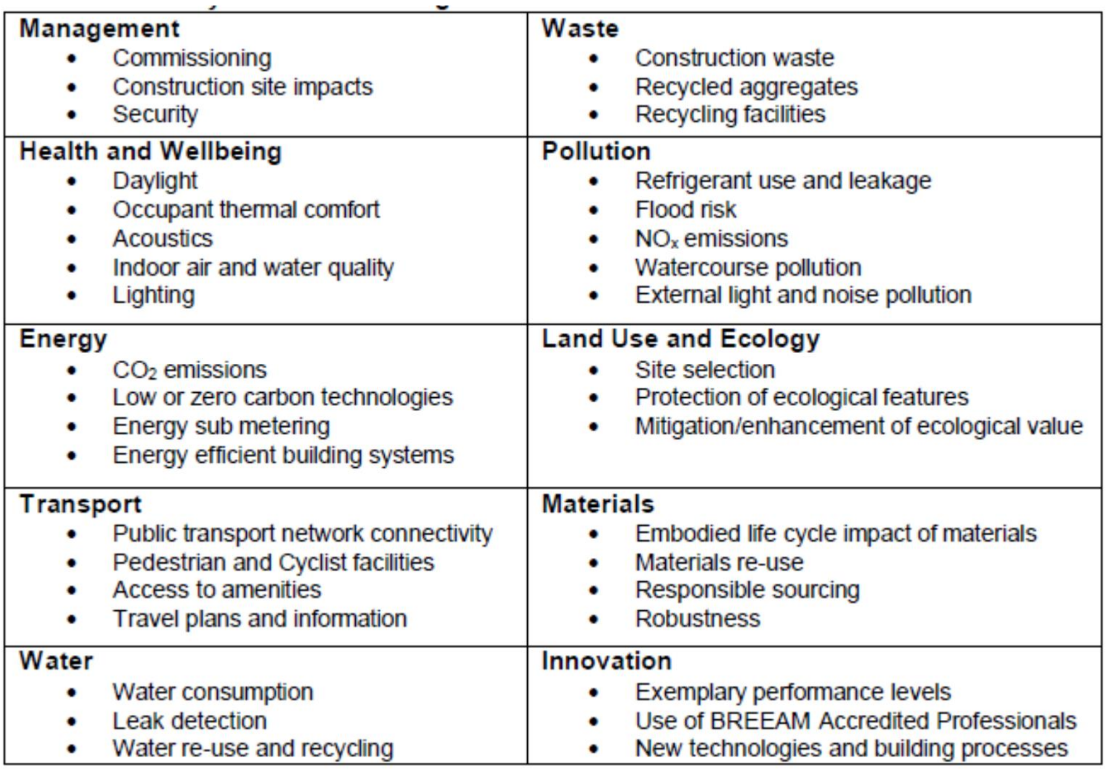
Figure 2.12: Percentage grade distribution within Benchmarks

Source: (Bruhns, Jones, Cohen, Bordass, & Davies 2011 p.5)

From these benchmarks it can be realised that there is a huge number of office buildings in the UK still performing at low energy benchmark levels and this is a challenge for the UK energy consumption agenda and for further investigation.

2.7.3 BREEAM

BREEAM is a widely-used environmental assessment method for buildings, with over 115,000 buildings certified and nearly 700,000 registered. Credits are awarded in ten categories according to performance (figure 2.13).



Management • Commissioning • Construction site impacts • Security	**Waste** • Construction waste • Recycled aggregates • Recycling facilities
Health and Wellbeing • Daylight • Occupant thermal comfort • Acoustics • Indoor air and water quality • Lighting	**Pollution** • Refrigerant use and leakage • Flood risk • NO_x emissions • Watercourse pollution • External light and noise pollution
Energy • CO_2 emissions • Low or zero carbon technologies • Energy sub metering • Energy efficient building systems	**Land Use and Ecology** • Site selection • Protection of ecological features • Mitigation/enhancement of ecological value
Transport • Public transport network connectivity • Pedestrian and Cyclist facilities • Access to amenities • Travel plans and information	**Materials** • Embodied life cycle impact of materials • Materials re-use • Responsible sourcing • Robustness
Water • Water consumption • Leak detection • Water re-use and recycling	**Innovation** • Exemplary performance levels • Use of BREEAM Accredited Professionals • New technologies and building processes

Figure 2.13: BREEAM assessment 10 categories

Source: (BREEAM 2009 p.13)

These credits are then added together to produce a single overall score on a scale of Pass, Good, Very Good, Excellent and Outstanding (BREEAM 2009).

BREEAM rating	% score
Outstanding	≥85
Excellent	≥70
Very Good	≥55
Good	≥45
Pass	≥30
Unclassified	<30

Figure 2.14: BREEAM score

Source: (BREEAM 2009)

The aims of BREEAM are to (BREEAM 2009):

- mitigate the impacts of buildings on the environment
- enable buildings to be recognised according to their environmental benefits
- provide a credible, environmental label for buildings
- stimulate demand for sustainable buildings

BREEAM for office buildings is an environmental assessment method and certification scheme that can be used at the design, construction, and refurbishment stages of a building's lifecycle. BREEAM for an office scheme can be used to assess (BREEAM 2009), general office buildings, office buildings with R&D areas, and office space within mixed use developments. It is also applied in refurbishment and fit-out. BRE Global is currently developing a new standalone scheme for assessment of non-domestic building refurbishment titled 'BREEAM Non Domestic Refurbishment 2014 (BREEAM 2009).

BREEAM by 2009 was undertaken by completing two stages(BREEAM 2009):

1. Design Stage (DS) - leading to an Interim BREEAM Certificate
2. Post-Construction Stage (PCS) – leading to a Final BREEAM Certificate

The 2009 BREEAM stages do not include a reassessment stage after the building has been operated to find out to what extent the previous BREEAM credits have been achieved. What goes wrong with the BREEAM evaluation and its certification is that buildings perform differently from what has been expected since the outcome of the assessment. Most of the BREEAM certified existing buildings have been assessed in their pre-construction stage. A review on the energy performance evaluation of the office building 'Palestra Building' in London indicates the real intentions for upgrading the initial BREEAM 'very good' to 'excellent'. In the Palestra office building (37,000m²) (figure 2.15) there has been a high investment in PV technology andin other technology advances that have been deployed initially to reduce carbon emissions and the building was certified by BREEAM as 'very good'. Later on, 14 wind turbines on the roof were installed and a £2.4m Combined Heat and Power (CHP) trigeneration plant (power, heating and cooling), including the hydrogen fuel cell, to generate energy locally, cut carbon emissions and save money on energy bills. This integration gave a BREEAM 'excellent' to the building (Building 4 Change 2011;Transport for London 2010). This raises concerns about the actual intention of BREEAM assessment; a statement for claimed sustainability popularity or a scheme that actually helps in reducing energy and CO_2 emissions of a building. Do BREEAM 'excellent' certified office buildings perform as 'excellent' or as 'very good' or even as conventional office buildings? How can office buildings withstand in the long run in a competitive market if they still operate at benchmark levels?

Figure 2.15: Palestra building, London

Source: European Commission, Energy, Manage Energy (http://www.managenergy.net/news/articles/83)

BREEAM's assessment by 2010 included one more stage of assessment, the 'in-use' stage. The aim of this stage is to (BRE 2013a; BSRIA 2013):

- view the overall performance of a portfolio of assets
- optimise an asset's performance
- make environmental improvements to asset and management systems
- determine which assets are underperforming and require refurbishment
- reduce the overall running costs of an asset
- create benchmarks for improvement
- report on Corporate Social Responsibility

The scoring of the in-use stage is slightly different from the previous 2009 scoring as it includes a star system (figure 2.16).

Assessment score (%)	Assessment rating	Star rating
<10	Unclassified	-
≥ 10 to <25	Acceptable	★
≥ 25 to <40	Pass	★★
≥ 40 to <55	Good	★★★
≥ 55 to <70	Very Good	★★★★
≥ 70 to <85	Excellent	★★★★★
≥85	Outstanding	★★★★★★

Figure 2.16: BREEAM Star rating for the In-use stage of assessment

Source: BREEAM in-use statistics

The in-use stage is divided into three parts, as shown in table 2.15, and each part includes an assessment on the categories mentioned in figure 2.13 (BRE 2013a). Also the in-use phase is assessed online where the user (the company that needs the assessment) provides data evidence and answers multiple-choice questions (BSRIA 2013). According to existing in-use assessment, the assessment takes about four hours and it is renewed every three years (BSRIA 2013). To what extent this In-Use type of assessment fulfills facility managers, owners and other stakeholders is still under question (BSRIA 2013). Energy assessment from energy metres alone is not enough to explain what is going wrong overall in the building design and construction and the way it is used. A set of different assessment methods must be further integrated to obtain realistic in-use data for the energy performance evaluation.

Table 2.17: The assessment parts of BREEAM In-Use

Part 1	**Asset performance – the inherent performance characteristics of the building based on its built form, construction and services**
Part 2	**Building management performance – the management policies, procedures and practices related to the operation of the asset; the actual consumption of key resources such as energy, water and other consumables; and environmental impacts such as carbon and waste generation**
Part 3	**Occupier management – the understanding and implementation of management policies, procedures and practices; staff engagement; and delivery of key outputs**

Source: BREEAM in-use statistics

2.7.4 Life Cycle Assessment (LCA)

LCA Definition

LCA's definition and framework was internationally standardized by ISO 14040 in 1996 and revised again in 2000. The LCA framework and principles have been revised and published in the most recent ISO standard, 14040-14044 (2006). LCA has been defined in ISO 14040 as:

> *“a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle”*.

LCA Framework

The LCA framework is based on two techniques (ISO 14040 2006; ISO 14044 2006):

1) The first technique is the modelling of a technical system which is shown as a process tree where all inflows and outflows are collected
2) The second technique is the modelling of the environmental mechanism. This mechanism examines the relevance of inflows and outflows, which means which emission, which effects and which damage.

Further, the LCA framework is divided into three spheres (ISO 14040 2006; ISO 14044 2006):

- **Technosphere:** refers to the modeling of technical systems. The value of uncertainty is not great as all measures are repeatable and verifiable.
- **Ecosphere:** refers to the modeling of environmental mechanisms as to what happens when emissions are emitted, verification is difficult and it all depends on the scope of the LCA study and the data collected
- **Valuesphere:** refers to the weighting of impact categories which is a subjective issue and is linked to social sciences.

These characteristics are important for communicating with experts from each sphere and for managing debates about uncertainties and reliabilities (Pre consultants, Introduction to LCA). The LCA methodology is divided into four methodology steps (figure 2.17):

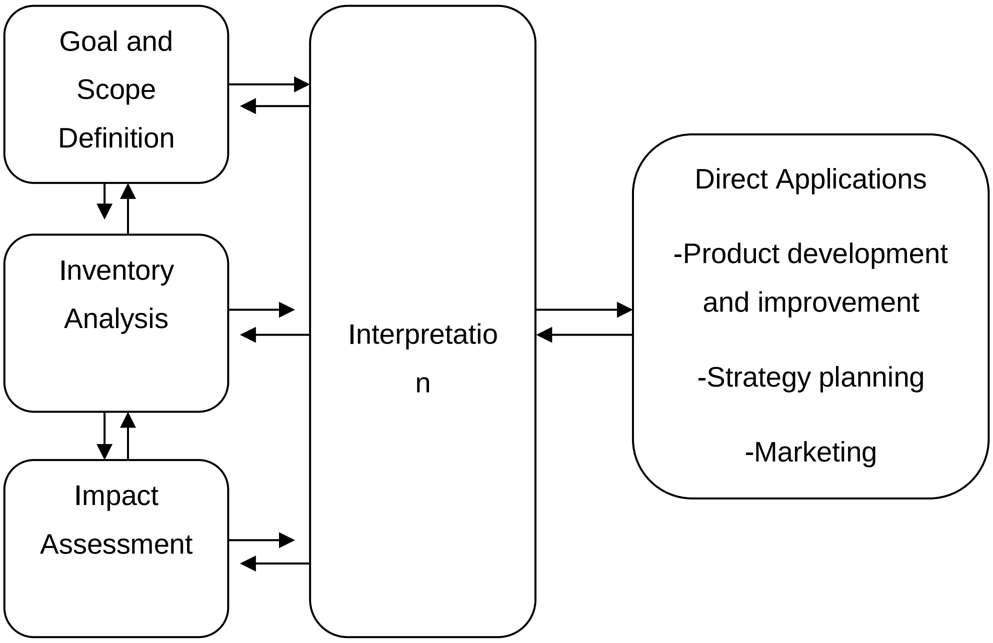


Figure 2.17: The LCA Framework

Source: ISO 14040

LCA Types

According to the ISO 14040-2006, there are four types of LCA. These are:

1. **Cradle-to-grave**

The environmental consequences of releases throughout a product's life cycle from raw material acquisition through to production, use, end-of-life treatment, recycling and final disposal

2. **Cradle-to-gate studies**

Life cycle from resource extraction (cradle) to the factory gate

3. **Cradle to cradle**

Where the end-of-life disposal step for the product is a recycling process

4. **Gate to gate**

LCA looking at only one value-added process in the entire production chain

5. **Well to wheel**

LCA used for transportation

Goal and scope definition of LCA

According to ISO standards 14040:2006, the goal of the study must include information for the intention of the study, reasons for carrying the work and to whom the results are to be communicated. The scope of the LCA must include information about the product systems to be studied, the function of the product systems, the functional unit, system boundary, allocation procedures, which impact categories will be studied and which impact assessment, what interpretation will be used, data requirements, list of limitations and assumptions, type of critical review and type of report format. Furthermore, functional unit defines the quantification of the identified function of the product, used as a reference to which inputs and outputs are related and when comparisons are made between products to show that they are made on a common basis. The systems boundary model is also an important characteristic at the scope definition. It defines which unit processes, life cycle stages and flows will be included in the study and it explains under which criteria the system boundary has been chosen for the study.

Life Cycle Inventory Analysis (LCI)

Modelling of technical systems

The inventory analysis is an iterative process which includes data collection for each unit process within the system boundary. Data has to be collected for the energy inputs, material inputs, ancillary inputs and physical inputs. It is then collected for the products, co-products and waste, for the emissions to air, discharges to water and soil if included in the study and for other environmental aspects. Once data is collected the next step is the calculation, including validation of data, relating the data to unit processes and to the reference flow of the functional unit. The calculation of energy flows must consider the fuels, electricity sources, efficiency of conversion, distribution of energy flow as well as the inputs and outputs associated with the generation and use of that energy flow. Another important procedure to be taken into account is the allocation of flows and releases. It is common for some industrial processes to have a single output but in most cases during manufacturing process more products are created which become recycled or discarded in raw materials (ISO 14040 2006)

Life Cycle Impact Assessment (LCIA)

Modelling of Environmental Mechanisms

The impact assessment phase of the LCA evaluates the potential environmental impacts using the LCI results. It involves inventory data, environmental impact categories, and category indicators. This information is divided into two elements. The ‘mandatory’ which includes a selection of categories and indicators known as characterization, the classification of the LCI and the calculation of the indicator category. The other element is the ‘optional’ which consists of the normalization of results through grouping and weighting category indicators (figure 2.18) (ISO 14040:2006).

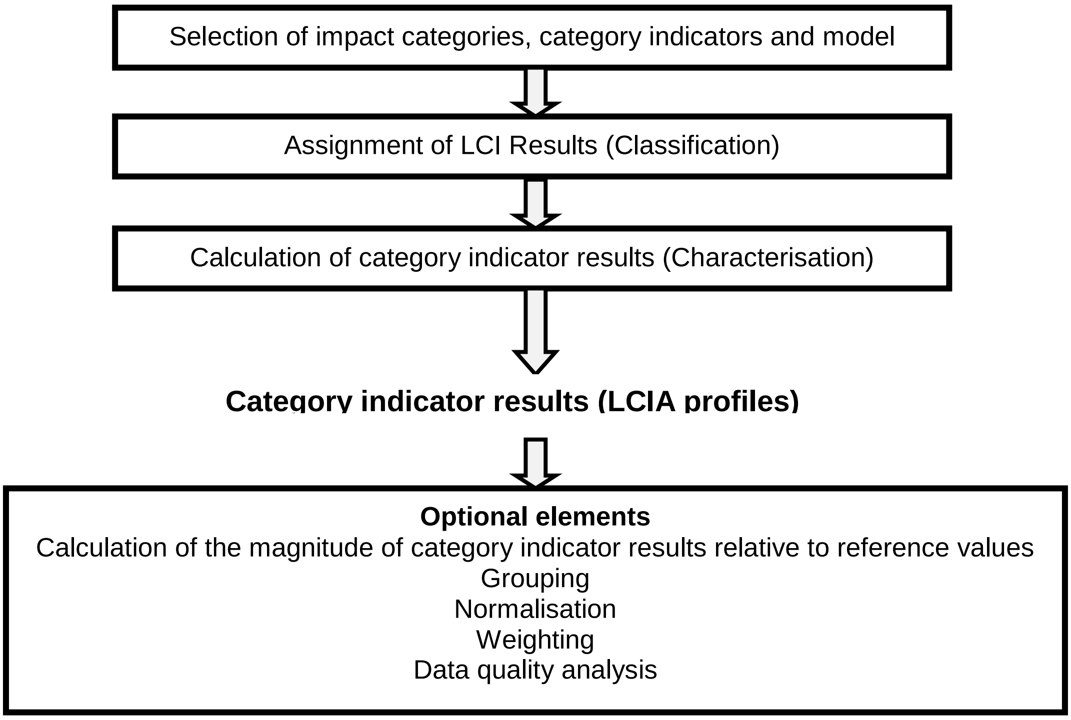


Figure 2.18: Life cycle impact assessment process

Source: ISO 14040

1. *Interpretation of results*

This stage of the LCA interprets the research findings from the undertaken LCA in an attempt to enhance understanding of the significance of the results and increase understanding of the magnitude of the issues unfolded prior to reaching conclusions and providng a recommendation (ISO 14040:2006). To support the interpretation stage of the LCA, there are also additional LCIA data quality analysis techniques. These techniques are:

- Gravity analysis is a statistical procedure to identify the data that has the greatest contribution to the indicator result to be further investigated, in priority, to ensure that sound decisions are made.
- Uncertainty analysis determines the uncertainties in data assumptions and how they affect the reliability of the results.
- Sensitivity analysis determines how changes in data and methodological choices can influence the results of the LCIA.

LCA Applications

LCA focus on office buildings

There have been few LCA studies in the office buildings sector; from the first LCA applications on office buildings (Cole and Kervan 1996), to (Junilla et al. 2006;Scheuer et al. 2003;Suzuki and Oka 1998) until today’s most recent study by (Kofoworola and Gheewala 2009; Xing et al. 2008). Most LCA studies focused on the embodied energy emissions and on the operational emissions while only few studies assess the full life cycle of office buildings. In all LCA studies on office buildings reviewed there is a consensus that the operational phase is the largest contributor to the overall environmental burden (table 2.16).

Table 2.18: Focus of the LCA studies on the life cycle phases of office buildings. The dominant life cycle impact phase is highlighted in red.

Authors	Year	Extraction	Production	Construction	Transportation	Installation	Use	Maintainance	Renovation	Disposal/ Demolition	Recyclying
Cole and Kernan	**1996**			x			x	x		x	
Suzuki and Oka	**1998**			x			x	x	x		
Thormark	**2002**						x				x
Yoannis	**2002**			x							
Koroneos at al.	**2007**			x			x		x		
Scheuer et al.	**2003**		x		x		x				
Junilla et al.	**2006**		x	x			x	x		x	
Kofoworola and Gheewala	**2008**		x	x			x	x		x	

Source: Own interpretation

One of the first life cycle studies was in 1998: an estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan by Michiya Suzuki et.al. Until then there were no quantitative analyses of environmental emissions, so the United Nations Convention on Climate Change suggested the need to develop a simplified method. The aim of Suzuki's study was to quantify the total amount of energy consumption and CO_2 emissions caused by the construction, operation, maintenance and renovation of office buildings in Japan. He estimated first the total quantity of domestic products and services used directly or indirectly during the life cycle stages of the building. For this purpose he used a set of input/output tables (Suzuki & Oka 1998).

One of the most influential LCA studies was that of Junilla, published in 2004, who examined the construction of an office of 24,000m^2. About 130 different building parts and fifty different building material groups were identified in the inventory phase. The calculations for the energy consumption for the building were done by HVAC and electrical design using the WinEtana energy simulation program. The environmental impacts that were examined were: climate change, acidification, eutrophication, summer smog and heavy metals by using the Ecl-Eco software with Ecoindicator 95 and data were taken from the Finnish LIPASTO, Eco 1999, Simapro and Boustead (Junilla 2004). Generally LCAs have focused on building materials, building components, energy, water, and waste management and most of them have concentrated on residential and less on industrial and commercial buildings, perhaps due to data limitations.

Other LCA studies and supportive methods

Kellenberger and Althaus (2009) provide a detailed analysis of life cycle assessment (LCA), the results of different building components (e.g. wooden wall, concrete roof) on different levels of simplification (from a comprehensive LCA including all materials and processes to the fully reduced component including only the main materials remaining in the component). The main objective was the determination of the relevance of materials and processes often neglected in simplified LCA of building components which aim at providing results of similar quality as comprehensive assessments with less effort. The studied simplifications were categorised in transportations of the building materials from the factory gate to the building site, some ancillary materials which are not obvious in the component, the building process itself and the associated cutting waste.

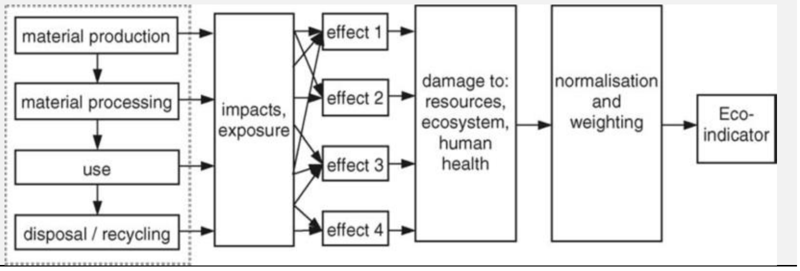
The LCIA method used was the Eco-indicator99 which models the effect of resource use and emissions on human health, ecosystem quality and resource quality. These objects have been weighted to a single score indicator. All the calculations have been made in the ‘LTE-OGIP’ assessment tool which is based on Life Cycle Impacts Assessment results from the ecoinvent database v1. 1[6,] based on Life Cycle Inventory studies for minerals, metals, wood paper and building products and processes (Kellenberger and Althaus 2009)

Oscar, O et al. (2008) presents a review of different LCA approaches and methodologies (based on international standard series ISO 14040) used to address the environmental and socioeconomic aspects of sustainability, from different practitioners, in the past seven years. The intention of this study was to explore and evaluate the different ways of using LCA in building materials and component combinations (BMCC) and of using LCA for the whole process of the construction (WPC). For this study twenty-five case studies were analysed, where 60% applied LCA to BMCC and 40% to WPC (Ortiz et al. 2009). Regarding methodology, different LCA tools have been used in the studies which have been classified in three levels. The first level is for product comparison and includes Gabi (GER), SimaPro (NL) and TEAM (Fra) LCAiT (SE). The second level was called ‘whole building design decision or decision support tools’ and these are LISA(Aus), Ecoquantum (NL), Envest (UK), ATHENA (Canada) and BEE (FIN) and the third level is called ‘whole building assessment framework or systems’ and consists of BREEAM (UK), LEED (USA) and SEDA(AUS) (Ortiz, Castells, & Sonnemann 2009).

LCA on heating and cooling systems

Prek’s study on building services focused on the consequences of designers’ choices during the design phase, using Eco-indicator 95 (Prek 2004d). Selecting and designing of heating and air-conditioning systems affects the costs and the environmental impacts (Prek 2004d). This study dealt with effects of selecting the heating system as a part of building services systems of a dwelling in a residential building (Prek 2004d). The service was defined to be heating the dwelling in a model building to a temperature level of 21˚C. The functional unit was the whole technical system, which is needed to fulfil the heating demand (table 2.17) (Prek 2004d).

Table 2.19: The aspects considered in an LCA study on heating and cooling systems in the goal and scope definition

Model building	Single family dwelling
The calculated total heat demand	11.8kW
Calculation computer program	Dendrit
System boundaries	On materials of the heating systems, to the use of energy during the production phase and to the environmental burdens caused by production. The disposal or recycling of the heating systems was not included in the examination
Method	The comparison between three different heating systems was made with Eco-indicator 95. 

Source: (Prek 2004a p.1024)

This research showed that three different concepts of heating systems with different construction materials vary the Eco-indicator value (Prek 2004d). We can see that for the radiator heating system the Eco-indicator value is far superlative than for a floor or fan coil convector heating system (Prek 2004d). Copper pipes and other copper parts contribute to the greatest environmental impact (Prek 2004d), while the radiator heating Eco-indicator (1.359 Pt-steel pipes and 4.0 Pt-copper pipes) showed a three times higher value for copper pipes than for steel pipes despite smaller dimensions; lowest values are obtained for floor heating systems (Prek 2004d).

Viral et al. (2007) applied LCA to assess the environmental impacts of three residential and cooling systems in four different regions in the U.S. The systems studies were central natural gas furnace heating and conventional central air-conditioning, natural gas powered hydronic heating air-conditioning and electric air-air heat pump. In the U.S. 76% of the homes use air-conditioning systems. The most popular heating system is the natural gas powered central warm-air furnace system and about 70% use central air-conditioning systems which work through an external conventional condenser to a heat pump (Viral, P.S et. al 2007).

The distinctiveness of the study has to do with the approach and method used to apply LCA. These heating and cooling systems have different characteristics from region to region, such as different source of energy, type of appliance, and distribution system; consequently they will vary on the environmental impacts. The objectives of the study are first to present the life cycle environmental impacts of the three systems by comparing them and secondly to assess decision makers like owners and property developers. The study has also developed and evaluated two hypothetical scenarios: the first was to replace the systems with currently available high-efficient systems of the same type and the second scenario concerned what would happen if renewable energy sources were used in the electricity mix (Viral, P.S et. al 2007). Alternative low/zero carbon technology could have a significant influence on the operational environmental impacts. This could be further expanded by looking in parallel at the consequences of low/zero carbon technology on embodied raw-material emissions. Further, the study could also be expanded by showing the energy and raw-material emission consequences in the long run, by developing hypothetical long run scenarios.

In the Viral et al. study a process based LCA approach was used by examining the extraction, manufacturing, transportation of the system components, operation and the disposal phase of the building. To model the systems, the SimaPro 5.0 software was used and the Franklin USA 98 with the ETH-ESU 96 database. Data for the system's components was taken from the manufacturer's literature. The operating energy consumption was calculated by the Home Energy Saver (Sartori and Hestnes 2007) web interface to the DOE-2 building energy simulation developed by US DOE. The inventory results were analysed by the Impact 2002$^+$ method, in 14 midpoint categories and into four damage categories (Viral, P.S et. al 2007). The study revealed that several parameters play a crucial role in the results, such as the spatial orientation, building envelope and climate. It has been estimated that the annual cooling and heating consumption will remain constant across a 35 year study period. It could be argued that what the actual temperature will be in the next few years is not really known, although a temperature increase is expected, and temperature difference in the future could influence the results in 35 years. Another alternative hypothesis scenario could be about whether energy related emissions could change if the temperatures rise in the next 25 and 50 years. As mentioned in previous studies the building envelope is playing a very important role in the performance of the building services systems. This study has also looked at the envelope insulation levels in the four different regions (Viral, P.S et. al 2007).

Another LCA study by Heikkila et al. (2004) compared the life cycle environmental impacts of two different combinations of air-conditioning in an office building in Sweden. Significant factors taken into account in this study were the source of energy and the type of conventional systems. The three heating and cooling systems under study were: a central natural gas furnace heating and conventional air-conditioning, natural gas powered hydronic heating and conventional central air-conditioning and the electric air-air heat pump for heating and cooling (Heikkila 2004b).

LCA studies on raw-materials

There are several notable LCAs on raw-materials, on metal production (Fthenakis et al. 2009), on waste and recycling (European Aluminium Association 2007), on resources (De Meester et al. 2009), on heating and cooling systems (Prek 2004a;Techato et al. 2009b), on renewable technology (Fthenakis et al. 2008), nuclear power and on other sustainable technologies such as on CHP (Combined Heat and Power) (Staffell and Ingram 2010). However, none of these studies were assessed according to a reference building. Evaluating the environmental impacts of HVAC without studying their building context could lead in misinterpretation of results. As explained in the introduction, building design and construction play a significant role in determining energy and raw-material emissions caused by the decision making on the selection of HVAC. Building design also determines the type, the size and the amount of HVAC equipments used in a building and in the market. Therefore LCAs on building products or systems should be studied within their overall building context.

LCA common limitations and barriers in its application

Buildings are complicated products to assess because(International Energy Agency. 2004):

1) The life span of a building cannot be predicted.
2) Buildings have a specific location which means local impacts will not be considered in the assessment. Neighborhood impacts (glare, micro-climate, solar access), indoor environment (indoor air quality), local ecology (sensitive areas) and local infrastructure (carrying capacity of the transportation system, water supply) cannot be addressed due to the extensive data needed for their processes (International Energy Agency. 2004).
3) Buildings and their products are ‘’heterogeneous’’ in their composition. Hence, much data is needed and the associated product manufacturing processes can vary greatly from one site to another.
4) Building life cycle includes phases such as the construction, use and demolition process which have variable behaviour in the environment.
5) Buildings are highly multi-functional which makes it difficult to make decisions on functional units.
6) The quality, consistency, and availability of data make LCA complex and time consuming. It is complicated to find comprehensive and detailed information about all the life-cycle aspects (Dimitrokali et al. 2009b;Junilla 2004).

The strengths and weaknesses of LCA applications in buildings are shown in table 2.18.

Table 2.20: A review of the strengths and weaknesses of adapting LCA in the built environment

LCA Practitioner	Aim of Study	Strengths	Weaknesses
Timothy Werner Johnson (Johnson 1996) Comparison of Environmental Impacts of Steel and Concrete as Building Materials Using the Life Cycle Assessment Method,1996	Compare the environmental impacts created by the steel and concrete construction industry. The study included major product systems and flows involved with concrete or steel construction and quantifid their impact in terms of total energy requirement, natural resources and harmful air emissions	It helps to answer which material is better from a sustainability perspective. It helps to make comparisons and answer which material is better. With the help of the impact assessment multiple outcomes can be related to environmental problems. Detail LCA can identify areas for potential improvements	The current life cycle assessment does not answer questions such as how the industry makes both building methods and associate materials better. The results are affected by assumptions and uncertainty in data
B.L.P. Peuportier Paris, (B.L.P.Peuportier 2001) Life Cycle Assessment applied to the comparative evaluation of single family houses in the French context 2001	Inventories evaluate the environmental impacts of material fabrication and other processes. The different phases in a building life cycle are: fabrication of components, construction, use of the building, renovation, renewal of components, final dismantling, treatment after use of components, recycling	Comparing different products by LCA is meaningful only if these products fulfill the same function. Rather, LCA can be used for the improvement of technical solutions (e.g. increasing the roof insulation in the solar house). The interest and potential of technologies like renewable energy systems can be assessed by this approach. It allows a link between evaluation, concerning materials and building	Still difficult to apply LCA to the selection of materials and components. Uncertainties and limits of the present state of the art of LCA. Uncertainties concern both the data (inventories) and indicators: for instance, the global warming potential (GWP) of gases other than CO_2 Indicators related to human or eco-toxicity are doubtful as the location of emissions is not considered. Indoor environmental quality is not assessed but has been taken into account in functional units. Accidental risk analysis is not concerned

LCA Practitioner	Aim of Study	Strengths	Weaknesses
Seppo Junnila, (Junilla 2004) The environmental Impact of an office building Throughout its life cycle, 2004	To quantify and compare the potential environmental impact caused by an office building during its life cycle. Determining the Lifecycle phases and elements that contribute most to the life-cycle impact	Sensitivity analysis indicated important issues to calculate the relevant significance of possible scenarios Life-cycle phases contributed similar to the environmental impact of the office buildings studied, with building operations dominating the climate change, acidification and eutrophication	Impact areas, i.e. Resource depletion was not covered or all environmental impact categories considered important, e.g. Ozone depletion, particulate matter emissions, radioactive waste, biodiversity, and indoor air quality Difficult to find comprehensive details about the life cycle of office buildings: lack of phases, lack of material inputs, lack of environmental data
Cecilia Matasci, (Matasci 2006) Life Cycle Assessment of 21 buildings: analysis of the different life phases and highlighting of the main causes of their impact on the environment, 2006	To perform LCA on a set of buildings requires assessment of which life phases and elements require particular attention during the effort of reducing the environmental impacts on the building and construction sectors	LCA allows a holistic assessment, considering the whole life cycle of a building. This avoids problems in shifting from one phase to another. Results outlined the importance of the refurbishment phase which has not been taken into consideration in previous studies	If LCA is a time consuming task, is it always necessary in the labeling of a building?

Source: LCA: The state-of-the-art approach to assess environmental impacts in buildings"(Dimitrokali et al. 2009a)

The ISO 14040 has listed the following limitations of the LCA framework:

- system boundaries
- selection of data sources and impact categories

It takes time to collect and analyse the data; it is difficult to include many indicators and all the life cycle phases as finding appropriate information is complicated. In existing applications some practitioners have avoided examining more than two indicators. This has happened because apart from the energy indicator, other indicators such as the raw-materials on building services do not exist in current EU Directives and polices. Also due to the complications listed above it is assumed that it is difficult to collect date from old buildings (explained in chapter 1). Another issue is the fact that certain indicators, such as the raw-materials on HVAC, need further development and LCA applications to show the significance. Also different indicators must be studied in parallel so that their interrelationships can be studied. This will further show the impact that different indicators have on different life cycle phases. The development of a new sustainability indicator that will gather data and evaluation on different indicators in one study is important. Other limitations are related to the assumptions and simplification made in relation to boundary setting, allocation, data sources, and also to the functional unit definition (TemaNord. and LCA-Nordic 1995). In order to be able to assess these impacts, they must be either excluded from the assessment in the system boundary, or separately inventoried and classified, or LCA must be combined with other qualitative evaluation tools (Millet and Bistagnino 2005). Table 2.19 presents the proposed approaches to overcome limitations in LCA.

Table 2.21: Proposed approaches to overcome LCA limitations

Main Limitations of LCA	Proposed Overcoming Approaches by Different Practitioners
Data collection (avoid assumptions and uncertainties) System boundaries (which impact indicators and which phases to include in the study to limit resource flows, emissions and life cycle stages) Functional Unit (comparisons of two products, life span) Socioeconomic & environmental aspects of sustainability	1. Use of a **toolbox**, which has been widely discussed and has already been formed in the European CHAINET Project. This toolbox will be constructed by several tools where each will deal with different aspects of a given problem. They will be complimentary to each other, there could over-lapping but they will provide separate results. For instance by combining LCIA with Environmental Risk Assessment (ERA), to analyze local problems, or LCA with Substance Flow Analysis (SFA) to analyze flows of substance groups such as nitrogen and chloride compounds, or LCA with Life Cycle Costing(LCC), which deals with all the costs include over the life cycle of a product. SETAC is about to develop LCC modeling structurally consistent with environmental LCA (Helias Udo de Haes and Heijungs 2004). 2. Another suggestion is the creation of a '**hybrid'** analysis which implies that different tools or approaches are connected with one another in hybrid models. These tools will be connected by data flows, but without full compatibility between the models at stake. Full compatibility would mean LCA extension and sheer luck would mean toolbox. The purpose of this analysis is to enlarge the scope/detail of a single tool analysis in a practical and yet science-based way (Helias Udo de Haes & Heijungs 2004). 3. Use '**socioeconomic whole systems'** to establish boundaries and then to create a table to show which sub-systems are appropriate for the LCA study and which have to be excluded (International Energy Agency. 2004) 4. Use a **database** where standardized information can be provided, for instance, extraction, production and manufacturing of materials, about transportation and generation of energy (United Nations Environment Programme Industry and Environment (UNEP) 1996). LCA practitioners could ask stakeholders to help characterize uncertain value judgments and preferences (Shannon Lloyd and Ries 2007).

Source: (Dimitrokali, Hartungi, & Howe 2009b)

The science behind LCA is still very new and limitations are expected to arise when adopted. The non-domestic sector is complicated due to its variability in building characteristics by region and country. However it has the benefit that a management team runs these buildings instead of approaching individual owners as in domestic buildings. This can enhance data collection and discussions even in old office buildings. LCA should not be limited in this sector. Instead more research is needed to have a broader idea of what still needs to happen so that 80% reduction in CO_2 emissions can be achieved by 2050. The more investigation in this area, the more limitations will be overcome.

2.7.5 Other available research-based quantitative energy performance evaluations

According to a study in 2012, the energy quantification method is the process of determining the amount of energy use or energy performance indicators of a given building based on relevant information collected (Wang et al. 2012). Utility bills, building audit data, end-use sub-metering system or BMS monitoring system, and computer simulations are common sources to quantify building energy uses(Wang, Yan, & Xiao 2012).. It can be divided into three categories (Wang, Yan, & Xiao 2012).:

1. Calculation-based quantification
    a. Dynamic simulations for energy calculations
    b. Steady-state methods for energy calculation (forward modeling and inverse modeling)
2. Measurment-based quantification
    a. Energy bill-based methods (energy disaggregation)
    b. Monitoring-based methods (BMS/NILM Sub metering)
3. Hybrid quantification methods
    a. Calibrated simulation
    b. Dynamic inverse models

Although simluations provide detailed output, there is often a problem in collection of data from existing builldings and it is not cost-effective (Wang, Yan, & Xiao 2012).. Measurment-based methods provide an easier access to overall performance at building level and also involve a disagreggation process to establish a split of total energy into end uses (Wang, Yan, & Xiao 2012)..Sub-monitoring can collect detailed data at a higher cost while non-intruisive load monitoring methods gather data with less cost but face many challenges in complex buildings (Wang, Yan, & Xiao 2012). Hybrid methods combine calculation-based and measurement-based methods although they use these methods in parallel rather than an ‘’integrated approach’’(Wang, Yan, & Xiao 2012). There are various quantitative energy performance methods although the systematic multi-level energy performance assessment/dignosis methods are very limited (Wang, Yan, & Xiao 2012). This is an area for further developement. Also some of these calculations can now be shown through images with advanced technologies such as thermographic survey via the use of infrared camera which is more user-friendly and easier to interpret by various stakeholders.

2.8 Energy and CO_2 research studies on office buildings

Beyond the forces of the energy and CO_2 policy drivers and the Building Regulations, different organizations take different approaches to lowering CO_2 emissions in their office buildings. These approaches are for different building development stages to assess different factors and parameters depending on what needs to be achieved and on the expertise. Different countries use different assessment approaches. The intention in looking at the current approaches is to show the variety of methods used to assess specific indicators in office buildings. There are several different ways to assess energy and CO_2 emissions but what does not exist is a user-friendly mechanism or a new indicator to combine all the information needed for energy, environmental and buildings performance evaluation.

A recent study by Nunes, Lerer and Graca (2013) has looked at the application of the Building Energy Certification and Indoor Quality System, (known as SCE) in two office buildings in Lisbon. One building is historical and the other contemporary. A cost–benefit analysis of different energy optimization scenarios was performed based on calibrated building thermal simulation models, using EnergyPlus (E+) (Nunes et al. 2013). The overall energy performance of a building was summarised by an index of primary energy consumption, the Energy Efficiency Index (EEI) (Nunes, Lerer, & Carrilho da Graça 2013). Two sets of simulations were performed for both buildings (Nunes, Lerer, & Carrilho da Gra+πa 2013):

(1) in real conditions of use and
(2) in standard conditions of use

Calibration was also used on the thermal simulation model in order to obtain predicted outputs that are similar to the equivalent measured parameters (Nunes, Lerer, & Carrilho da Graça 2013). In the present case, the focus is on simulation predicted energy consumptions versus energy bills (invoices). The calibration in the historic building showed that more focus is required on the occupancy patterns-use of the office until late hours (Nunes, Lerer, & Carrilho da Graça 2013). The simulation on the contemporary building showed very low heating requirements when compared to the consumption of natural gas recorded in the gas bills and very high lighting requirements (Nunes, Lerer, & Carrilho da Gra+πa 2013). Both buildings were certified with C (on a scale from G to A+), which is surprising considering the building construction and the building fabric. With a set of measures such as:

- improved lighting
- photovoltaic panels and
- with improvement/substitution of HVAC with better COP (Coefficient Performance)

the historic building could get a B- (with payback in 12 years) and the contemporary building an A (payback in 9 years) (Nunes, Lerer, & Carrilho da Graça 2013). However, if renewable energy is installed in the historic building, it could be upgraded to A+ (Nunes, Lerer, & Carrilho da Gra+πa 2013). Simulation modeling has helped to look at the real in-use issues in energy and electricity consumption, but what is needed is to know energy performance according to the building performance and building design, which does not come out from this study. Also, predicting energy use is fundamental and how effective are these tools in predicting overall and holistically long run energy and building performance?

Another current study in the USA by Duarte, Wymelenberg and Rieger (2013) reveals occupancy patterns in an office building through the use of Occupancy Sensor Data. This study has further focused on occupancy diversity factors for private offices and summarises the same for open offices, hallways, conference rooms, break rooms, and restrooms in order to better inform energy simulation parameters (Duarte et al. 2013). Long-term data were collected allowing results to be presented to show variations of occupancy diversity factors (Duarte, Van Den Wymelenberg, & Rieger 2013):

(1) in private offices for time of day,
(2) day of the week, holidays,
(3) and month of the year

The study shows that there is variability on a day-to-day basis on occupancy patterns, which has an impact on energy consumption (Duarte, Van Den Wymelenberg, & Rieger 2013). The simulations are important to study energy consumption prior to construction or major renovation, as with BREEAM. Data input parameters where collected according to the building design such as building size, shape, orientation, construction material, HVAC size-type, interior and exterior lighting (Duarte, Van Den Wymelenberg, & Rieger 2013). These influential parameters are occupancy related and weather related, considering occupancy hours, activities, number of staff, and number of visitors per building zone per day (Duarte, Van Den Wymelenberg, & Rieger 2013). The studies of these factors were determined as diversity factors (hourly fraction for a 24-hour/day) (Duarte, Van Den Wymelenberg, & Rieger 2013). Other types of factors are: the deterministic (studied using monitoring and the stochastic (probabilistic) (Duarte, Van Den Wymelenberg, & Rieger 2013). It can be argued that the in-use occupancy patterns cannot be specifically predicted as this depends on several other parameters such as building occupancy type per company and ownership. How the building will be actually used is perceived and estimated based on assumption, although how the buildings will actually be used daily, monthly, seasonally and per annum could be different from what has been expected. It would be better if such scenarios were divided in worst case, medium case and good case.

Depending on the background experience and the needs of the study, there are different types of assessment for the evaluation of building performance. Another recent study by Chong et.al (2013) has looked at integration of design tools with microclimate assessment tools. The study evaluated the building performance of offices in Singapore while taking into account surrounding morphology using GIS as a platform for integration with an urban climatic assessment tool (Zhun Min Adrian et al. 2013). Hourly weather data which accounts for the urban morphology (input to the model) is obtained by morphing maximum, minimum and average temperature (the output of air prediction model STEVE) into a typical 24 hour profile (Zhun Min Adrian, Nyuk Hien, Marcel, & Steve Kardinal 2013). Good agreement was found between predicted dry-bulb temperatures and measured data (Zhun Min Adrian, Nyuk Hien, Marcel, & Steve Kardinal 2013). A total of two indicators of envelope performance were used and they are (Zhun Min Adrian, Nyuk Hien, Marcel, & Steve Kardinal 2013):

(1) increase in conduction (wall, window and roof) heat gain and
(2) solar heat gain through glazing taking into account shading by surrounding buildings and morphology

The model was shown to have good agreement with building energy simulation programme IES-VE (Zhun Min Adrian, Nyuk Hien, Marcel, & Steve Kardinal 2013). This study highlights the urban morphology indicator and the impacts of its surroundings on building performance, which can have a great impact on energy consumption if the building is not designed according to its location needs (local temperatures, site and surroundings). For instance if a building is built on a sloping site and is compared with another building (of similar construction, size, occupancy characteristics) that is located on the same street but not in a sloping site then variations may be apparent by comparing the facade performance.

Previous studies mentioned on office buildings become confusing when looking at all these variations, parameters and indicators, which can have an impact on actual or else in-use of the office building energy consumption. It can be even more confusing for someone who does not have an engineering background and does not use simulations to understand clearly the interaction and the relationship between these indicators of building operation. All these are different assessment tools serving different purposes; what is needed is an assessment tool that takes into consideration in-use parameters and indicators holistically, on examples from existing office buildings. This information could then be integrated in GIS mapping so that real life benchmarks could be compared to predicted and actual office building developments.

Another recent study by Korolija et.al (2013) has used an archetypal simulation model in the development of regression models for predicting building energy consumption from heating and cooling demands on office buildings. The model represents variability in UK office building stock by parameterising built form, construction elements, and occupancy/usage, and an operational/control strategy has been developed thus enabling detailed energy performance simulation to be used for stock modelling and parametric studies (Korolija et al. 2013. The study suggests that the parameters that must be considered for influencing building energy performance are (Korolija et al. 2013):

- built forms
- fabrics (including thermal mass and insulation positioning)
- glazing percentages and characteristics
- daylight
- solar control measures
- and activity and operational related parameters (heating and cooling set points, ventilation rate, occupancy density and metabolic rate, equipment and lighting gain).

Previous studies on office buildings have developed integrated building decision support systems to assess existing office building conditions and to recommend an optimal set of sustainable renovation actions, considering trade-offs between renovation cost, improved building quality, and environmental impacts (Juan et al. 2010). This integration was based on algorythms. Other past studies have used multicriteria approaches for a greater consideration on sustainability for global scale retrofitting projects (Rey 2004). The environmental criteria were the annual use for heating, annual electricity use, and annual emissions (Rey 2004).

The environmental parameters, factor and criteria mentioned in the above studies on office buildings need to come together and studied on both existing old and recent BREEAM certified buildings using a holistic approach through a new indicator. In order to better understand the existing coverage on the environmental performance of office buildings, the following sections present further important indicators, the available assessment methods and their research gaps.

2.9 Energy and sustainability criteria and parameters unfolded for a new sustainability indicator

As mentioned in chapter 1, there is a need to bridge the gap between building design and building performance. From this chapter, several criteria and parameters have been unfolded throughout the literature. The usefulness of the parameters was to select those that could be evaluated in the environmental performance evaluation of this study and through them to develop selection criteria that helped in choosing and analysing the case study office buildings. This underpinning plays an important role for developing a new sustainability indicator for the environmental performance evaluation of office buildings.

In order to avoid confusion between indicators and criteria:

- **Indicators:** are the environmental performance indicators to be evaluated with LCA. These are energy and raw-materials
- **Parameters:** are the sustainable parameters unfolded from the literature review and some have been selected to be evaluated under the environmental performance evaluation. In addition the parameters play a key influencial role for the long run efficiency of the LCA indicators.
- **Criteria:** are the requirements for choosing the case study buildings in order to allow cross case comparisons. The selection criteria between sustainable and conventional office buildings must be as similar as possible.

A summary of the unfolded parameters and criteria is presented in table 2.20:

Table 2.22: energy and sustainability criteria for the development of a new indicator

Author/location in the thesis	Assessment type/scheme	Parameters for performance evaluation	Criteria for case study selection	Indicator
Nunes, Lerer and Graca (2013) Section 2.3.1	Building energy certification	-Occupancy	-Occupancy	Energy & raw-materials
Korolija at al. (2013) Section 2.3.1	Building energy consumption	-Building form -Building fabric -Glazing type	-Building Fabric	Energy & raw-materials
Zhun et al. (2013) Section 2.3.1	Envelope performance	-Building fabric -Increase in conduction (wall, roof, window heat gain) -solar heat gain through glazing -shading by surroundings and morphology -Temperature (maximum-minimum-average)	-Building Fabric -Location: 1.surroundings (shadows) 2.Temperature	Energy & raw-materials
Duarte, Van Den Wynelenberg and Rieger (2013) Section 2.3.1	Occupancy evaluation	-Building design -Size -Shape -Orientation -Construction-materials -HVAC type -Occupancy -Local weather	-Building design -Building Construction -Occupancy -Location -Heating/cooling system technology	Energy & raw-materials
Chong at al (2013) Section 2.3.1	Integration of design tools with microclimate assessment for building performance evaluation	-Morphology	-Location	Energy & raw-materials
Section 2.4.1 passive solar heating/cooling		-Design -Hours of-sunlight -Solar intensity	-Building design -Location: orientation	Energy & raw-materials
Section 2.4.1 mechanical solar heating/cooling		-Insulation -Air-tightness -h/c capacity in a building	-Building structure -Building fabric -Building space	Energy & raw-materials
Section 2.4.4 on CHP Mancarella and Chicco (2008)			-CHP technology	Energy & raw-materials

Author/location in the thesis	Assessment type/scheme	Parameters for performance evaluation	Criteria for case study selection	Indicator
Section 2.6.1 benchmarks	Energy and co_2 benchmarking	-Benchmarking	-Benchmarkability (building type)	Energy & raw-materials
Jones Lang (2007) Section 2.6.1		-Local climate -Number of storeys -Building height -Construction system -Volume ratio -Building shape -Architectural style -Building age -Building layout -Staff-security level -h/c operation -standard of maintenance and management	-Location -Building design -Building age -Occupancy -Management	Energy & raw-materials
BREEAM	Sustainability assessment	-Low/zero carbon technologies -Energy sub-metering -Energy efficiency building system	-Technology type -Energy control -Energy efficiency	Energy & raw-materials
Section 2.8.4 Limitations	Life cycle assessment	-Building life span -Location	-Building age -Location	Energy & raw-materials
Davis Langston from AECOM (table 3)	Refurbishment	-Building orientation -External elevation quality in terms of thermal performance -Glazing type -Plant space (infrastructure in the base building) -Occupancy density -Capacity of existing structure for additional floor area	-Building design -Location -Building fabric -Occupancy	Energy & raw-materials

Source: Own interpretation

Table 2.20 shows that several parameters and criteria have been unfolded that needed further exploration. These parameters had to be divided in sub-parameters, although that emerged throughout the empirical studies as can be seen in the discussion sections in the following chapters. To set the scene the following sections explain which parameters were chosen for this study.

2.9.1 Key selection criteria unfolded and their constraints for this study

From table 20, the selection of sustainable and conventional office buildings must meet four key requirements for comparison:

1. **Building design:** to have same or similar size, shape, floors, layout area
2. **Location:** to be located within as close a distance as possible from each other in order to consider local climate
3. **Life span:** to be structured/operated from the same period of time
4. **Occupancy:** to be occupied by the same/similar amount of occupants
5. **Structural materials:** similar style but not the same fabric
6. **HVAC:** similar system but different efficiencies

From the above, the key selection criteria most highlighted in the literature are the building design and the location. It is possible to find buildings of similar size, located in close proximity. However as office buildings are multi-functional buildings the occupancy criteria varies. Additionally, as sustainable office buildings are modern with energy efficiency measures and conventional are old existing buildings, the life span, the structural materials and the HVAC criteria vary also and they are meant to be different.

2.9.2 Key selection criteria for the study

Therefore from the above selection criteria, this study has chosen building design and location as being the primary selection criteria for the case study office buildings. The building life span is an important parameter to consider for developing future scenarios but not for primary selection criteria. The occupancy parameter is significant to consider understanding the energy consumption trends of the buildings but not as a selection criterion.

2.9.3 Relationship between selection criteria and selected parameters for the study

The building design and the location of the sustainable/conventional office building can play a significant role in influencing decision making and potential changes to the HVAC type, including their size and raw-materials used (see figure 2.19)

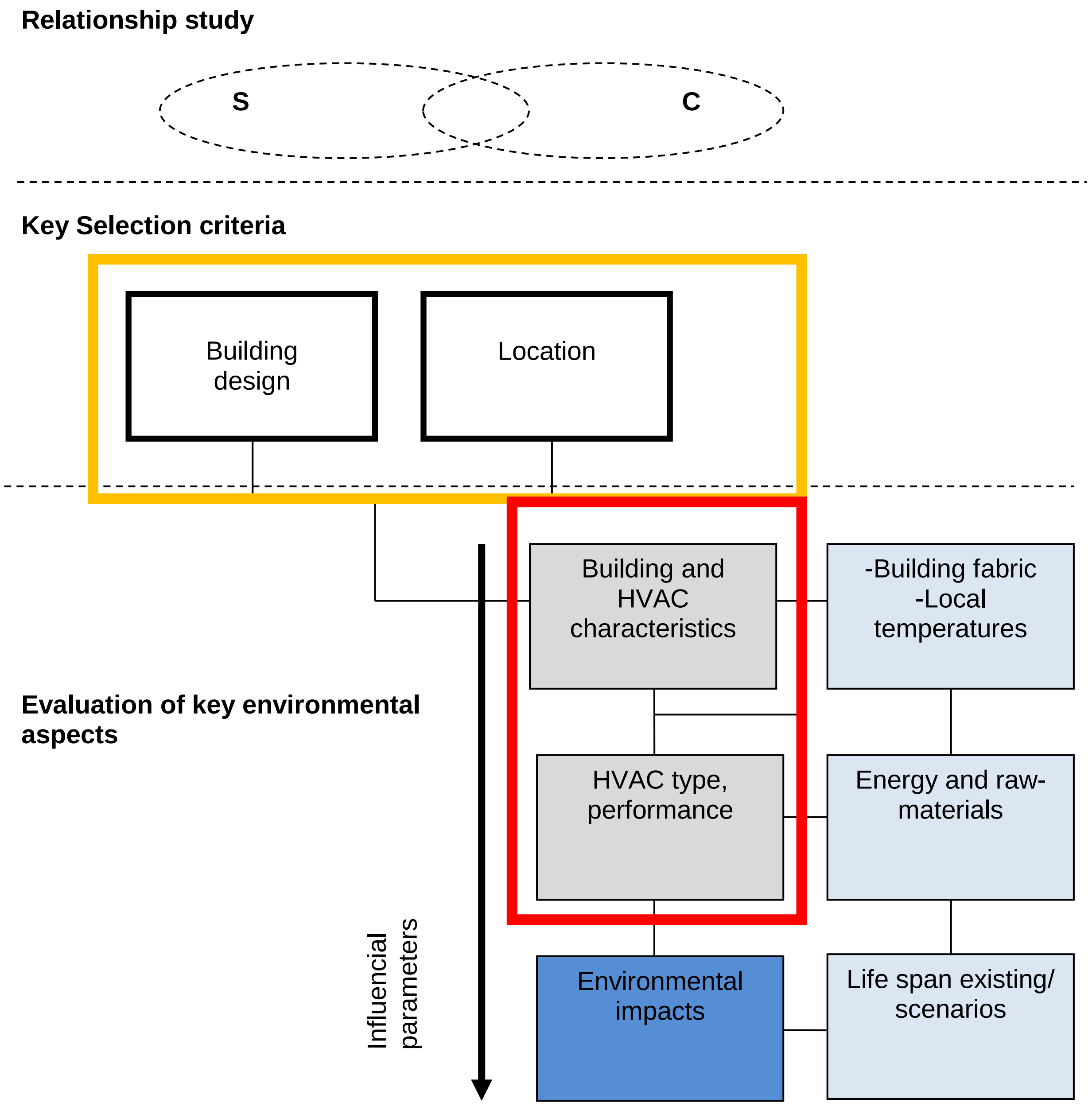


Figure 2.19: Key selection criteria of the case study office buildings for their comparison evaluation and their key

Therefore, the parameters that have been evaluated in this study to show the impact of building design and location are shown in table 2.21.

Table 2.23: Key performance parameters and case study selection criteria

Env. performance indicators	Energy indicator			
	Energy Indicator		Raw-material Indicator	
Case study criteria	Building design	Location	HVAC	Occupancy
Key performance parameters	objetives			
Building design and orientation	Style Size Layout Volume		Type Size Layout Number of equipment	Blocks Sections
Location	Co-ordinates Orientation Site	Local temperatures/ Seasonal-Zonal control		
Structure	-Structural materials -Building envelope-Thermal performance	IMPACT	Heating demand	
Life span	Interventions/ upgrades/ refurbishments	Interventions/ upgrades/ refurbishments	Interventions/ upgrades/ refurbishments	
Occupancy pattern				Number of occupants Ownership Type of occupancy Let/rent

2.10 Research Gaps

The key research gaps unfolded from the literature review are summarised as follows:

- **Office buildings**
    - A growing amount of literature on office buildings suggests that there is a need to bridge the gap between building design and actual performance.

  - Benchmarking for best practice in energy and CO_2 emissions is not up to date and new buildings are still compared to these benchmarks from 2003.
  - A large amount of existing office building stock without measures for reducing CO_2 at 80% by 2050.
  - Existing BREEAM certified office buildings from 2009 and older that had post occupancy evaluation proved that there is a gap between building design and building performance.
- **Heating and cooling systems**
  - The energy indicator has been taken into consideration for improving energy efficiency, although there is not enough evidence about to what extent energy efficiency can remain efficient in the long run according to its operation in office buildings.
  - The literature does not provide enough evidence about increasing energy efficiency in office buildings causes embodied raw-material emissions to rise.
- **Sustainable Assessment Methods (SAMs)**
  - The BREEAM scheme did not include an in-use phase and a post-occupancy phase for evaluation or even for predicting scenarios that could help to avoid reduced environmental performance in the long run.
  - The BREEAM scheme did not include the raw-materials of HVAC in buildings as an indicator for assessment.
  - Existing EPCs and DECs do not provide enough information and evidence of the building performance rating. They do not seem to influence positively long run improvement.
  - Life Cycle Assessment studies have mainly focused on energy of HVAC and few on raw-materials on HVAC, although there is still no robust evidence of the environmental impacts of HVAC installed in office buildings. This reflects the changes in policies and directives for driving this kind of change which currently is not happening.
  - No other LCA studied at the time of the survey attempted to compare heating and cooling environmental performance between sustainable and conventional office buildings.
  - No other LCA study explained how hypothetical scenarios can be developed to enhance long run effectiveness of the environmental performance of office buildings or of other type of buildings in general.

- **Key selection criteria and performance parameters for evaluation**
    - No comparison studies between sustainable and conventional office buildings were found at the time of the survey, to use for the case study selection of this study.
    - No explicit study was found in the literature with a list of environmental performance parameters to be evaluated based on the case study comparison evaluation.

Therefore the aim of the study was to evaluate the environmental performance of heating and cooling between sustainable and conventional office buildings through the development of a new sustainability indicator that can be used as a research model by other practitioners to bridge the above research gaps mentioned.

2.11 Summary

This chapter presented the key literature review and the research gaps unfolded to test the relationship that is illustrated in figure (?). From this literature a set of key selection criteria were infolded for selecting the case study office buildings and a set of key performance influential parameters that have been assessed in the following empirical chapters in an attempt to bridge the gap between building design and long run environmental performance of office buildings. The energy and the raw-material of heating and cooling systems are not the only sustainable indicators that are of value. The literature has highlighted the need to investigate the relationship of these two indicators to avoid environmental impacts shifting from one life cycle phase to the other using a gate-to-gate life cycle approach.

CHAPTER 3: GOAL AND SCOPE DEFINITION OF THE STUDY

3.1 Introduction

The purpose of this chapter is to explain what is the goal and scope definition of this study as a mandatory step when undertaking LCA studies. This chapter defines the LCA goal and scope within the overall goal of the thesis. Further to the research questions, the aims and the objectives provided in chapter 1, this chapter sets the system boundaries for the LCA study. Figure 3.1 below shows the boundaries that have been defined in chapter 2 and the need to further define the LCA goal and scope as a fundamental step before collecting data.

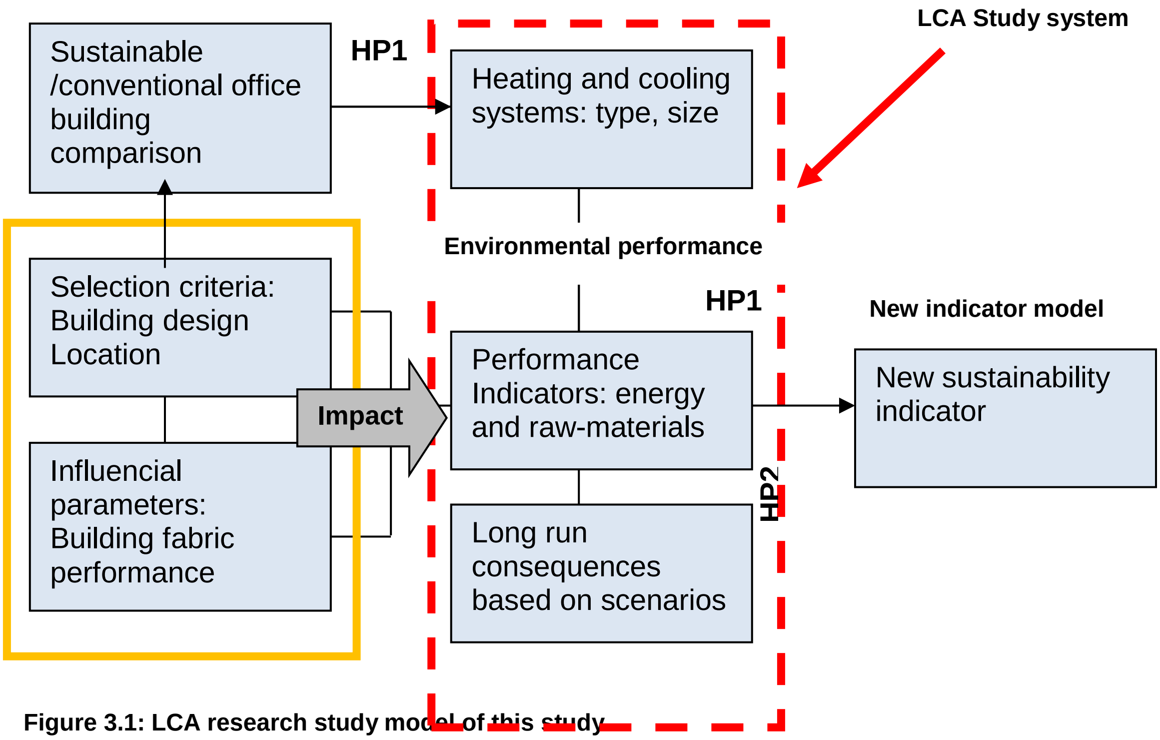


Figure 3.1: LCA research study model of this study

3.2 Goal and scope definition of the study

According to the research questions, the aim and the objectives mentioned in chapter 1 and according to the research gaps listed in chapter 2, the overall goal of the study was to show the impact that the unfolded influential parameters had on heating and cooling system environmental performance (based on energy and raw-material emissions) installed in conventional and in sustainable office buildings by considering their long-run performance. From chapter 2 it became clear that the key case study selection requirements are similar building design located within close distance. Chapter 4 provides more detail on the case study selection process.

3.3 Goal and Scope definition of the LCA system

According to the ISO LCA guidelines 14040 (2006), the product system that has been studied is the input and output of the two indicators, raw-materials and energy of heating and cooling systems, installed in sustainable and in conventional office buildings. A case study comparison approach has been used to evaluate the extent to which sustainable office buildings perform better than conventional.

3.3.1 Case studies of the LCA system

According to Grounded Theory for case study research (explained in more detail in chapter 4) a quantity of four office buildings that will form two case studies is appropriate for case study comparison.

1. **Case study 1:** a new BREEAM 'excellent' certified office building and a conventional office building.
2. **Case study 2:** a refurbished BREEAM 'excellent' certified office building and a conventional office building.

Beyond the key selection criteria for comparing sustainable with conventional office buildings which is building design and location, the selection criteria/boundaries for selecting sustainable and conventional office buildings need to be further expanded as unfolded from the literature review, shown in table 3.1.

Table 3.1: selection criteria/boundaries for selecting sustainable and conventional office buildings

Case study 1		Case study 2	
A new BREEAM 'excellent' certified office building	A conventional office building	A refurbished BREEAM 'excellent' certified office building	A conventional office building
Indicators: Energy and raw-materials		Indicators: Energy and raw-materials	
Criteria: Building design and location		Criteria: Building design and location	
Further case study selection criteria			
-A new building built before 2009 as BREEAM did not evaluate in-use and post-use phase (see chapter 2) -Multi-occupancy pattern. University buildings are occupied by staff and students at different times of the day and within districts. They have CHP installed as presented in chapter 2.	-An existing office building that had no upgrades or refurbishment -50 years life span so that scenarios can be made for refurbishment but also to help realise the life span of office buildings. -buildings from 1950s-1960s -Multi-occupancy pattern. Different occupancy patterns	-A building that previously had 50 to 60 years life span and was refurbished to BREEAM excellent standards -with government ownership to see the role that it plays in reducing emissions.	-An existing office building that had some upgrades in the heating or cooling system -from 1950s-60s -with government ownership

The additional criteria that emerged in this chapter following the research gaps in chapter 2 set the boundaries upon which the case study buildings have been selected.

3.3.2 LCA functional unit

According to ISO 14040 (2006) and to Prek (2004), the functional unit for the energy indicator in this study is the heating and cooling output (in KWh) of heating and cooling systems installed inside and outside of the conventional and of the BREEAM excellent certified office buildings, to heat and cool the indoor space of office buildings for two years of operation, 2009 and 2010. Another product included in the functional unit under the energy indicator is the refrigerant indicator. The refrigerant indicator is added to the cooling system during installation or maintenance, which are different life cycle phases. However the refrigerant use by cooling systems is still a highly significant issue for the GHG, thus it has been added to the LCA system study under the energy indicator.

The functional unit for the raw-material indicator is the amount of raw-material (in kg) used during the production of heating and cooling equipment in heating and cooling systems installed inside and outside of the conventional and of the BREEAM excellent certified office buildings, since the buildings had their last refurbishment, including all the equipment installed, working or not, switched on and off.

In order to hypothetically evaluate the LCA environment consequences in the long run, hypothetical long run scenarios have been developed. The functional unit for this evaluation is the heating and cooling output consequences in the next 25, 50 and 100 years considering no change in the existing energy consumption for heating and cooling. The functional unit also considers the consequences of existing embodied raw-material emissions in the next 25, 50 and 100 years, considering potential renovation or upgrade scenarios using sensitivity analysis.

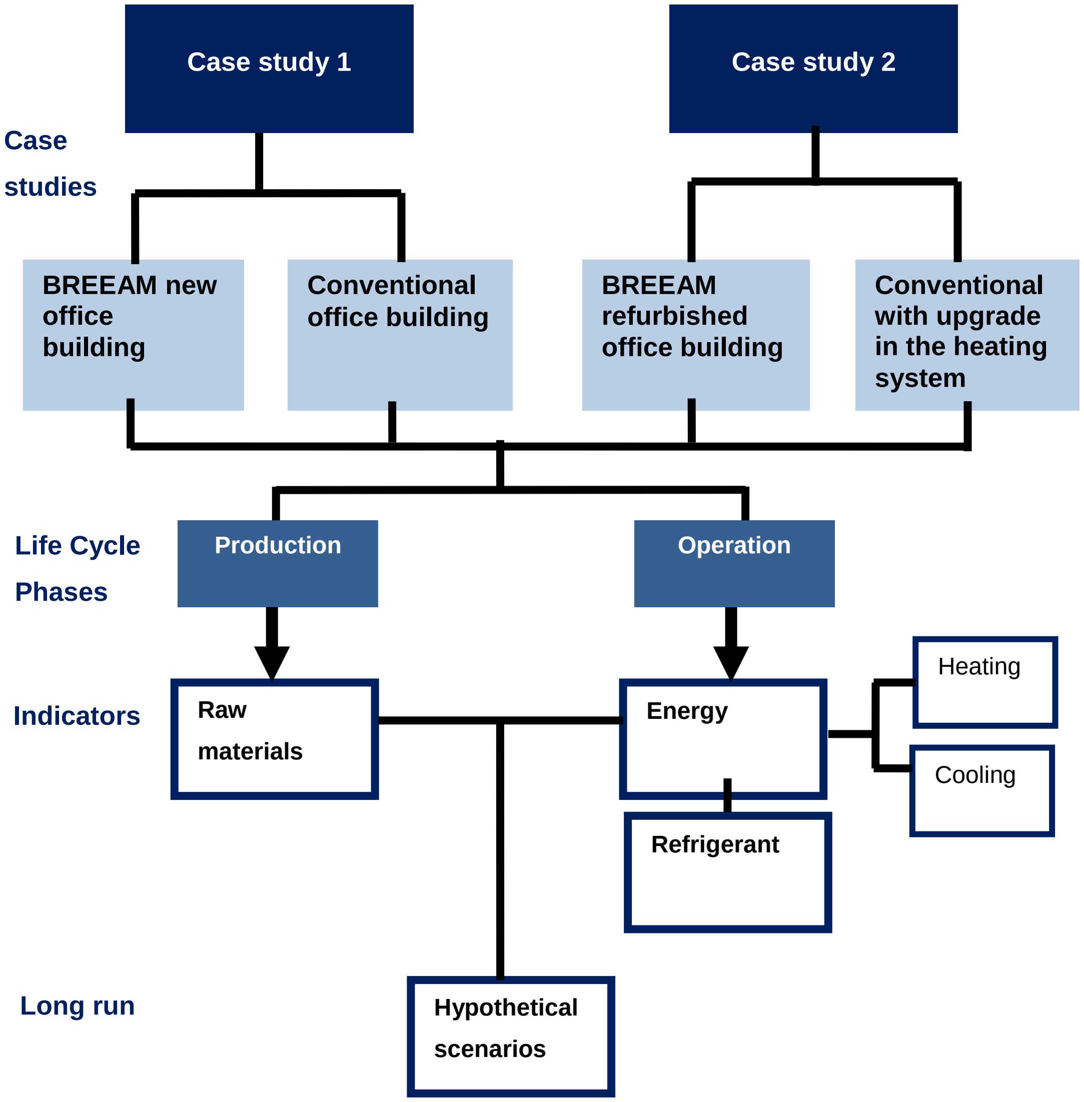


Figure 3.2: The LCA study system of the thesis

3.3.3 Heating and cooling system boundaries

According to the literature on heating and cooling systems in chapter 2, a heating or cooling system consists of heating-cooling generators and providers known as components (such as boilers, engines, pumps, radiators, air-conditioners), including their connection parts (screws, valves, etc.), their transfer parts (pipes), and their control parts and protection parts (filters and insulation).

In order to avoid complications in data access and data collection, data specific to small connection parts is excluded in most LCA studies, making even difficult to develop assumptions, and is therefore excluded also from this study. The protection system is also excluded from the study as types of filters or insulation used is mostly unknown for conventional office buildings, and since the systems are old it might be the case that protection parts are also old. Therefore only the key components are included in the LCA study system.

Table 3.2: LCA system boundaries of the thesis

Case Studies	Systems	Included in the LCA	Excluded from the LCA
Case study 1	Heating system	• Main components	• valves • controls • filters • screws foundation units • heating pipes • insulation
Case study 2	Cooling system	• Main components • Refrigerant use	• valves • controls • filters • screws • foundation units • insulation • piping system
	Heating system	• Main components	• valves • controls • filters • screws • foundation units • insulation • heating pipes
	Cooling system	• Main components • Refrigerant use	• valves • controls • filters • screws • foundation units • insulation • piping system

3.3.4 Functional unit for additional types of analysis

According to the LCA interpretation techniques mentioned in chapter 2, sensitivity analysis has been used to evaluate in comparison the heating and cooling technologies on the selected case study office building with alternative low/zero carbon technologies to check on the changes of the results per 1KWh of energy output. Several data limitations have appeared while collecting and analysing data, as discussed in chapters 4 and 8. Transparency has been used in reporting the limitations and assumptions were used to overcome them. Uncertainty analysis was used to check on the reliability of the results as a form of validation. More information on the limitations and assumptions is included in chapters 5 and 10.

3.3.5 LCA software

There are different LCA databases with different LCIA methods. This study reviewed the features of the available methods presented in this section. In this study, the SimaPro software has been used. SimaPro is widely used over 60 countries (Pre Consultants 2010); it includes a wide range of life cycle inventories and impact assessment methods needed for the study. The SimaPro version used is the PhD version that also includes the Monte Carlo uncertainty tool while the classroom version has limited usage. A justification on the selection of the LCI libraries and of the LCIA methods is provided in sections 3.2.5 and 3.2.6.

3.3.6 Selection of the Life Cycle Inventory Libraries

SimaPro includes several LCIA libraries and each includes different inventory data. The Model Basic Materials ETH-ESU 96 includes production data on different materials on LCA of Western European energy systems, such as mineralogical (sand, gravel, cement, ceramics), inorganic chemicals (chlorine, ammonia, iron sulfate), organic chemicals (propylene, refrigerants), metals (iron, steel, cast iron, aluminum), plastics (polyethylene), gases, biogenic materials (paper, wood, cardboard), processes and resource extraction data. This library was also used at Viral at al. (2007) LCA study. The data in this inventory includes a wide range of input data on metals, gases, plastics, organic chemicals that are needed for the inventory analysis of the air-handling unit. The Ecoinvent Inventory covers nearly 4000 processes of plastics, raw-materials, air-emissions, wastes from operations tracked back to the extraction of raw materials from earth and data from energy, transport, building materials, chemicals, metals, and waste treatment and agricultural. It also provides large data processes for the air-handling system. Ecoinvent consist of 2500 interlinked databases. For this study, all the available LCA libraries in SimaPro were used to ensure that all processes have been covered.

3.3.7 Selection of Life Cycle Impact Assessment Methods

The outcome of this study is the development of a new sustainability indicator which aims at evaluating the existing and long term environmental performance of heating and cooling systems in office buildings in order to support environmental decision making. The idea is that different practitioners can use the indicator as a tool to assess their buildings, providing results that are easy to understand. Also in order for them to compare their results with this study it would be better if single-score eco-indicator values were used. Therefore, it was decided that the impact indicator be presented in endpoint[2] level. The LCIA method chosen for this study is the Eco-indicator99. Also this study is closer related to the studies of Prek 2004d were the Eco-Indicator99 LCIA method was used. The characteristics of different LCIA methods are presented in table 3.3:

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[2] ISO 14040:2006 defines category endpoint as, “an attribute or aspect of natural environment, human health, of resources, identifying an environmental issue giving cause for concern” (ISO 2006 p.5).

Table 3.3: LCIA method characteristics in SimaPro

LCIA method	Assignment procedures	IPCC Equivalency factor	(DALY) percentage of the impact over an area during a certain period of time	Endpoint method	Midpoint method	Grouping of indicators through damage assessment	Weighting methods	World Wide method	European method	Damage Category: Human Health	Damage Category: Ecosystem Quality	Damage Category: Climate Change	Damage Category: Resources	Damage Category: Biodiversity	Damage Category: Cultural and recreational Values	Characterisation factor	Chosen Methods for analysis
Eco-indicator 99	*		*	*		*	*			*	*		*				*
CML 92		*			*			*				*	*				
EPS2000			*	*		*	*			*	*		*	*	*		
Impact 2000+			*		*					*	*	*	*			*	*
Case Study		*	*		*		*		*	*	*	*	*				

Source: Own interpretation

Most LCA studies on heating and cooling systems have used the Impact 2002+ method and the Eco-indicator 99. According to different LCA studies on building services systems, the most common methods were the Eco-indicator 99 (Eriksson et al. 2007 p.1352), (Prek 2004b p.1022), (Techato et al. 2009a p.321); the CML 2000 (Blom et al. 2010 p.2363), (Techato, Watts, & Chaiprapat 2009a p.321); the 2002+ (Shah et al. 2008 p. 504); and the EPS 2000 (Eriksson, Finnvenden, Ekvall, & Bjorklund 2007 p.1352), (Heikkila 2008 p.54), (Heikkila 2004 p.1135). Also the selection on the LCIA method has mainly to do with its availability in SimaPro and with its coverage on environmental impacts that are interested for the study.

A more complete impact assessment methodology (LCIA), followed by a weighting step (Prek 2004b p.1022,1023) is the Eco-Indicator99 method (figure 26). According to the Eco-indicator99 method when a chemical substance is released, its sequence finds its way into air, water, soil, and for how long it will stay and where it will go, depends greatly on the properties of the substance and the compartments (water, soil, air) (Goedkoop and Oele 2004 p.24). The impact indicator is expressed as the percentage of the impact over an area during a certain period of time. In the Eco-indicator99, a weighting triangle method, developed by Hofstetter (1999) can be used. This approach can actually be used for decision making and it is useful for product comparisons to show under which conditions (weighting factors) product A is better than product B (Goedkoop & Oele 2004 p.28).The eco-indicator uses a distance-to-target principle which provides correlation between the seriousness of the effect and the distance between the current level and the target level. At the same time it uses a top-down approach so that the more important issues can be separated from the less important. The top-down approach starts by defining the required result of assessment, which involves the definition of the term 'environment' and the method for weighting the different environmental impacts (Prek 2004b p.1022,1023).

Four types of analysis are used in the Eco-indicator99. With a ''fate analysis'' the degradability of the substance can be considered (figure 25). This analysis is important to model the transfer compartments and the degradation of the substance from which the concentrations to the compartments can be calculated (Goedkoop & Oele 2004 p.24). Through an ''exposure analysis'' it can be determined how much of the substance is taken by different ecosystems (figure 25)(Goedkoop & Oele 2004 p.24). With an ''effect analysis'' the frequencies of the diseases can be predicted, for instance those that lead to deaths (figure 3.3). The predicted diseases can then be transformed into damage units given by DALY in the ''damage analysis'' (figure 25) (Goedkoop & Oele 2004 p.24).

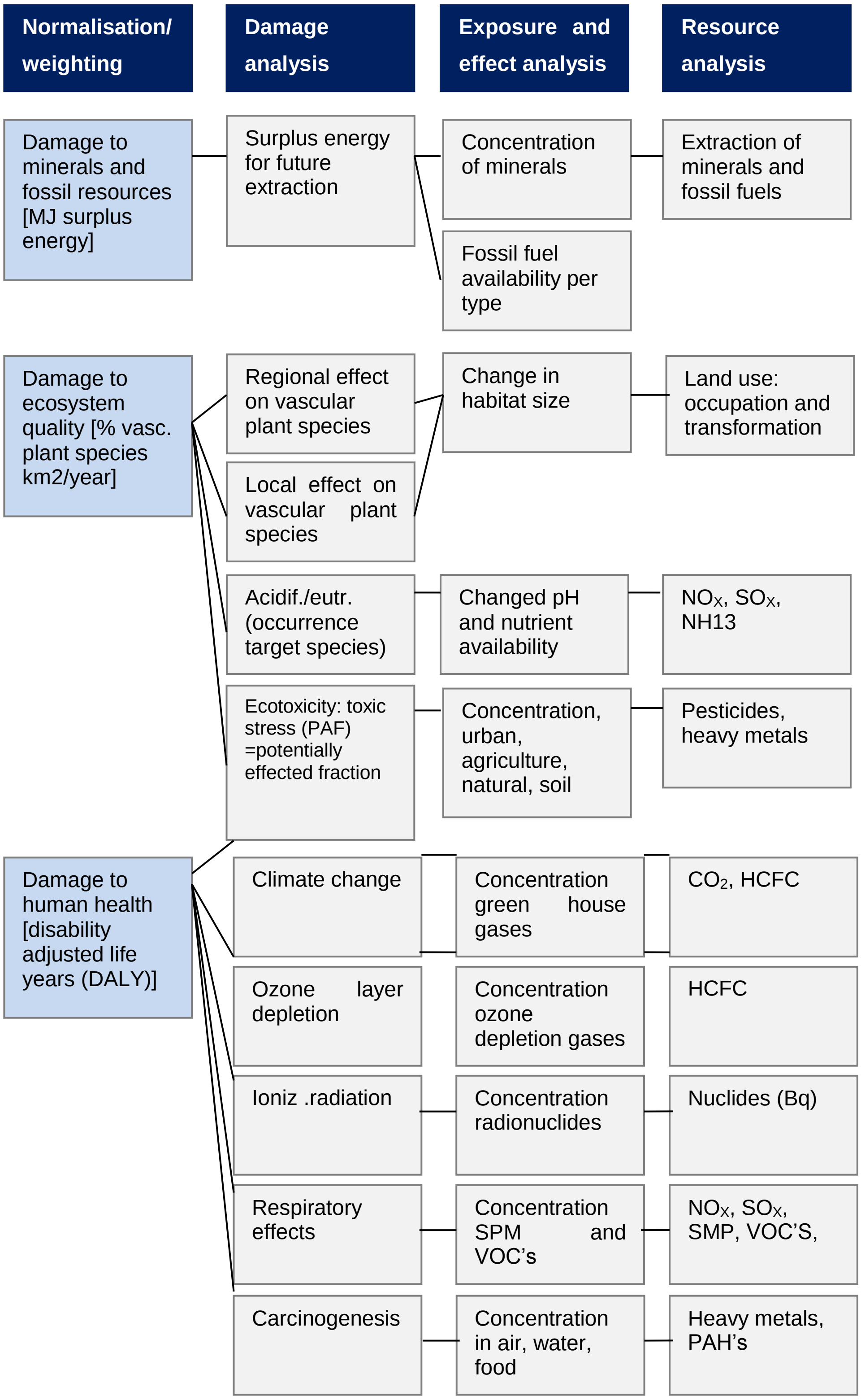


Figure 3.3: Eco-Indicator99 life cycle impacts assessment categories

3.4 Summary

This chapter has explained in detail the over scope of this study and the specific goal and scope of the LCA, including the study functional units, the system boundaries, and a list of further selection criteria/boundaries for the case study buildings, justifying the selection of LCA software packages and their content for the LCA evaluation in this study, as an overall contribution for the boundary system and the development of the new sustainability indicator.

CHAPTER 4: RESEARCH DESIGN TOWARDS A NEW SUSTAINABILITY INDICATOR

4.1 Introduction

The purpose of this chapter is to present the research design rationale towards the development of a new sustainability indicator for evaluation of the environmental performance of heating and cooling systems in office buildings. The chapter first explains which philosophical research paradigms and which theoretical approaches have been used, as a basis upon which the research has been designed. The next section is on the development of a research framework and explanation of its contents followed by a section on research models developed to collect and analyse data. The diagram below illustrates the key thematic contents of this chapter.

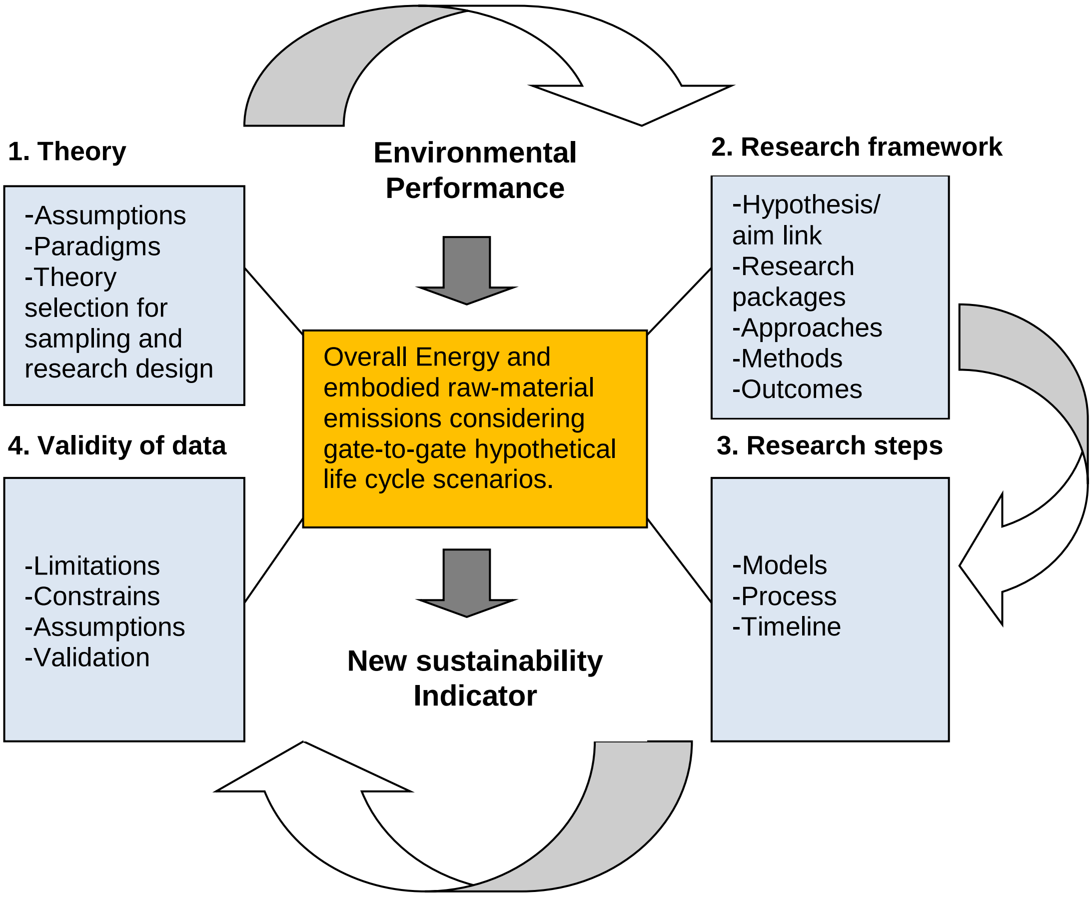


Figure 4.1: Key thematic contents of chapter 4

4.2 Philosophical and theoretical underpinning of case study research

The outcome of this study is a new sustainability indicator which is both scientific and social science-based; scientific research is a systematic, controlled empirical and critical investigation of propositions about the presumed relationships of various phenomena (Kumar 2005). Qualitative research is *"a situated activity that locates the observer in the world. It consists of a set of interpretive, material practices that make the world visible. These practices […] turn the world into a series of representations including fieldnotes, interviews, conversations, photographs, recordings and memos to the self"* (Denzin & Lincoln, 2005, p3). Paradigm or interpretive framework is *"a basic set of beliefs that guides action"* (Creswell, p.19). Each interpretive paradigm plays an important role for the researcher as it can influence the questions that the researcher will be asking and the interpretations the researcher wants to make (Denzin and Lincoln 2008 p.31). The research on this thesis can be determined by the positivism and constructivism paradigms, as in order to believe in the existing truth there is a need for experimentation and more realistic and critical thinking. The study could also be characterised as scientific, hypothetical driven, deductive, reliable, valid, reproductive, and objective. Thus empirical research with both qualitative and quantitative methods is important to ground, test, validate and generate the theory (table 4.2).

Table 4.1: The LCA theoretical framework on this thesis

Social and scientific orientation to knowledge	**Research Assumptions**	**Stage of the study**	**Research Paradigms**					**Methods in social sciences**
			Positivism	**Post-positivism**	**Pragmatist/ realism**	**Constructivist**	**Critical**	
Social orientation	Ontology	Recognition/ acceptance by other researchers	*			*	N/A	N/A
Social & scientific orientation	Epistemology/Methodology	-Research design and methods -Empirical work (fieldwork, data collection, data analysis)	*	*		*	*	*Qualitative & Quantitative*
Social orientation	Axiology	-Significance of the results-research -Validation -Contribution -Acceptability -Raise understanding			*	*	*	*Qualitative*

Source: Own interpretation

Emergent methodological design aiming at grounded theory is what is needed to address the objectives of this study. In grounded theory the researcher works inductively to generate theories, and it is common to produce methodological protocols at a later stage. Grounded theory must be flexible, iterative and emergent (O'Leary 2010) and it is supported through case study research approaches. *‘’Case is a bounded system or a particular instance or entity that can be defined by identifiable boundaries’’ (O'Leary 2010, p. 174). ‘’Case study is a method of studying elements of the social through comprehensive description and analysis of a single situation or case (O'Leary 2010, p. 174).* For instance, Junnila’s study (2004) on the environmental impacts of an office building through its life cycle used a multiple-case design with embedded units and a positivistic orientation, suiting both qualitative and quantitative methods. A case study method was chosen to investigate an open system, where 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. The cases were chosen based on the replication logic so that all cases have significant differences, using Eisenhartd’s (1989) emphasis on theoretical categories as factors for choosing the cases (Junilla 2004). In Grounded Theory (Eisenhardt 1989, p.545) a number of 4 to 10 cases will work well in building theory. Another tactic is cross case comparison patterns (Eisenhardt, 1989, p.540), by selecting categories or dimensions looking for within group similarities and differences. In this case the case study selection instrument will be a MATRIX table with cross-case data on characteristics (Wilson and Wolsky, 1997, p.60) according to different decision making criteria explained in section 4.2.1. The MATRIX tool is fundamental for checking similarities and differences across different building cases.

4.3 Research framework

According to the research gaps mentioned in chapter 2, and the aim and objectives of this study, a research framework has been developed that reflects the focus of this study. The key issues that this study has tried to address are i): the performance gap between building design and environmental performance of office buildings (heating and cooling), ii) the comparison evaluation between sustainable and conventional office buildings and iii) the fact that the raw-material indicator has not yet been considered and studied in parallel to energy indicator and the building design. These issues are explored within 7 key stages as shown in the following figure (4.2).

Key
BD=Building design
E=Energy, RM=Raw-material
Ev.=evaluation

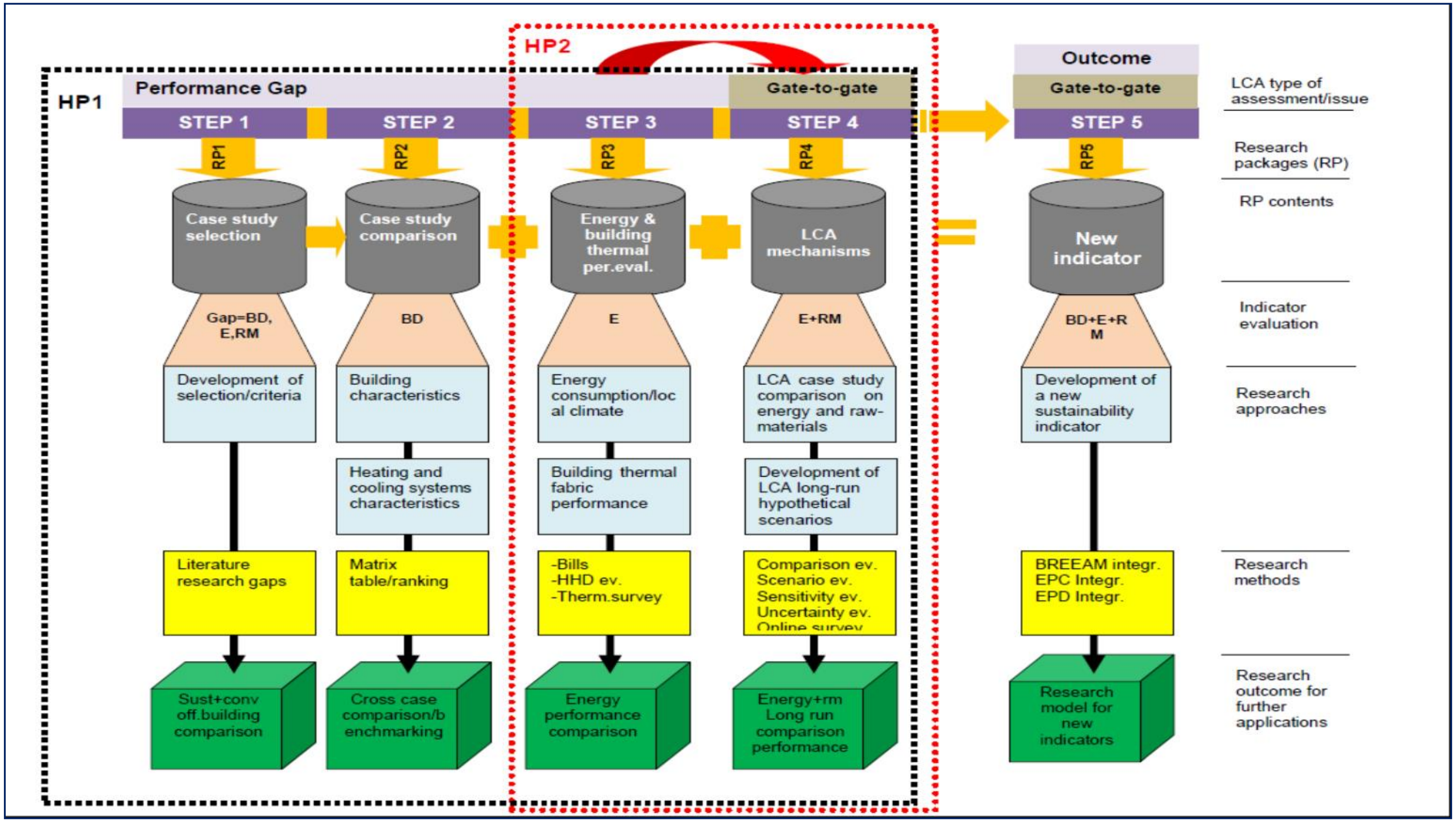


Figure 4.2: Research framework

4.3.1 Step 1: Selection of the case study office buildings

Chapter 2 section 2.11.3 presented the key selection criteria for the case study office buildings, ie, building design and location. These criteria were then expanded with performance influential parameters showing the impact that they can have on the environmental performance of the HVAC and on the way systems are used by the occupants, depending on occupancy patterns. These criteria have been further expanded as they emerged through the need to justify further the selection criteria. The added criteria have been selected considering the research gaps of the literature review and the problem statement in chapter 1.

This section presents the criteria categorised by their level of importance to enhance case study comparison and to address the goal and scope definition of the study and its further system boundaries. These criteria have been described in chapter 6 as case study building characteristics and in a MATRIX table provided in appendices (see more in section 4.3). The level of importance for the selection is presented in table 4.3:

Table 4.2: Case study selection criteria

Level of importance	Selection criteria	What to look for
Primary	**BREEAM excellent (certified before 2009)**	The first important selection criteria are to choose BREEAM excellent certified office certified before 2009.
Primary	**Building age** **-life span**	Building age is a significant criterion for selecting both BREEAM offices and conventional offices: 1. New BREEAM excellent offices to be built after 2008 and fully operated since 2009. 2. Existing old office buildings that were built after 1950s and had no building refurbishments. 3. Existing old office buildings that were built after 1950s and had an upgrade in their heating system to represent these types of buildings. 4. Existing old office buildings that have reached 50 years of age.
Primary	**Building design** **-size** **-shape** **-style** **-orientation**	The case study offices must be of: 1. Different architectural styles 2. Similar size in total m^2 3. Similar building shape 4. BREEAM offices west orientation 5. Conventional offices north or south orientation
Primary	**Location** **-temperature** **-heating Degree Data** **-surroundings**	1. For every case study, it is important to consider that the case study buildings are located in the same country and possibly in the same town/city within close distance. 2. The case study building must represent different regions in the UK in order to consider different local temperatures from North to South and to Midlands. Also the Heating Degree base temperatures must be different. 3. The surroundings can have a great significance in the environmental performance of the buildings so buildings that are located in open areas are preferable.
Primary	**Building occupancy (BO)**	1. BREEAM office buildings to be fully occupied (ie, all floors are occupied) 2. Conventional buildings that are fully occupied 3. Conventional buildings not fully occupied to represent a large number of existing office buildings in the UK, were major decisions need to be taken about demolition or renovation.

Level of importance	Selection criteria	What to look for
Secondary	**Heating/cooling technology** **-energy efficiency** **-conventional**	1. BREEAM office should have low-energy claimed heating/cooling systems types with passive cooling/heating. Natural gas condensing boilers with heat recovery and with local power generation such as CHP are needed for the study. 2.Conventional central heating low-energy efficient boilers
Secondary	**EPC**	1. Energy performance certification of B' on BREEAM excellent offices. 2. Energy performance certification of B' or worse for conventional office buildings. This is important to show that both a sustainable and a conventional office building can have the same EPC score (section 2.3.1, Nunes at al 2013 study).
Secondary	**Representable benchmarks**	The ECG 19 benchmarks are not up to date, although the criteria for the selection of the conventional office buildings is Type 3-Typical Practice and for the BREEAM offices Type 3 better than Good Practice in these benchmarks.
Secondary	**-Building Construction** **-Building Fabric**	1. The BREEAM offices must be of different construction materials to represent different building materials from different regions (brick, stone, pre-cast concrete). 2. The BREEAM offices must be fully insulated. 3. BREEAM offices must be double-glazed. 4. The conventional office buildings must be representative of 1950s onwards so pre-cast concrete is an ideal construction material. 5. Conventional offices must be non-insulated and single-glazed.
Secondary	**Ownership**	1. One case study to be public buildings/ government owned (some reductions in CO_2 have appeared, refer to introduction 3000 central government buildings). 2. Another case study to be privately owned.

Source: Own interpretation

The above selection criteria according to the level of importance depended on building selection process explained in the following section.

Sample: Case study selection process and constraints

Based on the above selection criteria and the level of importance, the identification of possible office buildings for the study started by searching BREEAM 'excellent' certified office buildings through the BREEAM's website under the office buildings case studies. Several case studies were found. The first two buildings that met the BREEAM criteria were the new office building called 'Palestra', located in London and the refurbished office buildings called '100 Hagley Road' in Birmingham. Access to the Palestra building was denied due to major publicity of its BREEAM case mentioned in the Introduction, chapter 1. Access on Hagley Road was provided and after the first site visit, requesting explicit data on energy consumption, access was denied.

A paper presentation of this study by Dimitrokali (2009), at the 'Central Europe towards Sustainable Building' conference in Prague was useful in identifying Bennetts Associate architects, having presenting their large portfolios of BREEAM certified buildings. This was a successful contact and two BREEAM office buildings were finally selected and these are:

1. **Potterrow:** BREEAM 'excellent' certified new office building, built in 2008 with CHP technology for heating and cooling, located in Edinburgh.
2. **Elizabeth Courts II (EIIC):** A BREEAM 'excellent' refurbished office building built from 2008, with energy-efficient claimed technology for heating and cooling, located in Winchester.

The selection of these two cases set the specific detail criteria for selecting the conventional office buildings. So the conventional office buildings, one in Edinburgh and one in Winchester, had to be of similar size as the pair BREEAM of office buildings in the same locations.

Desktop research through development and investment companies did not help to find the right match. The next thought was to look at project collaboration between the University of Central Lancashire and the School of Built and Natural Environment. Through this collaboration a building development company was identified that had a large portfolio of conventional office buildings, although the name of the company cannot be mentioned following a confidentiality agreement. The selection criteria for the comparison analysis, size and location were filtered in a database. A match for the case study in Edinburgh was found, which is:

1. **Argyle House:** A conventional existing office building dated from 1950s-1960s with conventional building-technology type, with heating and cooling systems that had no replacements-upgrade, located in Winchester.

The filter in the database did not find a match for the case study in Winchester, therefore a closer location was chosen in Birmingham, and the building is:

2. **Five Ways House:** A conventional existing office building dated from 1950s-1960s with conventional building-technology type, with heating and cooling systems that had its last upgrade in 1990, located in Birmingham.

The architects and the developer were approached by emailing a research brief of the purpose and needs of access to the office buildings, including an optional confidentiality agreement (see appendix 1).

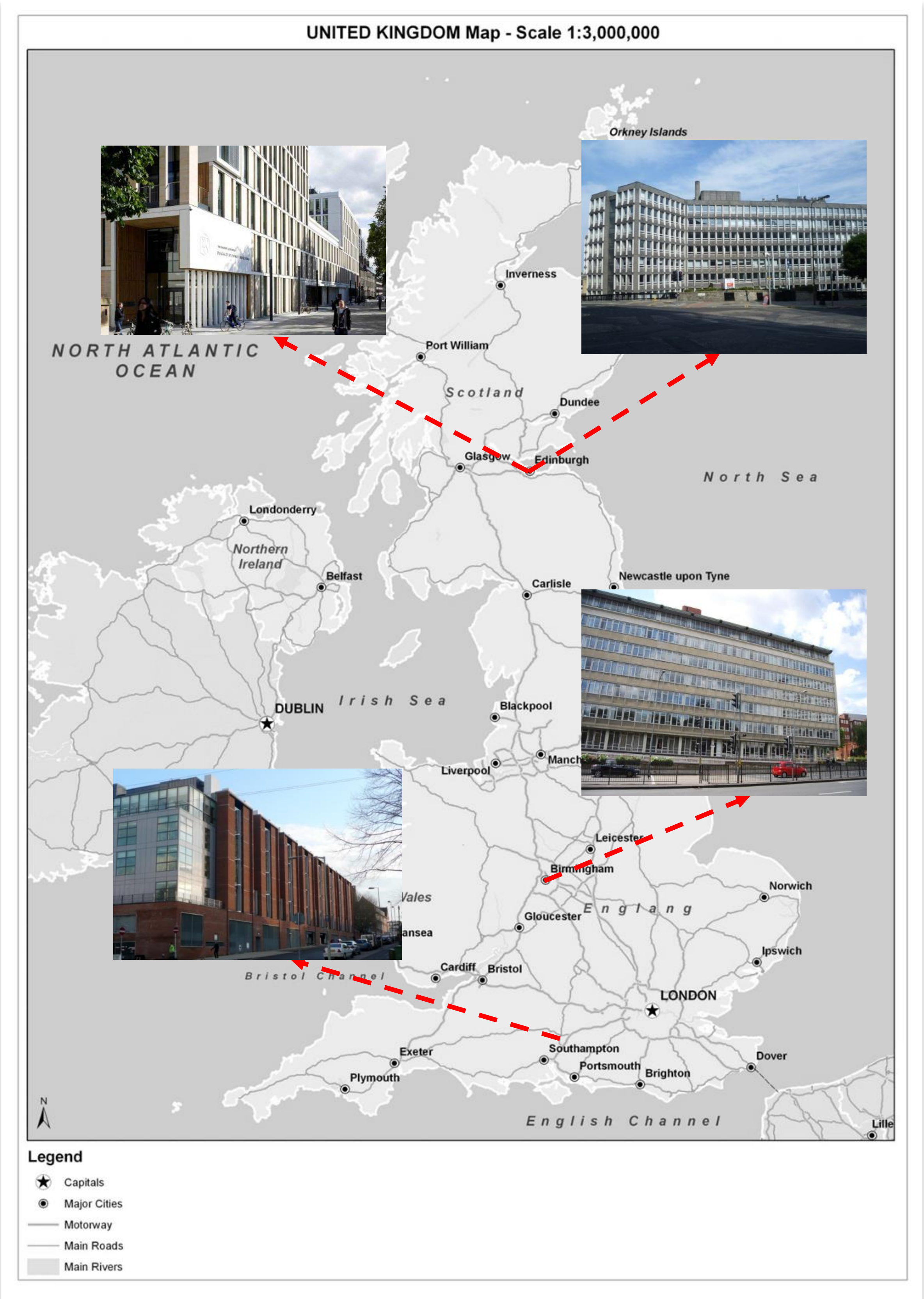


Figure 4.3: Case study office buildings location

Source: Ordnance Survey

The following section presents the research models upon which different stakeholders were contacted to provide data for the needs of this study.

4.3.2 Step 2: Case Study Comparison

In order to address the first hypothesis as shown in the research framework diagram, a case study comparison approach has been used between the sustainable and the conventional office buildings, as explained in the previous section. The case study comparison evaluation has focused first on showing the building characteristics and the heating and cooling system characteristics installed in the office buildings. To show this comparison of the characteristics the case studies have been described in parallel and a list of their key characteristics is given in three tables, to show a) the main building characteristics which represent the key selection criteria of the case studies, b) on structural characteristics, c) on building occupancy and d) on environmental characteristics. Further information is provided on the environmental building design approaches used on the sustainable office buildings.

Similarly, tables have been used to show the heating and cooling system characteristics. In order to evaluate the energy performance and the building performance it is important first to analyse the office building characteristics and the heating and cooling system characteristics. A literature review on energy efficient characteristics revealed key influential factors that have been provided, while the benefits and the limitations found are also presented in tables.

Towards the discussion section of this research step, the key case study characteristics have been ranked in a table in order to identify best practice and best sustainable characteristics across the four office buildings, considering the environmental approaches used. Further, the influential factors and parameters are also discussed based on their impact on the environmental performance considering both energy and raw-material consumption.

4.3.3 Step 3: Energy and Building Fabric Performance Evaluation.

The third step of the research framework is the energy and building fabric performance evaluation. Step 2 has focused on showing the differences between sustainable and conventional office buildings and step 3 has focused on the performance gap between the building design and the actual usage/operation of the building. This happens through estimating the heating and cooling consumption in relation to the degree set temperature parameter for different locations and in relation to building fabric thermal performance, recording building heat losses versus heating consumption.

4.3.4 Step 4: LCA mechanisms on heating and cooling systems in sustainable and conventional office buildings

Steps 3 and 4 of the research framework aim to test the second hypothesis about the fulfillment of existing indicators for determining long run sustainability. As the main aspect examined in this study is environmental performance, the data from step 3 helps to understand how the performance gap can impact on the increase of both energy and raw-material emissions and how hypothetical changes to enhance building and mechanical energy efficiency in the long run can have a significant impact on the increase of the embodied raw-material emissions. Therefore, on this step, LCA has been applied first on the heating and cooling for each building, then to compare case studies and then in evaluating long run hypothetical scenarios by using sensitivity analysis. Uncertainty analysis has also been used to check on the significance of data assumptions. An online survey (included in appendices) was used to collect expert advice and opinions on research findings. The next section presents in more detail the data collected and evaluation methods used.

4.3.5 Step 5: a new sustainability indicator

Step 5 presents the development of new sustainability indicators that has emerged after conducting and analysing research findings from steps 2, 3 and 4, on the grounds of creating a new conceptual approach. This step explains the significance of having this new indicator and in addition it recommends ways for its integration into the current sustainability assessment methods in office buildings.

4.4 Research models used for data collection and analysis

One of the key constraints in undertaking environmental performance evaluations is the data availability in terms of the sources of the data, the access of the data and which stakeholders can provide the data. This constraints and data limitations are explained in more detail later on in this chapter, however this section presents three key ‘research models’ that show the type of data that had to be collected, which stakeholders were approached, which sources were accessed, which instruments and methods were used and how this data has been used and can be used by others.

These research models are:

- **Model 1: First wave data collection - Building and heating-cooling system characteristics**
- **Model 2: Second wave data collection - POE on energy and building fabric performance evaluation**

- **Model 3: Third wave data collection - POE on environmental impact performance evaluation**
- **Model 4: Discussion and validation**

4.4.1 Model 1: First wave data collection on building and heating-cooling system characteristics

This research model lists the data requirements for steps 2 and 3 of the research framework (see table 4.4). This data is basically the background data of the energy consumption and the raw-material consumption of the heating and cooling systems in office buildings, so this data represents the key characteristics of the case study office buildings.

Table 4.3: Model 1

Background data of the heating and cooling systems on the selected case study office buildings		
Contents	Case study selection criteria	POE
Philosophical paradigms	Epistemology: Positivism and constructivism (development of constructs –categories) - Qualitative methods	
Type of data needed	Building design characteristics Building structure type Number-type of occupancy Heating and cooling systems characteristics Architectural project briefs Location maps Images from building perspectives Building shadows/surrounding typology Technical drawings Mechanical drawing Mechanical specifications Planning applications Images from indoor/outdoor spaces	

Background data of the heating and cooling systems on the selected case study office buildings	
Stakeholders	Architects Mechanical engineers Investment property companies Property development companies Facility management team Building manager Archive libraries MET office Carbon Trust
Research project collaborations	Bennetts Associates Telerial Trilium Burro Happold Engineers University of Edinburgh City Council of Winchester
Data sources (primary and secondary data collection)	Technical drawings Mechanical drawing Mechanical specifications Planning applications BREEAM documentation\energy certifications POE evaluation documentation Undertake POE evaluation Project documentation-briefings-brochures Photographs
Instruments	Camera, notebooks
Methods	Research briefs, invitation letters, recorded conversation, questionnaire survey, random e-mail requests, telephone discussions, site visits, stakeholder visits, desktop research, interviews on sites
Software	Ordinance Survey Google Earth SketchUp Pro
Outcome	MATRIX table for cross case comparisons

1. ***Site visit data collection***

The first wave data collection on the background data has been implemented through site visits, desktop research and telephone discussions with the stakeholders mentioned on the model.

Prior to the site visits, an invitation email was sent to all the stakeholders involved in providing data, with a project brief of this research study (appendix 1). The research brief states the initial aims and objectives of the study, it mentions the constraints, the data requirements, the ethical coverage and it provides a section on confidentiality.

During the site visits face to face discussions were held in the buildings with the key stakeholders on the building characteristics. The stakeholders provided the first wave of data collection as mentioned in model 1 (architectural drawings, project briefs etc.). The sits visits also involved walkthroughs inside and outside the buildings to become familiar with the building spaces, the materials and the technologies used, and interviews with key stakeholders on semi-structured questions (appendix 21).

In order to ensure that the appropriate data has been collected an evaluation list of data requirements was used on the site visits (see appendix 2).

In order to collect the first wave data collection two site visits were held in the case study office buildings.

Random emails of missing data requests were sent to the stakeholders following site visits. Stakeholders were also approached through planned telephone calls.

2. MATRIX table for cross case comparison of building and heating-cooling characteristic

The outcome from the first wave of data collection was the development of a MATRIX table. In order to allow cross-case comparison of different variables that influence energy and raw-material consumption, it was found in the literature that MATRIX tables used both in statistics for social and scientific research is the most common used method. The business dictionary defines MATRIX as *'Flat (two-dimensional) table in which the elements or entries appear at the intersections of rows and columns, governed by certain rules. Matrices condense different types of information and are used in studying problems where the relationships between their elements are amenable to tabulation, such as in linear simultaneous equations and Markov chains. Called rectangular array in mathematics'. David Howell (2008) explains that MATRIX has been used as a fundamental tool in statistics for the Behavioural Sciences in order to inter-correlate different variables. MATRIX analysis has also been used in online questionnaire surveys such as SurveyMonkey and Qqualtrics*

The MATRIX table is available in appendix 8 although the basic data characteristics are also presented in chapter 5 and it has helped in identifying a best practice office building as well as features from both conventional and sustainable office buildings that if were used in a potential office building development, could improve the environmental performance of office buildings. More discussion on this is provided in the following chapters.

4.4.2 Model 2: Second wave data collection- POE on energy and building fabric performance evaluation

The environmental performance of the office building characteristics including their heating and cooling systems (shown in MATRIX table), was evaluated using post-occupancy evaluation.

Model 2 represents the second wave data collection which has been used to measure heating and cooling system consumption, based on meter readings and in correlation with degree local temperature data. This data was also used to identify and evaluate the building fabric thermal performance in terms of heat losses.

This data has been collected through additional site visits, desktop research and telephone discussions with the key stakeholders. Some data requests emerged by conducting different surveys.

Table 4.4: Model 2

Background data of the heating and cooling systems on the selected case study office buildings		
Contents	Case study selection criteria	POE
Philosophical paradigms	Epistemology: Positivism and constructivism (development of constructs –categories) - Qualitative methods	
Type of data needed	Number-type of occupancy Electricity consumption data Identification of heat losses Environmental existing assessments BREEAM reports/scores EPCs and DECs Local temperatures Heating degree data Existing post-occupancy evaluations ➤ Thermographic surveys ➤ Other energy related surveys	
Stakeholders	Architects Mechanical engineers Investment property companies Property development companies Facility management team Building manager Archive libraries MET office Carbon Trust Department of Energy and Climate Change	
Research project collaborations	Bennetts Associates Telerial Trilium Burro Happold Engineers University of Edinburgh City Council of Winchester	
Software	Excell, Flir thermographic survey reports	
Instruments	Digital camera, infrared camera, measuring tapes	
Methods	PhD research briefing, invitation letters, recorded conversation, questionnaire survey, random e-mail requests, telephone discussions, site visits, stakeholder visits, desktop research, thermography survey, Heating Degree Data evaluation	
Outcome	Case study comparison evaluation of energy and building fabric thermal performance	

1. Post-Occupancy Evaluation (POE)

POE is the evaluation of a building during its operation. POE in BREEAM certified office buildings is a necessary tool to find out whether the building performs as expected or claimed. Currently the Low Carbon Group of the School of Architecture in Oxford Brookes University uses POE techniques in the work package 2 of the

ESRC/RCUK EVALOC research project which is on the evaluation of Low Carbon Communities. POE offers a rich picture of energy use in buildings than is available from a purely technical approach. Action research has been used in the project to look at the 'why' as well as the 'what' of energy performance considering those that are involved rather than the object of the research (Gupta and Darby 2011). Research findings from the EPSRC/Carbon Trust funded CaRB project reveal that valuable new insights can be gained by collecting hard data, i.e. measurement, monitoring, questionnaires and surveys on existing buildings (Lomas 2009). The University of Westminster has produced a guidance-toolkit to POE funded by the AUDE and the HEFCE. The POE process overview developed is the following (Blyth and Gilby 2006):

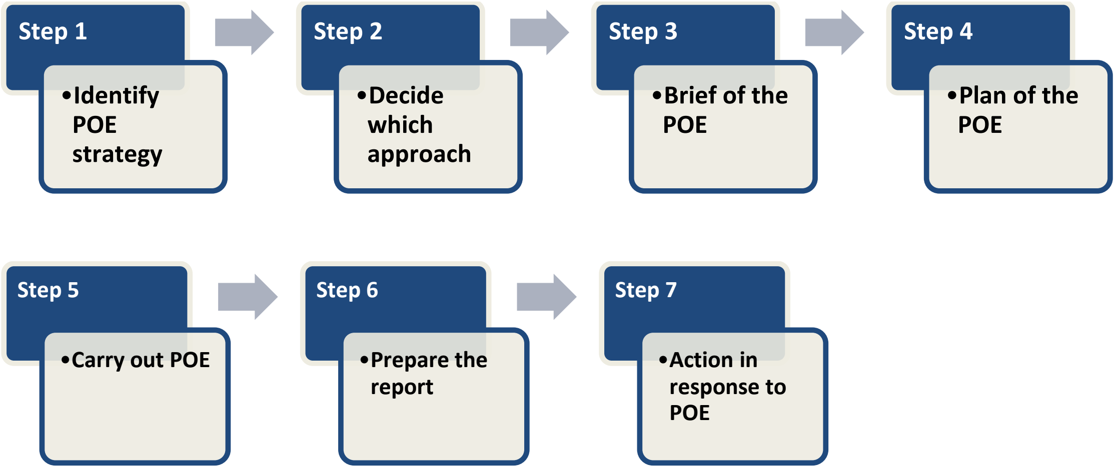


Figure 4.4: POE process produced by the University of Westminster

Blyth and Gliby (2006), defines POE as *'an umbrella that includes a review of the process of delivering the project as well as a review of the technical and functional performance of the building during occupation'*. It is a way of providing feedback through a building's lifecycle from initial concept through to occupation. According to the POE prototype guidance, the purpose of the POE in this thesis is (Blyth & Gilby 2006):

- Identification of and finding solutions to problems in buildings
- Understand building implications related to energy and building performance

This POE lies on the Project Review stage of the process; this means that it will be carried out at least a year after its occupation and building services operation. Through this stage it can be seen how the building performs under a variety of conditions and it gives a chance to identify whether the building meets the long term needs as included in the hypothesis of the thesis (Blyth & Gilby 2006). The Project Review stage is divided into three review types:

(i) POE's indicative review

POE has been used to provide an indicative review that gives a quick snapshot of the project where few interviews are combined with walk-throughs of the buildings. This goes back to the first research model, first wave data collection. This review lasts from 3 to 6 months.

(ii) POE's investigative review

An investigative review has been conducted to investigate influential parameters of the environmental performance of the building (part of the research model 1), in combination with investigations on energy efficiency and energy consumption for heating and cooling. This review normally lasts from 9 to 18 months although the LCA took most of this time to collect and analyse the data. Thus this type of review can be conducted within a post-doctoral research.

Before explaining which methods were used in the diagnostic review, a literature on POE evaluations discovered that the Soft Landings framework by BSRIA, has used a similar process approach to indicative and investigative review. The Soft Landings framework explains that POE is about periodic reviews in buildings that can be conducted individually depending on what has to be investigated. Therefore it includes:

- Monitoring performance
- Performance reviews
- Occupancy feedback
    - Occupancy satisfaction surveys
    - Technical and energy performance queries

The Soft Landing framework covers the whole life cycle of a building project, from concept to procurement and design, although in this study the closely related areas are the stage 4 Initial Aftercare and the stage 5 Years 1-3 Extended Aftercare and POE.

- **The Initial Aftercare involves**:

  Guidance notes for building users, technical guidance and walkabouts so that occupants get to better understand the building and its operation demand.
- **The Extended aftercare takes up to 3 years and it involves:**
    - **Year 1: fine-tune systems, occupant feedback and changes in weather and occupancy patterns**
    - **Year 2: recording operation and reviewing performance through:**
        1. Meetings
        2. Logging environmental and energy performance

3. Systems and energy review
4. Tuning of systems
5. Records and usage change
6. Walkabouts
7. Measure environmental, energy and human factor performance
8. End year review

From the above performance evaluation, number 7 is the main focus of this study within 2 years of data collection, as explained in the goal and scope definition (chapter 3). The point of this task is to compare annually recorded performance with design targets. The performance metrics can be a mix of scientific data, statistical data and anecdotal feedback. The most informative performance feedback may come from occupant stories rather than hard data. Independently-curated occupant surveys help to put energy consumption and other scientific data into human and operational context.

This study goes beyond the typical POE approaches mentioned from the literature, looking at investigating and evaluating the interrelationship of building design, energy and raw-material indicators within the development of one sustainability indicator that provides more detail on current state simplified scientific approaches that can be used by facility managers and building managers and can also be understood by the occupants. Therefore the following methods have been used for the diagnostic review:

(iii) Thermal imaging part of the POE's diagnostic review

The deeper diagnostic review has been conducted to a certain extent to evaluate-monitor the building performance, through a thermographic survey (Blyth & Gilby 2006). Further monitoring of the office building energy and environmental performance through this review would normally take from three to five years. Thus a PhD focusing only on this type of review or a research fellowship focusing on the three review types would be ideal (Blyth & Gilby 2006).Thermal imaging is a fundamental instrument used on POE projects. It is applied to detect whether there are any heat losses or moisture detection or whether heat is generated and transferred in electrical equipment. Thermographic surveys are mainly qualitative methods as they show locations of anomalies and they do not attempt to quantify the heat loss from the anomaly (FLIR 2009) (Pearson.C. 2011). Infrared (meaning below red) is the name given to the part of the electromagnetic spectrum just beyond the red end of the visible spectrum. It travels through space similar to visible light but at longer wavelengths (approx. 0.7 microns to 1000 microns). The amount of the two wavelength bands used for thermal imaging, shortwave (sw) and longwave (lw) varies within its surface temperature. The transmissivity of the air or other material between the source and the observer can impact infrared radiation. Thermal imaging produces a picture that maps the intensity of IR radiation across the field of view (Pearson.C. 2011).

- **Regulations**

The focus is on the *2010 England & Wales Building Regulations* and supporting guidance, specifically *Part L (Conservation of Fuel and Power)*. Supporting guidance is included in *Scotland (Section 6)* and *Northern Ireland (Part F)*. A separate supporting guidance for Wales will be published in 2013. Building Regulations for England and Wales require that ***"reasonable provision shall be made for the conservation of fuel and power in buildings by...limiting heat gains and losses...through thermal elements and other parts of the building fabric"*** (Pearson.C. 2011)***.*** This is further supported by guidance in four approved documents:

- L1A-New Dwellings
- L1B-Work in Existing Dwellings
- L2A-New Non-Dwellings
- L2B-Work in Existing Non-Dwellings

<u>These four documents provide the following guidance:</u>

''the building fabric should be constructed so that there are no reasonably avoidable thermal bridges in the insulation layers caused by gaps within the various elements such as those around window and door openings'' (Pearson.C. 2011)***.***

- **Specifications**

In its 2011 edition BREEAM gives credit for thermal imaging of new building provided that remedial action is taken for any serious defects found in the survey (Pearson.C. 2011).

- **Thermal performance**

There is a temperature difference between the inside and the outside of the building so that heat flows through the building components. The resistance of heat depends on the properties of the materials and their thickness. For instance brick structure has poor resistance to heat flow so insulation is vital. Also high thermal resistance of thin layers of air can act as insulators called boundary layers and this results in differences between the surface and the ambient temperature. In rapid air movement in windy conditions the boundary layer is diminished and the surface tends to be ambient temperature. Thus the U-value plays a significant role in infrared imaging (Pearson.C. 2011).

- **Applications**

An infrared (IR) application in buildings can assist:

- Visualise energy losses
- Detect missing or defective insulation
- Source air leaks
- Find moisture in the insulation, in roofs and walls
- Detect mold and poor insulated areas
- Locate thermal bridges
- Locate leaks in flat roofs
- Detect breach in hot water pipe
- Detect construction failure
- Locate radiant floor heating faults
- Monitor the drying of buildings
- Detect electrical faults
- Find faults in supply line and district heating

The thermographic survey is conducted by the PhD researcher in each building case. Examples of similar work done have been examined and advice from key suppliers' guidance notes before the survey has been taken into consideration. Advice on how to use the infrared camera has also been given by senior users. The equipment that has been used is an infrared camera by FLIR, with resolution at 640x480 pixels (FLIR 2009). The survey is conducted only externally. External surveys give a useful overview of the building. For practical purposes the temperature difference between the outside and the fabric should be at least 10^0C and the wind speed for external imaging must be no more that 5 m/s and the weather should be neither hot/sunny nor very cold. Best results are obtained on cold, cloudy, dry still winter nights (Pearson.C. 2011). The survey has been applied in two conventional concrete office buildings, in a sustainable new office building made of concrete stone and in a sustainable refurbished office building with brick and metallic facades. The purpose of the application in these buildings is mainly to detect heat losses as well as to observe the material fabric resistance from building to building in an attempt to understand whether heat is maintained inside the building in the winter and cool in the summer.

2. ***Heating degree days (HDD)*** **part of the POE's diagnostic review**

HDD evaluation is a quantitative energy performance method (section 5.6.5). It is a steady-state method for energy calculation under inverse modelling (Wang, Yan, & Xiao 2012 p. 879, 880) . Heating degree days are a measure of the severity and duration of cold weather. The colder the weather in a given month the larger the degree-day value for that month. HDD is also a summation over time of the difference between a reference or base temperature and the outside temperature. When the outside temperature rises above the base temperature, HDD are zero. The summation for each calendar month is published as historical data. This data can be used to detect energy waste and system faults, as well as to set realistic savings targets and heating budgets (Carbon Trust 2012b). The base temperature is defined as the outside temperature above which the heating system in a building would not be required to operate. The average temperature is 15.5^{0}C although buildings with passive strategies would have lower base temperatures (Carbon Trust 2012b).

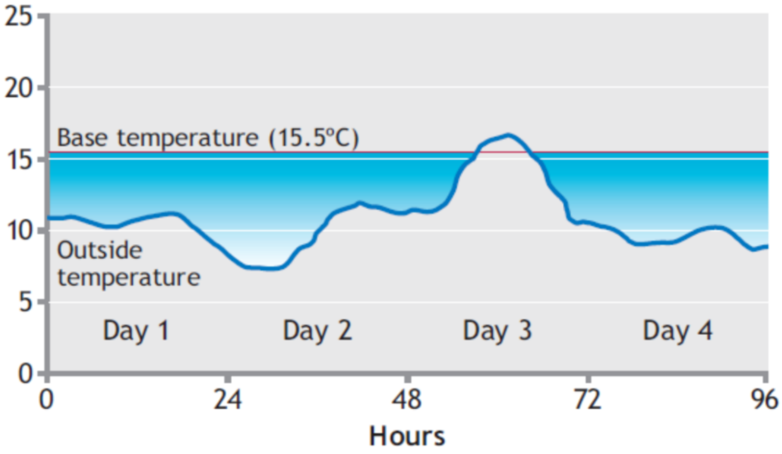


Figure 4.5: Heating Degree Day Base Temperature/hours

Source: (Carbon Trust 2012b)

The HDD was collected separately for each building by region from the DECC guidance oh HDD calculation (Carbon Trust 2012b) (appendix 3,4,5). Based on the DD by region map (appendix 4), Edinburgh in East Scotland has base temperature 14, Winchester in Hampshire South of UK has 3 and Birmingham in Midlands has 6. The data needed for the HDD evaluation is:

- Metered energy consumption readings (ideally metering at the end of each month).
- Plotting scatter graph with monthly energy consumption/monthly degree days for the same year (Carbon Trust 2012b).

For the LCA comparison analysis HDD are calculated for the years 2009 and 2010. HDD results indicate the energy performance of a building, whether meter readings were taken correctly, and the performance line of the scatter graph indicates how much energy the building is expected to use for a given number of DD. During the time of the data collection, some values from the energy metering data for certain months were missing. The assumption will be to use the values from either 2009 or 2010 to fill the gaps (appendix 5). The CDD (cooling degree data) was not evaluated and the office buildings are mainly considered as naturally ventilated.

4.4.3 Model 3: Third wave data collection-POE on environmental impact performance evaluation

This model is about LCA data collection and evaluation using case study comparison analysis. This part is also about developing long run hypothetical scenarios for long run considerations. It involves data collection to evaluate the environmental impacts of heating and cooling systems during operation and during production, examining the two indicators raw-materials and energy used (table 4.6).

Table 4.5: Model 2 During-LCA data collection

During the production and the operational phase of the life cycle		
Contents	LCA Raw-materials & energy	LCA comparison to test hypotheses
Philosophical dimension	Epistemology-Axiology: Positivism-empiricism, both qualitative &quantitative methods, hypothetically driven	
Kind of data needed	Heating and cooling system specification: size, weight, materials, energy efficiency Material specification Electricity consumption for heating and cooling	
Stakeholders	Facility management Product designers Building services consultants (academia) Mechanical engineers Manufacturers Suppliers	
Data sources	Schematic drawings Heating and cooling system specifications Electricity figures	
Instruments	Measuring tape, LCA software-SimaPro, digital camera	
Methods	Questionnaire survey, desktop research, specific or alternative building services specification, recording, specific or alternative material specification, expert advice, hypothetical scenarios, Eco-indicator99	
Outcome	LCA individual case analysis, LCA case study comparison analysis including hypothetical scenarios.	

1. Raw-materials

To collect data from the production phase of the LCA structured questionnaires were used using existing survey examples (appendix 3). Where data through questionnaires could not be provided, alternative ways of collecting data was through the literature, looking at similar LCA studies or by desktop research looking for specific equipment and material specification or for similar specifications. Where archive data did not hold such information, a measurement survey of the equipment used in the heating and cooling systems was carried out, recording which equipment was in operation (appendix 20). Two experts in the field of product design and mechanical engineering were selected to assist in creating assumptions. A senior lecturer in mechanical engineering, Darious Tabrizi, at the University of Central Lancashire, and a product designer, Dr. Adam Bedford, based at the Centre for Energy and Power Management at the University of Central Lancashire.

2. Operation

For the operational phase of the building, electricity figures for heating and cooling were collected. Mechanical engineering specifications-descriptions, supplier specifications and loggings are important to map the heating and cooling process during its operation. Schematic drawings were collected, showing heating and cooling equipment and its location in the building. A measurement survey was conducted to record the equipment installed in old buildings were HVAC schedules were not available. Specific suppliers were contacted to collect data on raw materials and to ask for advice. Alternative data was collected from similar schematic drawings (as suggested by the suppliers).

3. Development of hypothetical long run scenarios

A new sustainability indicator has been developed throughout this study (explained in detail in chapter 8). The indicator is called **'Overall Long Run Life Cycle Impact Indicator'** (OLRLCII). The OLRLCII includes hypothetical long run scenarios to hypothetically evaluate the long run consequences of the raw-material emissions and the energy emissions (figure 4.6). The long run scenarios have considered worst case, medium case and good case scenarios for the energy efficiency and raw-material efficiency increase or decrease in the next 25, 50 and 100 years, during winter and summer months (presented analytically in the development of the new indicator, chapter 10) .

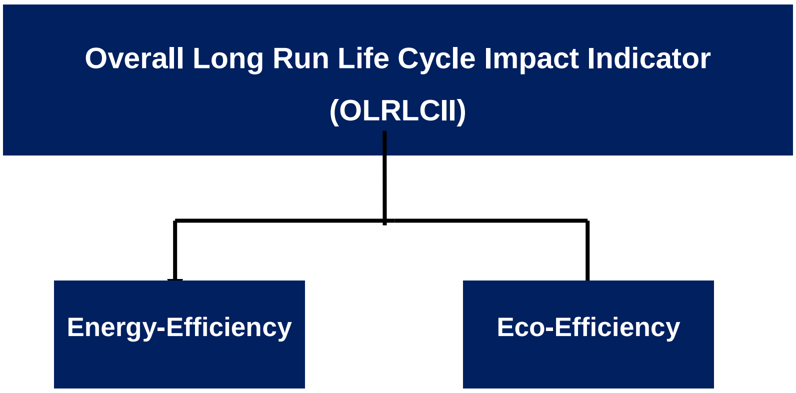


Figure 4.6: The new proposed sustainability indicator

The outcome of the hypothetical scenarios is to answer which office building is assumed to be a better long run practice in terms of its environmental performance (table 28).

4. LCA sensitivity analysis

In addition to the development of the hypothetical scenarios, LCA sensitivity analysis has been applied to assess the potential refurbishment of heating and cooling systems with alternative low or zero carbon technologies. 1 KWh of energy consumption has been used to evaluate the impacts caused between a range of different technologies and in comparison with the technologies used in the case study office buildings.

5. Uncertainty analysis

This type of analysis has been used to evaluate the significance of the uncertainty issue of the LCA results after using the existing raw-material data of the SimaPro software and the energy data.

6. Discussion on interrelationship of the results according to the seasonal data evaluation

In analysing the LCA results and in developing further the application and understanding of the new sustainability indicator, the following inter-relations have been addressed, in an attempt to identify best practice office buildings for heating and cooling during different periods of time, for energy and raw-material efficiency.

Table 4.6: OLRLCII analysis in this thesis

Comparison Analysis	
Energy efficiency-Winter months	
Case study 1	Technology on the sustainable office building (?) compared to the conventional office building
Case Study 2	Technology on the sustainable office building (?) to the conventional office building
OLRLCII for Energy efficiency-Summer months	
Case study 1	Technology on the sustainable office building (?) to the conventional office building
Case study 2	Technology on the sustainable office building (?) to the conventional office building
OLRLCII for Material efficiency	
Case study 1	Technology on the sustainable office building (?) to the conventional office building
Case study 2	Technology on the sustainable office building (?) to the conventional office building
OLRLCII Overall	
Case study 1	Sustainable office building (?) to the conventional office building
Case study 2	Sustainable office building (?)to the conventional office building
Better Practice	Case study 2 (?) Case Study 1

4.4.4 Model 4: Discussion and validation

This model is about providing discussion and validation on the research findings (table 4.8).

Table 4.7: Model 3, Meta-LCA analysis

Heating and cooling system	
Contents	Discussion-Validation-feedback
Philosophical dimension	Axiology
Kind of data needed	Qualitative &quantitative methods
Stakeholders	Stakeholders from different backgrounds: Architects Mechanical engineers Energy assessors Facility management Building manager Construction management Energy and power management
Data sources	Evaluate
Instruments	Structured questionnaires, send results via e-mail
Methods	Expert advice, sensitivity analysis, online questionnaire survey asking for expert advice-comments on research findings which can be used as validation, research publications (see a list of publications in the first pages of the thesis).

An online questionnaire survey was used to support the discussion on the research findings, sent to different stakeholders from different institutions (appendix 21). The online survey was sent out to (n=10) experts in the field of the built environment. The online survey included 15 questions that focused on:

1. People’s expertise.
2. People’s knowledge on the life span of building services, which helped to consider the long run hypothetical scenarios for refurbishment.
3. People’s perception on the life span of building services to enhance long run energy efficiency.
4. People’s knowledge through rating of influential factors of energy-efficiency for cooling systems, fed by CHP unit during summer.
5. People’s knowledge through rating of influential factors of energy-efficiency for heating systems, fed by CHP unit during summer.
6. People’s knowledge/perception of how to enhance CHP energy efficiency in the long run.
7. People’s perception on possible hypothetical scenarios for increase, decrease or retention of existing embodied raw-material emissions in the long run.
8. People’s perception on the effectiveness of suggested solutions in order to enhance raw-material emission decrease in the long run, through rating.

9. People’s perception on the importance of using the raw material indicator in the decision-making for choosing sustainable building services and ensuring sustainability in office buildings.
10. People’s perception on the highest significance between energy-efficiency and eco-efficiency, using rating.
11. People’s perception on the most effective combination-optional recommendation in order to achieve zero carbon in non-domestic buildings from 2016, through rating, considering only energy -efficiency.
12. People’s perception on the most effective combination-optional recommendation in order to achieve zero carbon in non-domestic buildings from 2016, through rating, considering both energy efficiency and raw material efficiency.
13. People’s perception on the proposal for raw-material indicator integration in the existing eco-labeling as a medium to enhance the production of low carbon embodied technologies and systems.
14. People’s perception on whether this survey influenced their decision making.
15. People’s feedback and comments for the study.

Validation of the results of the LCA analysis is a significant step to give good reason for the magnitude of the results. Expert advice has been provided by the internal experts (as mentioned, from the University of Central Lancashire). External experts involved in the questionnaire survey are the key stakeholder-contacts; facility managers and architects. The validation process also involves parts of the results discussed in international and national conferences, in peer-reviewed conference proceedings and journals. The following sections explain in detail the data limitation and constraints, assumptions used to overcome limitation and methods used to validate this study.

4.5 Data limitations and constraints

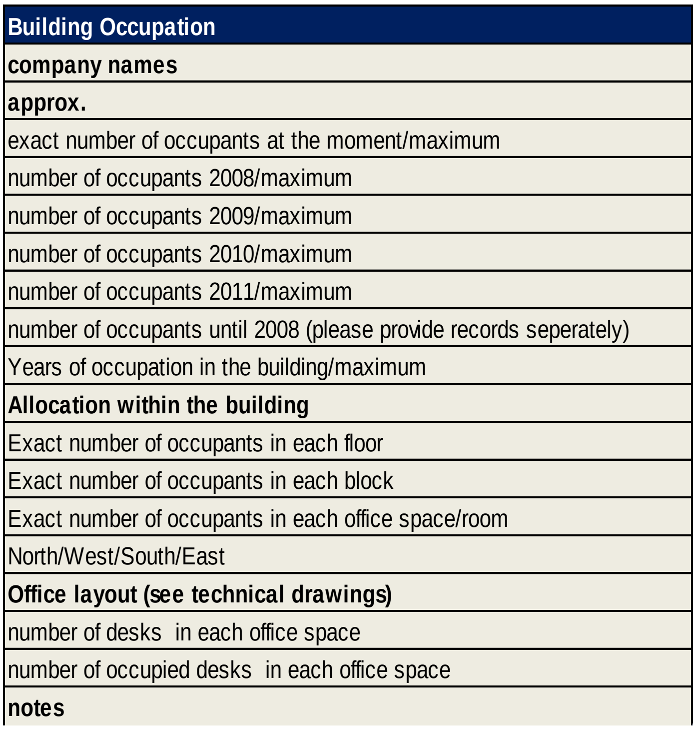
Although the research has achieved its aim there were some unavoidable limitations.

The limitations identified were recorded in parallel with collecting data, practicing SimaPro and analysing data. This section summarises the limitations identified specific to the LCA data inputs, energy and raw-materials. The discussion section provides further explanation on the limitations. Energy data has been collected for the operational years 2009 and 2010 where the raw-material data has been collected since the installation of the existing equipment in office buildings (any raw materials used on equipment before system upgrades and building retrofitting were not considered.)

Data limitations were identified in:

- Archive data in energy consumption and raw-materials of the equipment studied. The conventional offices do not have mechanical specifications and schematics of the heating-cooling systems. Thus assumptions were used (section 5.3).
- On existing data (mechanical specifications, energy metering) on raw-materials and energy consumption. Energy data was not available for all the months for the years 2009-10. Therefore assumptions were used (section 5.3).
- Raw-material processes were difficult to collect from the manufacturers even though structured questionnaire were used (appendix 2).
- Existing inventory data in SimaPro does not include the exact raw-materials found to be used in the equipment so close alternatives were chosen.

One of the constraints of the research was the case study building access for the fieldwork. Fieldwork data in office buildings was difficult because it was not possible to interrupt office staff for questions. Also all the data providers from all the offices did not want the staff to be contacted directly for questionnaire surveys so office building contacts were limited. This is also due to the fact that there are various stakeholders involved in office building management-development. However data collection responses arrived on time. Another important constraint was to undertake interviews with the occupants of the office buildings. This study intended to collect detailed data on the occupancy level of the office buildings as presented in figure 4.7. The human resources and the building managers were approached to find out this information; however only an approximate number of building occupancy was provided. Other information on the multi-occupancy of Five Ways House, which is a government building, was found from the internet. The FM manager from Argyle House has only explained which floor areas were unoccupied. The Potterrow building has single type occupancy (students and university staff) and EIIC staff from the Winchester County Council.



Building Occupation
company names
approx.
exact number of occupants at the moment/maximum
number of occupants 2008/maximum
number of occupants 2009/maximum
number of occupants 2010/maximum
number of occupants 2011/maximum
number of occupants until 2008 (please provide records seperately)
Years of occupation in the building/maximum
Allocation within the building
Exact number of occupants in each floor
Exact number of occupants in each block
Exact number of occupants in each office space/room
North/West/South/East
Office layout (see technical drawings)
number of desks in each office space
number of occupied desks in each office space
notes

Figure 4.7: Building occupancy factors

Another important constraint that delayed the production of the LCA results was the fact that that initially the LCA SimaPro software was ordered by the university in classroom version so that more people could use it. The issue with that was that only one person could use it at a time. Apart from the networking issues, update authorisation from the IT services and renewal on the license were not happening on time and the software could not operate for a certain period of time. Also the classroom version had limited access to inventory data and it had no uncertainty analysis option. Due to these constraints the Pre Consultants from the Netherlands were approached to ask for permission to get the PHD version license for free, to be installed on a private laptop. This worked, although it was a trial version and operated only for a month. All the previous results were changed to the current version.

4.5.1 Assumptions

According to the data limitations mentioned in section 5.2 the following assumptions were used:

1. **Production phase: Raw-material content**

In order to estimate the raw-material content on equipment used in both heating and cooling systems, the equation in table 4.9 was used.

Table 4.8: Equation for the calculation of the amount of raw-material used in equipment

Equation 1: Assumptions to find out the amount of material used in an element of the heating or cooling system
((Width*height*depth) =volume) – (thickness of material assumed to be used from each dimension) = input dimensions)) ((output dimensions) - (input dimension)) x (density of material) = amount of material in the element

Source: Interview with mechanical engineer, Dr. Adam Bedford, Centre for Energy and Power Management, University of Central Lancashire

2. Production phase: manufacturing processes

Data on the manufacturing processes has not been collected because of the time and archive limitations mentioned already. Few manufacturing processes have been identified in the literature, on heat pumps, air-conditioners and radiators. This data has been used as reference data in the appendices to show the processes of manufacturing (appendix 6).

3. Operational Phase: Energy consumption for the heating system

One of the key issues identified from the fieldwork is the availability of the heating metering from the conventional office buildings. In order to address the energy consumption for heating or cooling, the existing literature was reviewed on calculations of energy consumption. The equation that has been used is shown in table 4.10.

Table 4.9: Equation for the calculation of heating consumption

Equation 2: Heating Consumption
Considerations
1. The boiler's output is 1500Kw 2. The heating is on from 6am to 4pm from October to January=10 hours per day minus 1 hours (for lunch) 9 hours per day, thus 1500x9=13500KWh/day 3. From Feb-April the heating is on from 6am-3:30pm =8.5 hours/day, thus 1500x8.5=12750kwh/day
Calculations
• Oct has 31 days-8days of the weekend, therefore 13500x23days=310500 • Nov has 30 days-8days of the weekend, therefore 13500x22=297000 • Dec has 31 days-10days,13500x21=283500 • Jan has 31 days-8days, 13500x23=310500 (34 days between Oct-Jan heating is off during the weekend) • Total from Oct to Jan=1201500kwh • Feb has 28 days-8days of the weekend=12750x20=255000 • March has 31 days-10=12750x21=267750 • April has 30days-8=12750x22=280500 • Total from Feb-April=803250 • Total in the year: 1201500+803250=2004750kwh/1000=2004.75MWhx2years=4009.5MWh

The above equation does not consider indoor and outdoor temperatures and heat losses of the building. The central heating system of Argyle House has no significant control over its distribution, which means that when the heating is on, occasionally all the radiators in the building will provide heating even in the unoccupied areas. So occupancy is not a great factor here but it does play an important role for impacting energy consumption. Another way to measure the heating consumption is by the order and the consumption of the litres of oil and converting this into MWhs of heating output. For that the equation in table 4.11 was used, which equation was suggested by experts in the field.

Table 4.10: Equation for the assumption of the heating consumption for Argyle House

Equation 3: Heating consumption assumption for Argyle House
Considerations
• At the height of winter, the building consumes 18,000 litres of oil every 10 days • For the remaining months 18,000 litres of oil is ordered twice per month.
Calculations
• Dec every 10 days 18,000 litres, therefore 3 times per month, 18000x3=54000litres • January 54000 litres • Feb 54000 litres • March 2 times per month, therefore 18000x2=36000 • April 36000 litres • May 36000 litres • June off • July off • August off • Sept off • Oct 36000 litres • Nov 3600 litres • Total 342000 litres, in gallons 90346.8419
Further considerations
• 1 gallon of crude oil produces 40KWh of heat with poor efficiency 42% about 17KWh • Gasoline produces 36.6KWh • 0.0423 gallons=1KWh • 1 litre diesel= 10KWh • It is assumed that gasoline is the type of oil used in Argyle house, therefore if 0.0423 gallons are consumed in 1 KWh, in 90346.8419 x? • X=1x(90346.8419/0.0423)=2135859.147KWh=2135.859147MWh

Source: Interview with mechanical engineer, Dr. Adam Bedford, Centre for Energy and Power Management, University of Central Lancashire

Assumptions were also used for the Potterrow building, directed by the FM manager. The Building Log Book (Kilpatrick 2009) provides a heating-LTHW meter diagram (appendix 19), so these meters have been calculated from the metering readings provided on an Excel spreadsheet. In order to estimate how much heating and cooling has been consumed by the Potterrow office building, a workbook with the energy data for both the Informatics Building (phase 1) and Dugald Building (phase 2) was provided. The meter readings were only added to the AMR system in June 2010 for electricity and in November for the heating and cooling, so little data was available yet. The calculations used were based on the equations provided by the facility management team (table 4.12).

Table 4.11: Equation for the assumption of the heating consumption for the Potterrow building

Equation 4:Heating Consumption assumption for the Potterrow building

- To calculate the total heat for the Dugald Steward Building the consumption meters have been added:

  283NH001S+283NH002S+283NH003S
- To calculate the total heat for the Informatics Building the consumption meters have been added:

  282NH001S-(283NH001S+283NH002S+283NH003S)
- To calculate the total cooling load for the Dugald Steward Building the GIA (?) has been used:

  GIA for the Dugald Stewart=5381 m^2

  Cooling load for the Dugald Steward Building: (282NC002S-282NC003S)*5381/ (13959+5381)
- To calculate the total cooling load for the Informatics Building the GIA (?) has been used:

  GIA for the Informatics=13959 m^2
- Cooling load for the Informatics Building: meters (282NC002S-282NC003S)*13959/ (13959+5381)

Source: Facility Management team of the Potterrow Building.

Based on the above calculations, table 4.13 presents the MWh of electricity, heating and cooling in the different phases of the building.

Table 4.12: MWh calculations of the electricity for the Potterrow building

KWh calculation based on GIA		Conversion of KWh to MWh (multiplied by 0.001)	Period		Assumptions of the MWh for the period 2008-2009 and 2009-2010 (in total 2 years)
Electricity for Informatics	1398174	1398.174	May 2010-Dec 2010	8 months	If we assume that 174.77175 MWh is consumed per month, for 24 months= 4194.522
Electricity for Dugald	202738	202.73800	May 2010-Dec 2010	8 months	If we assume that 25.34225 MWh is consumed per month, for 24 months=608.214
Total gas use	209000	209	Jul 2008-Oct 2010	2 years and 2 months	209x2=418
Total heating for Informatics	172610	172.61	Jun2010-Dec 2010	1 year	Multiplied by 2 years 345.22
Total heating for Dugald	208190	208.19	Jun2010-Dec 2010	1 year	Multiplied by 2 years 416.38
Total cooling for Informatics	21938.87	21.93	Nov 2010-Jan 2011	3 months	For the six months within 2 years 43.86
Total cooling for Dugald	8457.12	8.45	Nov 2010-Jan 2011	3 months	For the six months within 2 years 16.9

4.6 Data validation

4.6.1 Validation of the OLRLCII

In order to find out whether the new indicator is convincing, an online questionnaire survey has been used (appendix 21) to find out how recommendations made by using the OLRLCII are perceived by different experts in the field. Out of the 7 responses, 6 agree that the questionnaire has unfolded considerations that will influence their decision making. The questions raised were about the life span of the building services in order for the energy efficiency to be enhanced in the long run. This has been considered in the hypothetical scenarios and in the recommendations made.

Existing and long run recommendations about the seasonal efficiency of the CHP for heating and cooling have been rated by the experts. This has helped to prioritise the measures and to understand their significance in order for the energy efficiency to be enhanced. The hypothetical long run scenarios about the raw-material emissions have also been rated by the experts. It is believed that either the total environmental impacts will remain the same over time due to correct and regular service or due to the recycled materials that will be used. All experts have rated this indicator as very important for consideration. To avoid embodied raw-material emissions increasing in the long run several suggestions given have been rated by the experts, considered in the recommendations made in the previous section.

4.6.2 Validations of the ERMEI

To evaluate this indicator an online questionnaire survey was conducted with questions regarding the importance of material efficiency compared to energy efficiency (appendix ?, questions 3,9,10).Interviewees stated that this is a very important indicator although less important than energy efficiency. The research argues that by considering the amount of current equipment used to enhance energy efficiency the ERMEI is fundamental in reducing the overall embodied emissions of the buildings.

4.6.3 Validity and reliability of the research findings

Discussion on the LCA research study limitations and on the issues of validity and reliability was questioned from the conceptualisation stage of this thesis prior to the research methodology. A whole chapter has been devoted to the philosophical and theoretical dimensions of this PhD research. The research theory used is grounded theory and the approaches used have been driven by the positivism and the constructivism paradigms.

The LCA methodology used to evaluate the environmental impacts is mainly a scientific method although qualitative methods and approaches were used to collect data and to ensure that research findings were valid and reliable. The LCA ISO standards (14040, 2006) make clear the importance of data validity. Also several LCA studies have focused on emphasizing the importance of LCA reliability, suggesting approaches to improve reliability (Bjorklund 2002 ;Dimitrokali, Hartungi, & Howe 2009a; Dimitrokali, Hartungi, & Howe 2009b; Van den Berg et al. 2013). In order to establish the quality of empirical social research four tests are used, common to social science methods (Calder et al. 1982; Junilla 2004; Koskelo 2005;Yin 2009), 1) internal validity, 2) external validity, 3) construct validity and 4) reliability.

Internal validity

Internal validity is for explanatory or causal studies only, seeking to establish causal relationship, whereby certain conditions are believed to lead to other conditions, as distinguished from spurious relationships (Yin 2009 p. 40). In explanatory case studies the investigator must intend to answer how and why *x* led to event *y*, knowing why that same factor *z* has caused *y*. Causal relationship x and y threaten internal validity (Yin 2009 p. 42). The investigator must ''infer'' that a particular event resulted from some earlier occurrence, based on interview and documentary evidence, questioning the reliability of the inference (Yin 2009 p. 43). According to Yin (2009), evaluating validity may be facilitated by asking: is the interference correct? Have all the rival explanations and possibilities been considered? Is the evidence convergent? Does it appear to be airtight? Koskelo (2005, p. 215) adds questions of Peura (1996, p. 279): how generalisable does s/he think the results of the research are, how much does s/he think that external issues have affected the results, what are the researcher's own values, what are the relationships between the researcher and persons involved in the research (Peura 1996).

The intention of this thesis was not to create causal relationships between the areas of study but to get an understanding based on realism, on real life cases. It also seeks to ensure that the outcome of the research can be used by other LCA practitioners and practices from different office building stakeholders to support their decision making for building refurbishment, new building construction or for upgrading existing heating and cooling systems. The purpose of the study and its potential use has been clearly justified in the goal and scope definition. Therefore, since the results are for external use, reliable data collection was mandatory.

A multiple case study comparison approach has been used, using LCA and a cross-case building characteristics analysis, shown in the MATRIX table (appendix 7). The case study buildings have been selected according to ISO standards criteria for LCA comparison. Data collection selected methods have been chosen following the ISO standard reported guidance and reported guidance from the Pre Consultant of Life Cycle Assessment. For other methods used like the Heating Degree Data Evaluation, published guidance has been used by the Carbon Trust. Guidance for how to use the infrared camera and interpret the results was taken from the BSRIA, considered to be a reliable source. Data was collected individually for every office building selected. A timetable was provided in the methodology chapter (section 4.4.2) that lists the data collected from different sources of evidence (documents, archival records, interviews, observations, recording, etc) and the period that was collected. Several site visits have taken place in the case study buildings to make close observation while having recorded discussions with key case study building stakeholders such as architects, building managers, staff representatives and facility managers. Even though data collection comes from reliable sources, limitations have occurred in data availability for certain cases (Potterrow building, Elizabeth Court), such as incomplete energy metering reading and incorrect methods of taking metering readings, which were identified from the HDD evaluation. This has an impact on the results.

Due to these issues assumptions were used to ask for advice from experts in the field. The approaches used are presented in detail in the methodology chapter. Data for the raw material content has been difficult for the reasons mentioned in the limitations. Advice on assumptions has been taken from other experts in the field, from published literature on raw materials, from peer-reviewed similar LCA studies mentioned in the methodology chapter. Therefore it can be said with confidence that the results are representative of the actual situation.

External validity and construct validity

External validity defines the domain to which a study’s finding can be generalised (Yin 2009 p. 40). The developed theory is the level at which the generalisation of the case study result will occur (Yin 2009 p. 38).

This role of theory has been divided into:

a) Analytic generalization and
b) Statistical generalization.

In statistical generalization an inference is made based upon empirical data and access to quantitative formulas for determining confidence (Yin 2009 p. 38).

In analytical generalisation multiple cases are used in which a previously developed theory can be used as a template with which to compare the empirical results of the case study (Yin 2009 p. 38). Through replication logic the empirical results are considered as more potent when the same theory is supported and not a plausible rival theory (Yin 2009 p. 39). In constructing validity, it has to be shown that what is to be measured can really be measured.

Yin (2009), suggests five tactics to construct validity, also mentioned in Koskelo’s study (2005):

1. Choose cases that most evidently have something to offer regarding the research problem,

2. Demonstrate that measurements/measures used are connected with the phenomena studied through realistic judgment, questionnaire surveys and how method is perceived,
3. Use of multiple sources of evidence, like data source triangulation and methodological triangulation,
4. Use chain of evidence,
5. Have case study reports reviewed by key informants.

In this study the case studies are distinctive cases of conventional and BREEAM sustainable office buildings in the UK, from which various informants have been used, supplying different kinds of data, from different levels of the office building sector.

As a form of validation of the measurement and measures of this study, an online survey has been conducted collecting answers by targeting different experts with a multidisciplinary background from the field of architecture, facility management, construction, mechanical engineering, waste management, civil engineering and from product design (of building services). The online survey aimed to collect opinions and different perceptions on the research findings, to validate the logic of the research findings and to inform stakeholders on areas revealed that need further considerations.

Confidence and reliability of the research design and on the research findings and outcomes has been enhanced through research publications. The LCA data analysis of the sustainable new office building in Edinburgh has been peer-reviewed and accepted for publication (Dimitrokali 2011). Positive feedback on the research findings has been given for the presentation of the results in front of an audience with experts in life cycle analysis (Dimitrokali et al. 2011a) from the Centre for Life Cycle Analysis at Columbia University, New York. Understanding of the passive solar building characteristics has been confirmed through a journal accepted for publication (Dimitrokali, Howe, & Hartungi 2011b).

Whether the research findings are of interest can be shown by the fact that the development company of Five Ways House, Telereal Trilium, has shown interest in sharing the research findings from the thermographic survey outcomes so that a stronger case can be put for potential refurbishment of the building. Also the facility manager of Elizabeth Court has been informed about the research outcomes from the HDD evaluation via e-mail, asking for clarifications of the data in case there were any mistakes in the data collection. The manager has confirmed the research findings identified. This has helped to ensure validity of the research findings and to inform on areas that need further considerations and improvements.

Using triangulation it can be seen that the research outcomes are relevant to the research being conducted and in accordance with other LCA findings. As in Koskelo's (2005) example, cross-case analysis has been used. A database MATRIX table has been developed to allow for future comparisons with other case study office buildings by other practitioners. Additionally, part of the theoretical replication, the LCA evaluation has also performed a sensitivity analysis to increase understanding and enhance reliability by comparing a smaller unit of energy consumption (1KWh) across the different low carbon and zero carbon technologies. The results can be used to support decision making for potential improvements in existing office buildings or to be used as considerations for new developments. Finally, this PhD thesis has examined hypothetical scenarios and provided a template which can also be used from other LCA practitioners and decision makers in considering best case, medium case and worst case scenarios in the long run. Upon these scenarios recommendations are provided. To further support replication and understanding of the research findings on the case study buildings, a new rating system has been suggested and produced to evaluate the ERMEI indicator (material efficiency) and the energy indicator (material efficiency) of the buildings. The ratings show former, current and potential rating that needs to be achieved. Based on these ratings, the recommendations were provided.

Reliability

Reliability of the research findings means that the operation of the study, such as the data collection procedures, can be repeated and bring the same results (Yin 2009 p. 40). The aim of reliability is to minimise the errors and biases in a study (Yin 2009 p. 45). Yin (2009, p. 45) suggests two tactics that boost reliability: a) the use of the case study protocol and b) the development of a case study database. Koskelo (2005) has concluded that replicability is indeed impossible; it is unlikely that there are two similar case projects available. Junilla (2004) concludes that her study was supported by conducting all the case studies according to the same research protocol and by reporting both the protocol and the results at a detailed level.

The intention of this study has been to be as comprehensive as possible although certain research limitations while conducting LCA have made replicability in terms of getting exactly the same results impossible to a certain extent. The limitations identified are explicitly documented in the methodology chapter, so that other researchers can use it. Equations were used to calculate raw-material mass, as advised by experts in the field.

By the time data was collected (2010-2011) on energy consumption, metering data was not available for certain months and thus assumptions have also been used (see methodology chapter).

The reliability of the study is case sensitive and time sensitive. After trying without success to contact manufacturers, data on raw-materials was acquired by desktop research. Hundreds of different sites have been visited, which is difficult to document. The research on LCA is ongoing and iterative. By the time another researcher else will try to replicate this study, internet information may change or not exist. This study has done its best to document these challenges.

4.7 Timetable of tasks and research activities

A list of the case study data collection and analysis activities is presented in table 4.13.

Table 4.1324: Data collection activities

Baseline data collection activities	PhD research period					Individual office building cases			
	2009	2010	2011	2012	2013	Potterrow	Elizabethh II Courts	Argyle House	Five Ways House
Literature review	🟨	🟨	🟨	🟨	🟨				
Methodology	🟨	🟨	🟨	🟨	🟨				
First wave data collection									
Recruitment of case studies									
research brief		🟨				🟪	🟪	🟪	🟪
consent form		🟨				🟪	🟪	🟪	🟪

Baseline data collection activities	**PhD research period**					**Individual office building cases**			
	2009	**2010**	**2011**	**2012**	**2013**	**Potterrow**	**Elizabethh II Courts**	**Argyle House**	**Five Ways House**
Building Characteristics									
open- recorded discussion		🟨				🟪		🟪	🟪
discussion		🟨					🟪		
walkthrough		🟨				🟪	🟪	🟪	🟪
observations		🟨						🟪	🟪
recording-photos		🟨						🟪	🟪
technical drawings		🟨				🟪	🟪	🟪	🟪
Occupancy data collection									
desktop research (e-mails to trusts, commissions, libraries, building estates)		🟨	🟨	🟨		🟪	🟪	🟪	🟪
semi-structured questionnaire self-completion (for all the occupational years counted for the LCA)		🟨	🟨	🟨		🟪	🟪	🟪	🟪
Second wave data collection									
Assessment of energy use									
previous POE/monitoring data collection		🟨				🟪	🟪		
BREEAM documentations		🟨				🟪	🟪		
energy performance certificates		🟨				🟪	🟪		🟪
electricity figures/metering		🟨				🟪	🟪		🟪
building schedules		🟨				🟪	🟪		🟪
schematic drawings		🟨				🟪	🟪		
maintainance frequences		🟨							🟪
Third wave data collection									
Eco-material assessment									
measurement survey on heating and cooling equipment		🟨						🟪	🟪

Baseline data collection activities	**PhD research period**					**Individual office building cases**			
	2009	**2010**	**2011**	**2012**	**2013**	**Potterrow**	**Elizabethh II Courts**	**Argyle House**	**Five Ways House**
recording of equipment where schedules are not available		🟨						🟪	
questionnaire survey through e-mail to collect opinions on material content		🟨	🟨			🟪	🟪	🟪	🟪
contact manufacturers with specific questions through e-mail		🟨	🟨			🟪	🟪	🟪	🟪
contact manufacturers with structured questionnaire		🟨				🟪	🟪	🟪	🟪
equipment specification		🟨				🟪	🟪	🟪	🟪
material specifictaions		🟨				🟪	🟪	🟪	🟪
review of LCA related studies	🟨	🟨	🟨	🟨	🟨	🟪	🟪	🟪	🟪
review the literature on materials	🟨	🟨	🟨	🟨	🟨	🟪	🟪	🟪	🟪
review the literature of specific building equipment characteristics	🟨	🟨	🟨	🟨	🟨	🟪	🟪	🟪	🟪
life cycle assessment		🟨	🟨	🟨		🟪	🟪	🟪	🟪
Heating Degree Data (HDD)				🟨		🟪	🟪	🟪	🟪
energy metering		🟨				🟪	🟪	🟪	🟪
Fabric Testing									
Thermal Imaging				🟨		🟪	🟪	🟪	🟪
Ongoing data collection									
on-going requests through e-mail and telephone conversation		🟨	🟨	🟨	🟨	🟪	🟪	🟪	🟪
Feedback-Validation									
online questionnaire survey to specific people with related backgrounds			🟨			🟪	🟪	🟪	🟪
conference/event paper presentations	🟨	🟨	🟨			🟪	🟪	🟪	🟪
expert advisory board		🟨	🟨			🟪	🟪	🟪	🟪
peer-reviewed articles-papers	🟨	🟨	🟨			🟪	🟪	🟪	🟪
other similar LCA studies		🟨	🟨	🟨		🟪	🟪	🟪	🟪
FM stakeholders comments		🟨				🟪	🟪	🟪	🟪

Baseline data collection activities	PhD research period					Individual office building cases			
	2009	2010	2011	2012	2013	Potterrow	Elizabethh II Courts	Argyle House	Five Ways House
Analysis									
life cycle assessment case study comparison-sensitivity analysis-uncertainty analysis-development of long run scenarios		🟨	🟨	🟨	🟨	🟪	🟪	🟪	🟪
discussion on empirical chapters			🟨	🟨	🟨	🟪	🟪	🟪	🟪
discussion on the development of a new sustainability indicator				🟨	🟨	🟪	🟪	🟪	🟪
Validation									
conference/event paper presentations and through feedback (see above)		🟨	🟨	🟨		🟪	🟪	🟪	🟪

4.8 Summary

This chapter has focused on the research design of the study by explaining first the philosophical and theoretical dimensions of this study using positivism but also constructivism point of views and how that reflected on the research design. Using grounded theory and the logic of emerging theories from case study approaches, this chapter explained the process of the case study selection by considering the key selection criteria unfolded from the previous chapters. Then, this chapter presented the research framework of this study that showed the research steps and the contents of each research step to achieve contribution to knowledge (explained in chapter 1). Further, three research models were developed to show the types of data collected and the sources that supplied this data, followed by a detailed description of the data limitations and the data assumptions, closing with methods used to validate the findings of the study.

CHAPTER 5: SUSTAINABLE AND CONVENTIONAL OFFICE BUILDING CHARACTERISTICS

5.1 Introduction

The purpose of this chapter is to present the building and heating and cooling system characteristics of the sustainable and conventional office buildings selected for this study as the background context of the environmental performance evaluation in the following chapters. Figure (5.1) illustrates the content of this chapter.

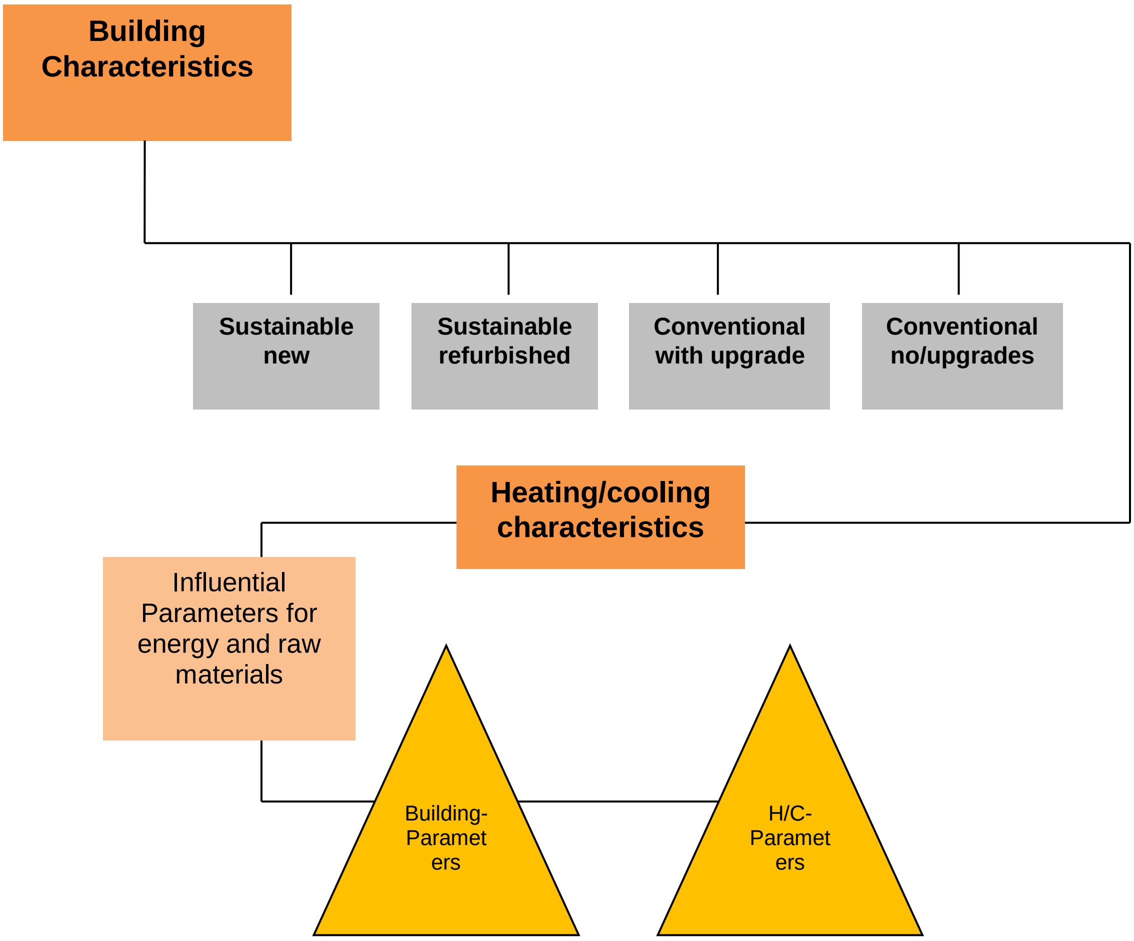


Figure 5.1: Content of chapter 5

By exploring the office building characteristics, this chapter aims to:

- Present the key differences between sustainable and conventional building technology
- Identify which features make a building sustainable
- Identify best practice in terms of its building and systems characteristics
- Unfold and rate influential factors and parameters based on their significance for influencing energy efficiency and raw-material consumption.

- Identify areas for improvements such as heating/cooling system upgrades or building refurbishments.
- Allow case study cross-case comparisons
- Add content to the MATRIX table (appendix 8)

5.2 Building Characteristics

1. Building aesthetics

The key differences between sustainable and conventional office buildings can mainly be understood by the building aesthetics. Conventional office buildings have old, pre-cast concrete structure with most surface areas covered by single-glazing, dating from the 1950s to 1990s. Sustainable office buildings have different sides of the buildings made by different structural materials, with a different design in the window pattern, according to passive design principles and building regulations (mentioned in chapter 2).

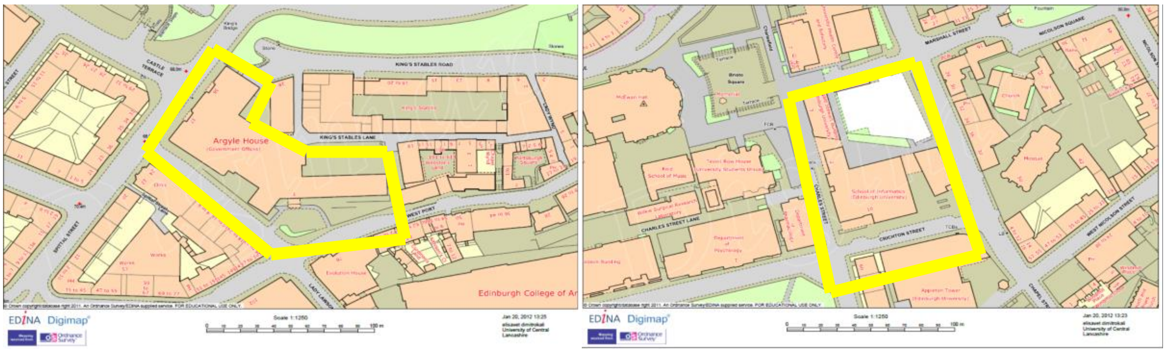
Argyle House, Edinburgh **Potterrow building, Edinburgh**

Five Ways House, Birmingham **Elizabeth II Courts (EIIC), Winchester**

Figure 5.2: The selected case study office buildings

2. Building design and structure

In terms of selection criteria for choosing these office buildings, the case study buildings have small differences in the gross floor area (see building size in MATRIX, appendix 8). A highly important difference between conventional and sustainable office buildings is the building orientation. This plays a significant role in the energy performance of the buildings if they have need been designed according to passive building standards. From the digimaps (figure 5.3) it can be seen that both conventional office buildings have north and south orientations, with their longer facades facing north and south, where the main working office spaces are located. Without insulation, with high ceilings, with single-glazed windows that cover most of the building surfaces and with open plan office spaces, it can be assumed that the heating demand is high in the winter (see more images from different sides of the buildings in appendix 9 and architectural drawings in appendix 10). On the other hand, the sustainable office buildings have east and west orientations, having their longer facades facing east and west. Each building facade is composed of different structural material (see details in MATRIX table, appendix 8) with different thermal mass, exposed thermal mass, having different u-values, insulated exterior walls and double-glazing and shading systems facing the southeast.



Argyle House **Potterrow building**

Five Ways House **Elizabeth II Courts**

Figure 5.3: Location maps from the case study office buildings

Source: Ordance survey

Some of the key building characteristics are shown in table 5.1. This table has been extended into a MATRIX table in appendix 8.

3. Building occupancy type: ownership, occupancy pattern and services provided

The ownership is another considerable factor that influences decision making on refurbishments, and such decisions can be complicated and difficult if the ownership is mixed (as with Argyle House). Occupancy is a crucial factor for energy consumption. There are differences in the amount of people working and visiting the case study office buildings, depending on the services provided by the office building which could vary if different companies operate within an office building. For instance, more staff work in the Winchester City Council (Elizabeth II Courts), with a different amount of visitors daily, compared with a University building (Potterrow) or a privately owned building (Argyle House). As the occupancy in office buildings has multiple aspects to be explored, and access to this kind of data was not provided as two of the office buildings belong to the Government, this study has excluded the occupancy evaluation. However, this study has shown that it is recognised as a significant factor to be taken into consideration (see details on data limitations in chapter 4).

4. Site typology: Site nature for building design and surroundings

Another significant factor for energy performance related to building design and orientation is the site typology. For instance, whether a building is located won a sloping site or in an open area where the surroundings will not have an impact on the passive heating or cooling of the building. Argyle House is located within a polymorphic sloping site that presents differences from each side, reflecting the building design requirements. Even a refurbishment of this building will be challenging considering the site typology. Similarly, Five Ways House is also located on a slightly sloping site which does seem to have polymorphic issues.

In terms of the building surroundings, higher surrounding buildings on the site, buildings at a particular close distance and the location and size of trees can all have an impact on energy performance of certain parts of the buildings, causing building shadows.

Argyle House is surrounded by other traditional buildings in Castle Street and in Lady Lawson Street with a modern building on the corner of the West Port (figures 5.4, 5.5, 5.6, 5.7). The north side of block A is partially shadowed due to a wall fenestration in front of the north yard (figure 5.6) and due to the trees (figure 5.7) and the surrounding buildings in the West Port.

Figure 5.4: The heights of the buildings across the south side of Argyle House

Source: Site visit

Figure 5.5: View from Lady Lawson Street from the west side of the building

Source: Site visit

Figure 5.6: View from the front-yard and of the wall fenestration on the south side of the building

Source: Site visit

Figure 5.7: North side of the building (zone 3)

Source: Site visit

Argyle house is surrounded by Victorian style buildings on the sloping site to the west, although it is taller than the surrounding buildings. The surrounding buildings are located 4-6 meters away from Argyle House. The building angles to the southwest and northeast and the shorter block C, the fenestration wall outside the building, and some trees create shadowed areas and areas that rarely see the sun.

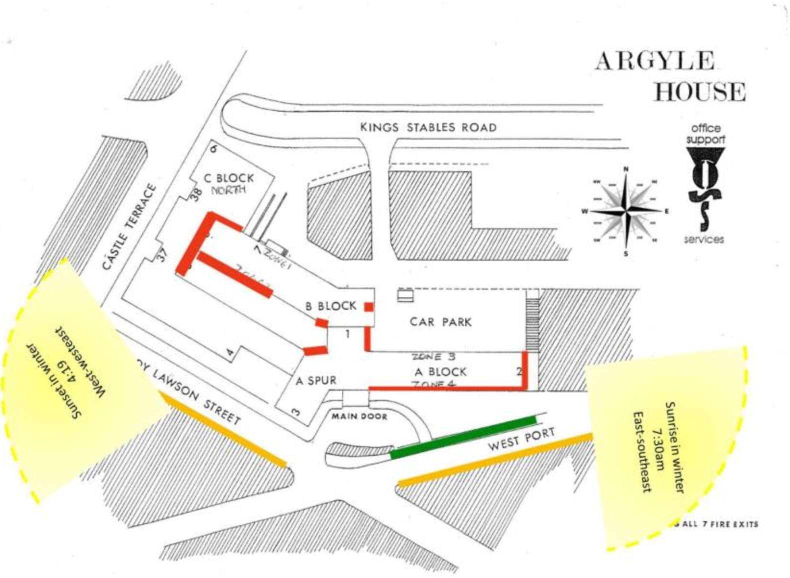


Figure 5.8: Site plan and mapping of the sun orientation and of the shadowed areas (green lines-shadows from trees, orange lines-shadows from buildings-red lines shadows from building design)

The Potterrow building is shadowed by other taller buildings and trees on the site. These areas can be colder in the winter and it is believed that they require more heating. This could explain that the facades in these areas are narrower than the long facades in the west and north-east courtyard. However the shadowed parts have been supported by insulation, double glazing with aluminium frames and with trench heater systems.

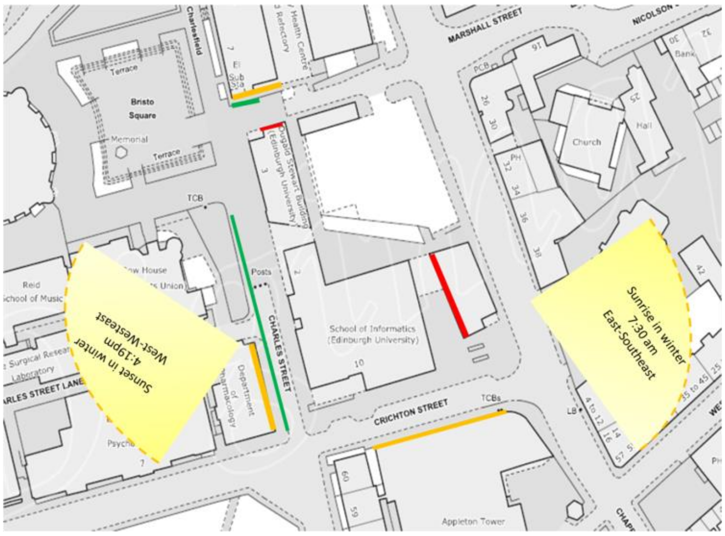


Figure 5.9: Site plan and mapping of the sun orientation and shadowed areas (green lines-shadows from trees, orange lines-shadows from buildings-red lines shadows from building design)

The east, south and west benefit from sunlight over the winter, which is in a lower position while the east part of the building is more exposed to sunlight in the morning hours due to its angle. Glare is overcome with the use of internal blinds. Shade is caused by trees on the east side of the building and in the winter, shadows on the building during the day do not allow the building to get warm. The surrounding buildings to the east are mostly residential from 2 to 4 floors. In the south, there are two buildings located at a close distance from Five Ways House that can be reached by bridges (figures 5.11). These structures create shadows to a large part of the building. The north and the west do not have any issues with shadowing.

Figure 5.10: View from the east. Shadows from trees

Figure 5.11: View from the south looking east. Shadows from the shorter building on the site

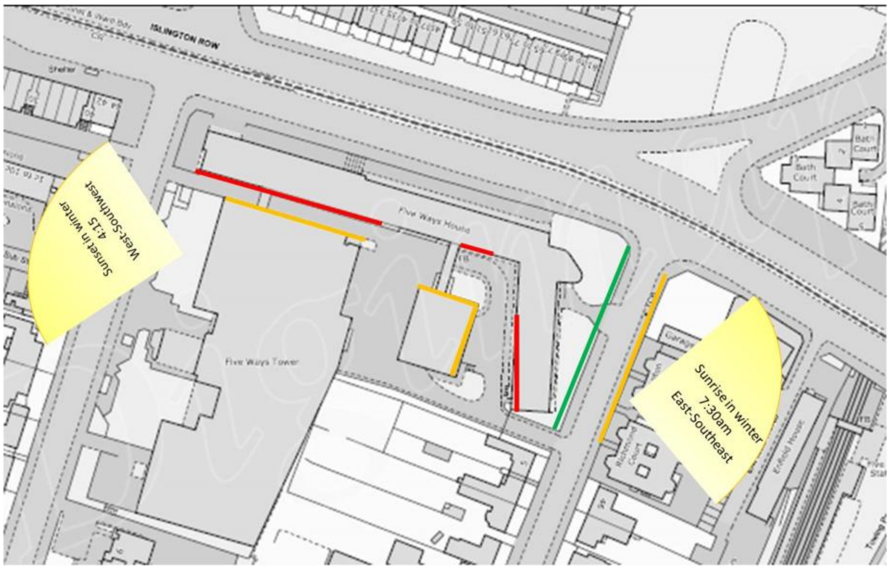


Figure 5.12: Site plan mapping of the Five Ways House

The building is orientated along an east/west axis, so that the long facades are easy to shade with its front entrance in the west. The front entrance is from the west (figure 5.13). From the site plan (figures 5.3, 5.13) the shape of the refurbished building and the orientation of each block can be seen. The building has three blocks, one to the west, one to the east and one in the north. The southern area of the building includes the courtyard space. The rear of the north block has shading systems installed to avoid glare. The facade at the rear of the west and the east block looking at the courtyard is glazed, while the fronts of the west and east have brick cladding with aluminium and timber frames from the inside windows. The ducts throughs are installed on the west and east and the ducts are exposed from the brick mass covers with brick cladding. The approximate time of sunrise over the winter is 7:30 am and sunset is at 4:30 with direction from southeast to southwest. The site plan below also shows the shadowing from the residential surrounding buildings (highlighted with orange) and from the trees (highlighted with green). The residential buildings on the site are lower in height than Elizabeth Courts, about the same height as the carriage space. There few trees on the site, to the west and east, but these do not cause any shadows on the building as over the winter they have no leaves. In the summer the trees create some shadow but again this does not influence the building substantially.

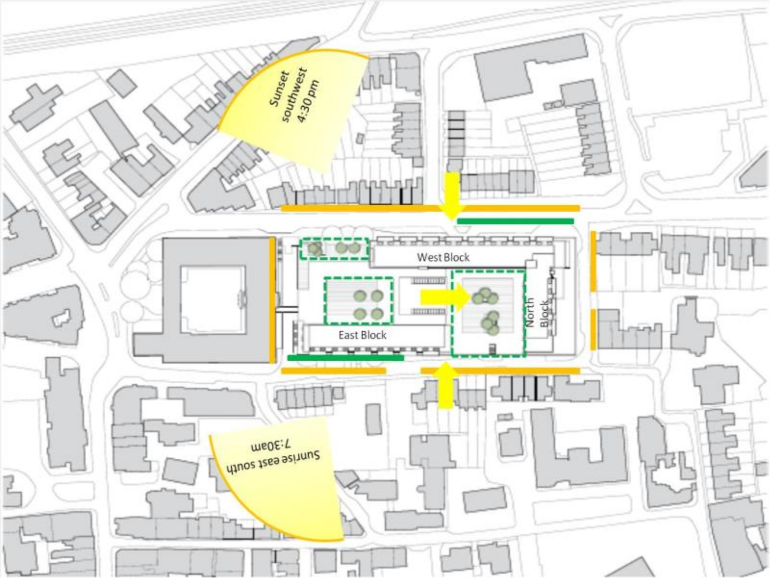


Figure 5.13: Site plan of the Elizabeth II Courts, mapping of the building orientation to the sun, direction of the sun around the building and of the surroundings.

The above characteristics, and some further building characteristics, are presented in tables 5.1-5.4 and in appendix 8.

Table 5.1: Building location, orientation and basic building characteristics

Building characteristics/Building	Argyle House	Potterrow building	Five Ways House	Elizabeth Courts II
Status	Existing	New	Existing with some refurbishment	Refurbished
Building location	Old Town of Edinburgh Lady Lawson Street, sloping site	Old Town of Edinburgh within walking distance from Argyle House, located east from Argyle, on the University of Edinburgh campus.	Birmingham	Winchester
Latitude	N55 56	N 51 3	N52 28	N55 56
Longitude	W 30 12	W1 19	W1 54	W3 11
Building orientation	South orientation	South/west	North	West/East
Sunlight and sunset approximate longevity time/orientation	From east 7:30am to southwest 4:19pm	From east 7:30am to southwest 4:19pm	From east/south-east 7:30am sunrise and 4:15pm sunset from the west	From east 7:30am to southwest 4:30pm
Building shadows and surroundings	Mainly from the east side and from the south parts from trees in the warm months. The lower floors below the street level in the south from wall fenestration.	Partly shadowed from the trees on part of the west façade.	Partly shadowed from the east from trees and from the south from surrounding structures.	Partly shadowed from the east/west from trees
Age	1960	2009	1950	1950 and refurbished in 2008, occupied by 2009.

Building characteristics/Building	**Argyle House**	**Potterrow building**	**Five Ways House**	**Elizabeth Courts II**
Building shape/blocks/phases	L' shape with the longer facades facing north and south	L' shape. Currently 2 phases; Phase 1: Informatics, Phase 2: Dugald Steward building, Phase 3 in future. Longer facades face west, south and east	L' shape Longer facades face north and south.	L' shape Longer facades face east and west and parts the south.
Building style	Post-war architecture	Modern architecture, built in 2009	Post-war architecture	Modern architecture, built in 2009
Building size /Gross floor area	20,472m^2	16,100m^2	15,000m^2	12,600 m^2
Number of floors	11 with main entrance on the 5th floor.	3, 6, 8 floors from different sides of the building depending on the sunlight	6	4

Table 5.2: Building structural-envelope characteristics

Building characteristics/Building	Argyle House	Potterrow building	Five Ways House	Elizabeth Courts II
Wall type	Pre-cast concrete loadbearing panels with Walley Thurock blue flint exposed aggregate on Orrock fines to harmonise with the Castle rock. Loadbearing mullions of Eglinton white limestone aggregate on white cement.	-Exposed reinforced concrete frame maximised internally for thermal storage. -External panels are prefabricated -External façade design for creating proportions for solid/void to maximise daylight and minimise solar gain -Facades are made from pre-cast concrete panels. -Polished white pre-cast concrete panels face the courtyards and part of the east side	Pre-cast concrete	Brick gadding facing east and west and metal cladding facing north and partly the south and partly glazing on the south. Part of the south
Window type	Ribbon which is a row of windows separated by vertical mullions used for additional lighting and ventilation. Double glazing with PVC frames.	Windows with vertical emphasis and a percentage of solid to void 60:40 to match surroundings and maximise daylight. Glazing rati0 40 % Double-glazing with U-vale 2.08	Ribbon, single-glazing covering about 70% of the overall façade.	Double glazing with timber frames.
Insulation	No	Yes	No	Yes

Building characteristics/Building	**Argyle House**	**Potterrow building**	**Five Ways House**	**Elizabeth Courts II**
Doors type	Inside: timber frame, with single glazing and air-gaps in joints. Outside: single glazing siding doors at the entrance.	Air-tight glazing sliding doors at the entrance. Timber interior doors in rooms with holes to maximise air-circulation/ventilation.	Inside: timber frame, with single glazing and air-gaps in joints. Outside: single glazing siding doors at the entrance.	Air-tight glazing sliding doors at the entrance. Timber interior doors in rooms.

Table 5.3: Other building characteristics

Building characteristics/Building	**Argyle House**	**Potterrow building**	**Five Ways House**	**Elizabeth Courts II**
Office layout (see architectural drawings in appendices)	Open plan facing mainly the north side. Some private meeting rooms facing the south.	Phase 2: open plan Phase 1: closed/study rooms with balconies that face internally the atrium space.	Open plan facing north and south.	
Ownership	Privately owned by different companies. Main occupier in the building Telereal Trillium.	Owned by the University of Edinburgh.	Government building. Many different departments/ministries inside. Main contact Telereal Trillium.	Government building/Council.
Building occupancy	Partly occupied/since 2004 occupancy started to decrease/there was an occupancy evacuation plan for 2013. At the time of the PhD survey, 300 staff left in the building from the 1000 staff before 2004.	Fully occupied approximately 600 people university staff and research students with flexible timetable but usually 9am-5pm.	Fully occupied. About 600 staff.	Fully occupied. About 1000 staff.

Table 5.4: Environmental building characteristics

Building characteristics/Building	**Argyle House**	**Potterrow building**	**Five Ways House**	**Elizabeth Courts II**
BREEAM	n/a	'Excellent' 2004 at pre-construction phase, 71.99% from which 13% was allocated in energy and 7% allocated in materials	n/a	'Excellent' 2006 at pre-construction phase, 72.89% from which 13% was allocated in energy and 7% allocated in materials
Key environmental features	Natural ventilation	**Summer:** •Night cooling of concrete slab •High windows maximise natural daylight •Opening windows-use to moderate daytime temperature •Cooling run-on switch in meeting rooms •Additional cooling in some meeting rooms with internal gains •Low energy displacement ventilation in floor void with atrium air return path •Warm air is extracted from the atrium at high level (that involves also fresh air supply) •Attenuated air-path	Natural ventilation	

Building characteristics/Building	Argyle House	Potterrow building	Five Ways House	Elizabeth Courts II
		Winter: •Warm air returns to atrium for thermal recovery •Combined up lighting and down lighting •Blinds reduce glare on bright days •Radiators •Heating run-on switch at each stair core-use if working late •Low energy displacement ventilation in wall diffusers through floor voids with the atrium and the corridors as return paths. •Attenuated air path •Perimeter heating •Under floor heating		

5.3 Environmental approach to building design

Potterrow

The Potterrow building was certified by the BREEAM assessment scheme of 2004, at the pre-construction stage, as ‘excellent’ with 71.99% score from which 13% was allocated to energy (available 17, see BREEAM scoring appendix 10) and 7% was allocated to materials (available 12%). However, as explained in section 2.7, these scores were based on predicted data and not on actual in-use data. This development has become a benchmark for achieving the 6 key Environmental Performance Indicators promoted by the Movement for Innovation (M4i) (m4i 2011)[3] (figure ?). This section mentions only the two that are closely related to this study. These indicators are:

1) Operational CO_2

- Predicted CO_2 emissions: 19kg/CO2/m^2/annum asset (42 kg/CO_2/m^2/annum).
- Energy demand of 160kWh/m^2/annum and 110 kWh/m2/annum
- Air-tightness targets of 5m^3/hr/m2@50 Pa from which 6.55 has been achieved in Phase I.

2) Embodied CO2

- Envest analysis on principal building materials
- BRE Green Guide to specification used for low environmental impacts of key components.

The development of the Environmental Performance Indicators M4i, can be an important component for the development of the new sustainability indicator to study in parallel life cycle performance indicators like the operational energy, the embodied energy and the embodied raw-material emissions caused by improving operational energy in buildings through technological advances. Such integrations are discussed in the last two chapters.

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[3] The Movement for Innovation was formed in November 1998 to implement, across the whole of the industry, the recommendations contained in The Government Task Force's report 'Rethinking Construction'. The report proposed the creation of a 'movement for change' which would be a group of dynamic people inspired by the need for change. Since the beginning of 2004, it has been a part of Constructing Excellence (m4i 2011).

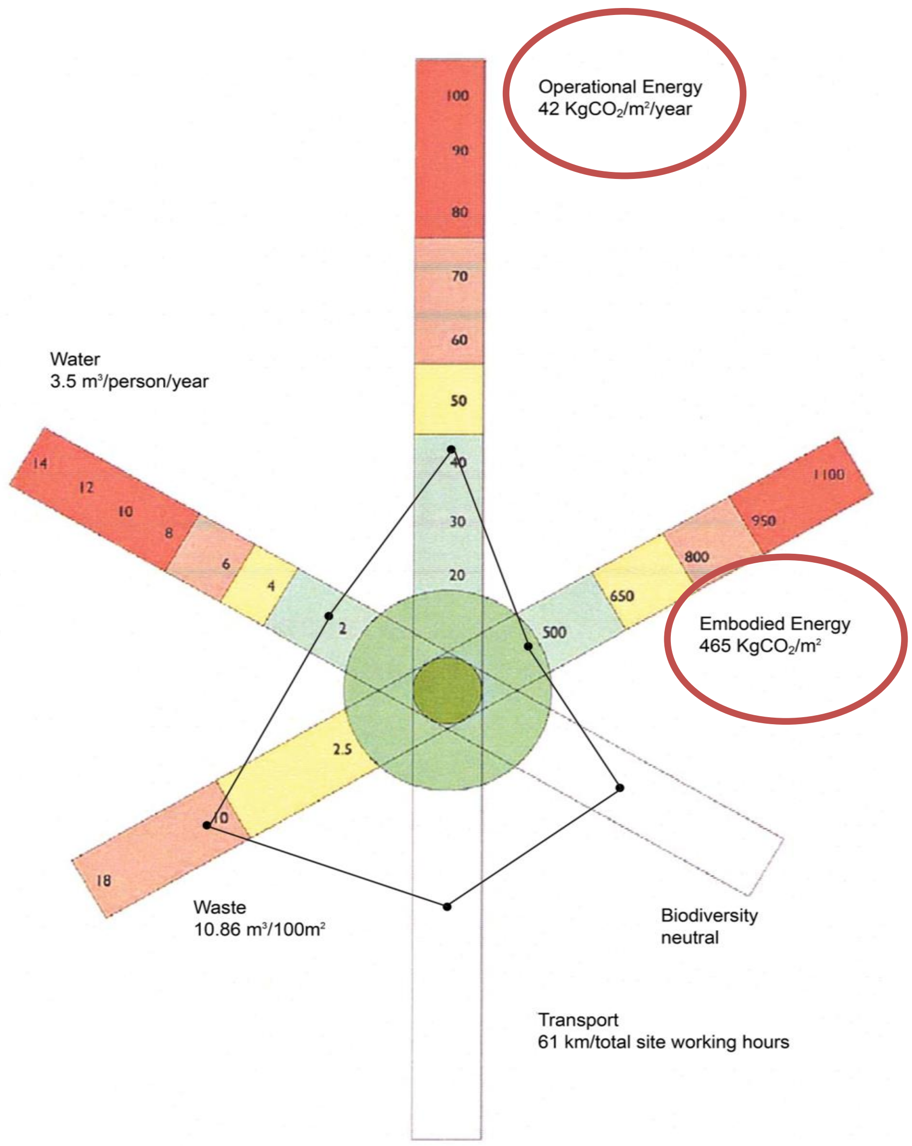

Figure 5.14: The 6 key Environmental Performance Indicators promoted by the Movement for Innovation (M4i)

Source: Bennetts Associates

The environmental approaches for the summer include:

- Night cooling of concrete slab
- High windows maximise natural daylight
- Opening windows-use to moderate daytime temperature
- Cooling run-on switch in meeting rooms
- Additional cooling in some meeting rooms with internal gains
- Low energy displacement ventilation in floor void with atrium air return path
- Warm air is extracted from the atrium at high level (that involves also fresh air supply)
- Attenuated air-path

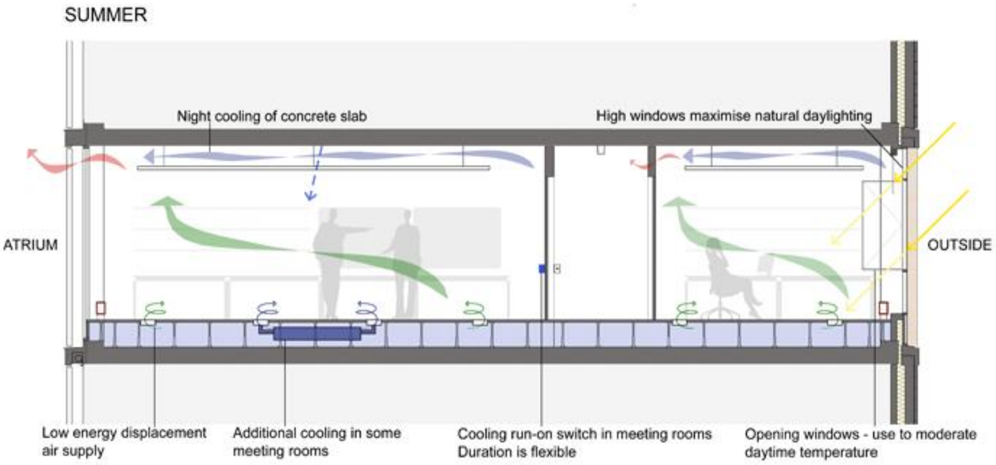

Figure 5.15: Environmental design and technological approaches for the summer

The environmental features of the building for the winter include:

- Warm air returns to atrium for thermal recovery
- Combined uplighting and downlighting
- Blinds reduce glare on bright days
- Ratiators
- Heating run-on switch at each stair core-use if working late
- Low energy displacement ventilation in wall diffusers through floor voids with the atrium and the corridors as return paths.
- Attenuated air path
- Perimenter heating
- Underfloor heating

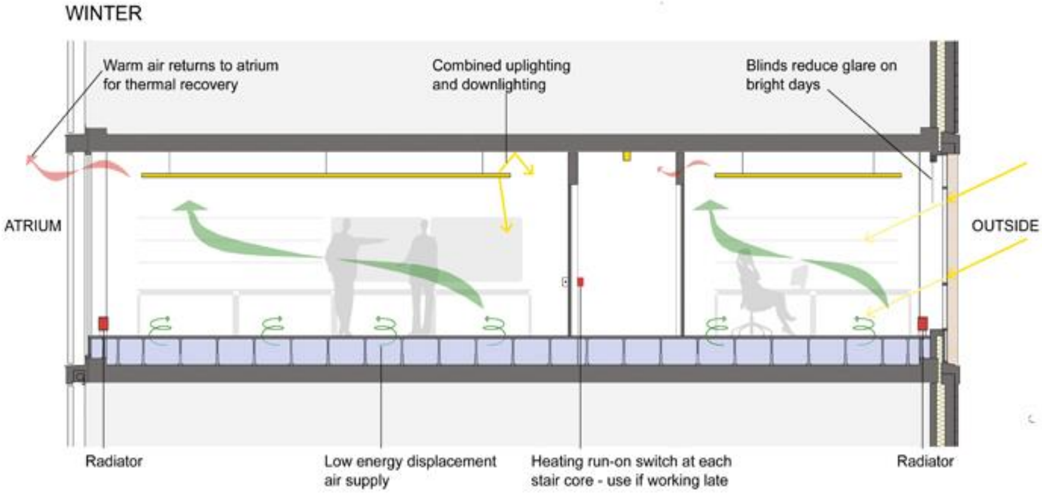

Figure 5.16: Environmental design and technological approaches for the winter

Elizabeth Courts II

BREEAM certified the Elizabeth Court II with a 72.89% score of excellence (appendix 10). A statement for the design team confirms that approved software (TAS) was used for the building modeling and the modeler was suitably qualified (Blencowe 2010 P.28). The E1 calculator tool has determined that there was a 24.07% improvement over building regulations and 10 credits were allocated for that (Blencowe 2010 p.28). Up to 7 credits were allocated where evidence demonstrates that major building elements specified have an ‘A rating’ as defined from the Green Guide to Specification. About 3 credits were allocated on the material and waste category of BREEAM (Blencowe 2010 p.40).

Building alterations

The building is two simple 12.5 m wide floorplates with a central atrium space in between. High heat emitting functions that would require mechanical ventilation (such as meeting and IT rooms) were removed from the office floorplates and collected at the east and west ends of the building to act as a thermal buffer. The thermal mass of the in-situ concrete structure was exposed to act as a heat sink during the day, which is then purged at night (Fisher 2008). Massive alterations to Ashburton Court include (Colliers Cre. 2006):

(i) Removal of:

- The pedestrian bridge link structure (approximately 356 m²) connecting Ashburton Court and Elizabeth II Court (figure 5.18).
- The top floor of the North and West wings (approximately 1613 m²).
- The concrete fins to the car park elevations and the cladding to the remainder of all elevations
- The *brise-soleil* around the top floor of the East wing.
- The vehicular access ramp on the northern side of the North wing
- The loading bay attached to the courtyard side of the East wing (approximately 80 m²).
- The existing external surface finishes at podium level.
- The chiller units at the southern side of the vehicular access ramp between Elizabeth II Court and Ashburton Court.
- The deletion of 243 (approximately) HCC staff parking spaces at podium level and the deletion of 10 (approximately) spaces at basement level to allow for the proposed cycle parking (100 spaces) (figures 5.17-5.19).

- Remove and replacement of seven existing Raywood Ash trees on the western side of Tower Street, adjacent to Ashburton Court.
- Removal of old partitions on corridors to open up office space (figure 106).

Figure 5.17: View from the Ashburton Court on the left and of the Elizabeth Court II on the right, view from the east. Source: Bennetts Associates and Tim Crocker

Figure 5.18: View from the Ashburton Court on the left and of the Elizabeth Court II on the right, view from the south facing courtyard. Source: Bennetts Associates and Tim Crocker

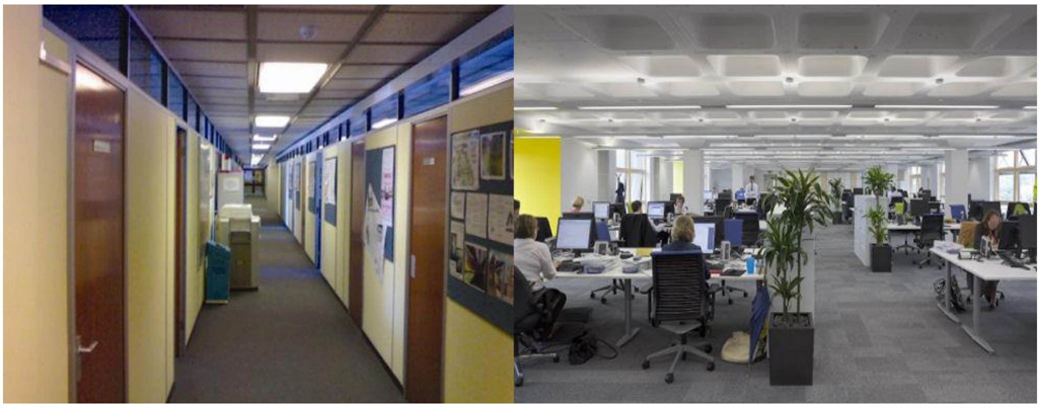

Figure 5.19: Before and after view of the office space of the Ashburton Court

Source: Bennetts Associates

(ii) Erection of:

- The erection of a new extension (approximately 821 m²) at fourth (above podium) floor level of the West wing to provide replacement office accommodation (Class B1) (figure 107, 108).
- Infill extensions (total of approximately 2790 m²) under North, East and West wings at podium level to provide additional office and ancillary accommodation (Class B1) (figure 107-111).
- The erection of a single storey extension (adjacent to the West wing, approximately 1257 m²) within the existing courtyard at podium level (figures 5.20, 5.21).

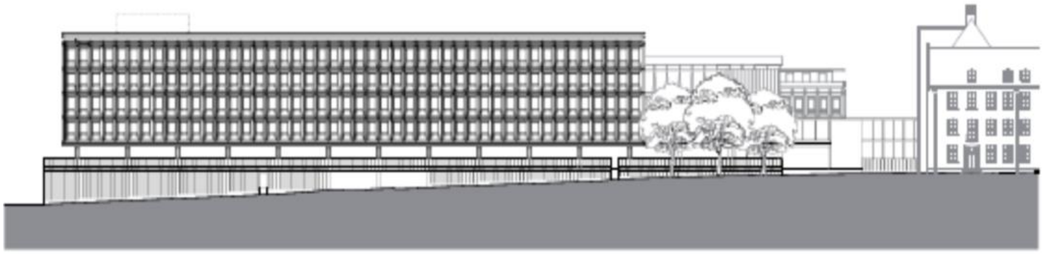

Figure 5.20: West elevation of the Ashburton Court in Winchester

Source: Bennetts Associates

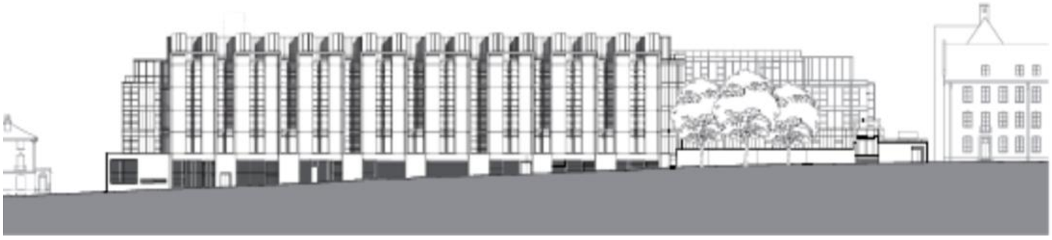

Figure 5.21: West elevation of the refurbished Ashburton Court in Winchester

Source: Bennetts Associates

(iii) Other new work:

- Installation of various plant and equipment (total of approximately 188 m² enclosed and approximately 618 m² open) including chillers and ventilation air-handling units in the following locations:
  - the roof of the west wing
  - a new lowered roof of the north wing
  - the northern and southern ends of the east wing

    - on the podium adjacent to Sussex Street and Tower Street
- New elevational treatment above podium level to all street elevations to comprise new brickwork, fenestration and ventilation ducts (part of the low energy system). Courtyard facing elevations to be finished with new fenestration and lightweight cladding with timber solar shading in certain locations.
- Overall there was a net increase in floor space of approximately 3657 m² (including 188 m² of enclosed plan) to Ashburton Court.

A summary of the key alterations mentioned is included in table (table 5.5).

Table 5.5: Summary of the Ashburton Court alterations

Before	After
Connection bridge between the blocks has been removed.	The building is composed of two main blocks, the smaller east block and the ‘L’ shaped north and west block, which together form a large courtyard.
Cladding, internal fittings and services were beyond their working life.	Interior office refurbishment and new brick cladding.
In-situ concrete structural frame was in good condition	Retention
The site being surrounded on three sides by trafficked streets.	Studies carried out by Arup Acoustics had concluded that any ventilation system could not rely on windows opening to the streets.
The overwhelming majority of the facades faced either east or west, meaning the worst possible orientations, which suffered from low angle morning or afternoon sun respectively.	Adaptation measures to the building’s existing orientation. Brickwork on the long facades in the east and west and metal panels in the north and the small part in the south.
Limited floor to floor heights ruled out displacement ventilation, due to insufficient space for the stratification of air to take place.	Natural ventilation with exposed thermal mass
The existing building was set back from the road and raised two storeys from the ground, which divorced the building from the surrounding streetscape. Its architecture was also relentlessly horizontal, in a city that is mostly vertical in nature.	The building aesthetics match the architectural character of the city.
The materials, mostly pre-cast concrete cladding units, were also clearly at odds with the city.	A desire to break down the mass of the building into a series of bays and to introduce a more vertical rhythm that would reconnect the building to the street and reflect the typology of the city.
Existing Structure - the cladding panels were removed and crushed.	Use as hardcore in other HCC projects.
Internal fittings were also stripped.	In order to expose the thermal mass of the existing structure. The thermal mass acts as a heat sink during the day, contributing something in the order of 25w/m^2 of additional cooling.

Source:(Fisher 2008)

Environmental approach

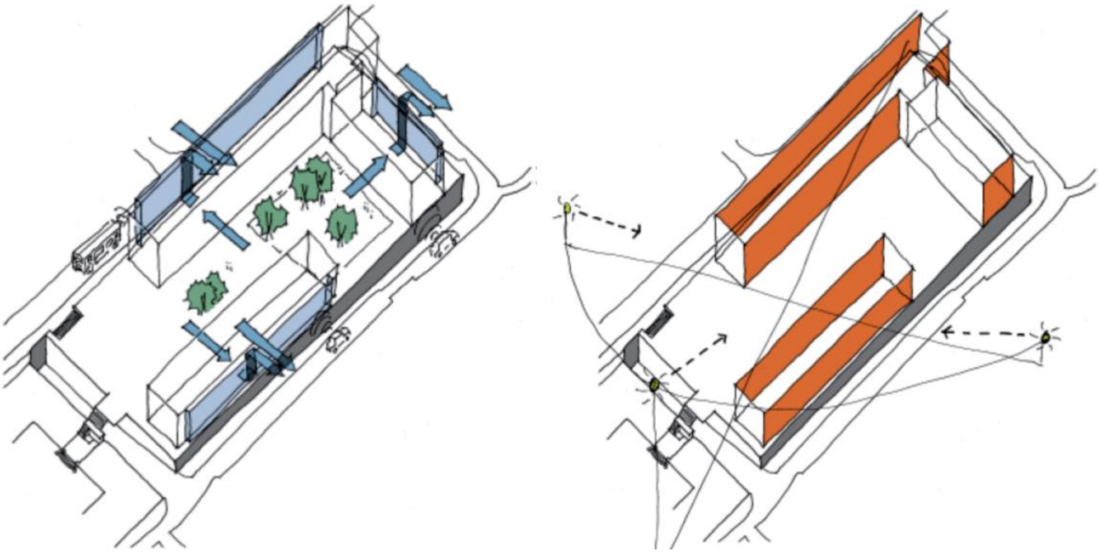

Figure 5.22: Environmental design showing ventilation on the left image and shading on the right image

Source: Bennetts Associates

The design was a complex synthesis of several different challenges. These can be seen as considerations for the infrared analysis of the building envelope further down:

I. The building is naturally ventilated (figure 5.22). Ventilation air is drawn into the building from the courtyards and then up through the acoustically attenuated ventilation ducts on the street facades of the building. The 'wind troughs' on top of the ducts exploit wind blowing across the roof to create suction, which draws air through the building (figure 113, 114). This can influence the thermal temperature of the building surface by cooling it down.

II. The brick clad ventilation ducts help to shade the east and west long facades protecting the increase of the surface temperature.

III. Exposed thermal mass is used to enhance night ventilation and to moderate night temperature. Existing Structure - the cladding panels were removed and crushed for use as hardcore in other HCC projects. Internal fittings were also stripped out in order to expose the thermal mass of the existing structure. The thermal mass acts as a heat sink during the day, contributing something in the order of 25W/m^2 of additional cooling.

IV. Courtyard Façade - this was re-clad with a simple timber/aluminium composite cladding system. The glazing ratio was kept below 40% to balance the need for light with mitigating solar heat gains. High level windows are BMS controlled to allow ventilation air into the building from the courtyard. Lower windows, while not assumed as being open by the thermal modelling, can be operated manually by the occupants.

V. Ventilation Ducts - these are acoustically attenuated and used to draw air out of the building. They are formed by a steel structure ‘clipped’ to the street façade of the existing structure and bearing onto the podium slab. As well as forming the ducts this also pushed the façade of the building out to the street edge. As with the courtyard facades the glazing ratio was kept to below 40%. The depth of the ducts also provided shading from low angle morning or afternoon sun on the east and west facades.

VI. Wind Troughs - these provide the ‘motor’ at the top of the ventilation ducts (figure 113). They are open topped boxes that create negative pressure (suction) irrespective of wind direction. A BMS controlled vent at the top of the ventilation ducts opens into the wind trough and is used to control air movement.

VII. Street Façade Windows and Brickwork – the cladding to the ventilation ducts and street façade is a simple timber/aluminium composite system, once again with a low glazing ratio of below 40%. The brickwork was used to articulate a series of bays that re-connect the building to the street level and introduce a vertical emphasis to counter the horizontality of the original building. Due to structural limitations, brickwork could only be used on the outer facades of the building, which again helped to break up the blocks of the building. Windows on this façade can be manually opened if occupants wish to, but do not form part of the ventilation strategy.

VIII. During the summer automated opening windows are used during the day to cool the structure.[4]

IX. The main facades that face east and west are both difficult to shade due to low angle morning or afternoon sun. Thus vertical rather than horizontal solar shading has been used with additional vertical louvre blades.

The design of the building underwent extensive computer modelling by EDSL, using its TAS software. Local weather data was used, but a decision was made to use warmer temperature data for London to simulate the effects of increased temperatures due to global warming over the next thirty years. Due to the complexity of air movement around buildings, the results were also verified by a number of wind tunnel tests in Cardiff. The pressure differential between each wind trough and associated courtyard opening window was tested to ensure that negative pressure was always present. This

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[4] On courtyard facing facades half of opening windows are controlled by the BMS, while the remainder is occupant controlled

was done for 16 points of the compass (Fisher 2008). Two areas were found to not always have negative pressure within the wind trough. These were the southern end of the east block, due to wind rising over the higher neighbouring Elizabeth II Court, and the north end of the west block, where there was no route into the building for air at courtyard level. As with previous projects, these locations were used to accommodate functions that would need mechanical ventilation anyway, such as meeting and print rooms (Fisher 2008).

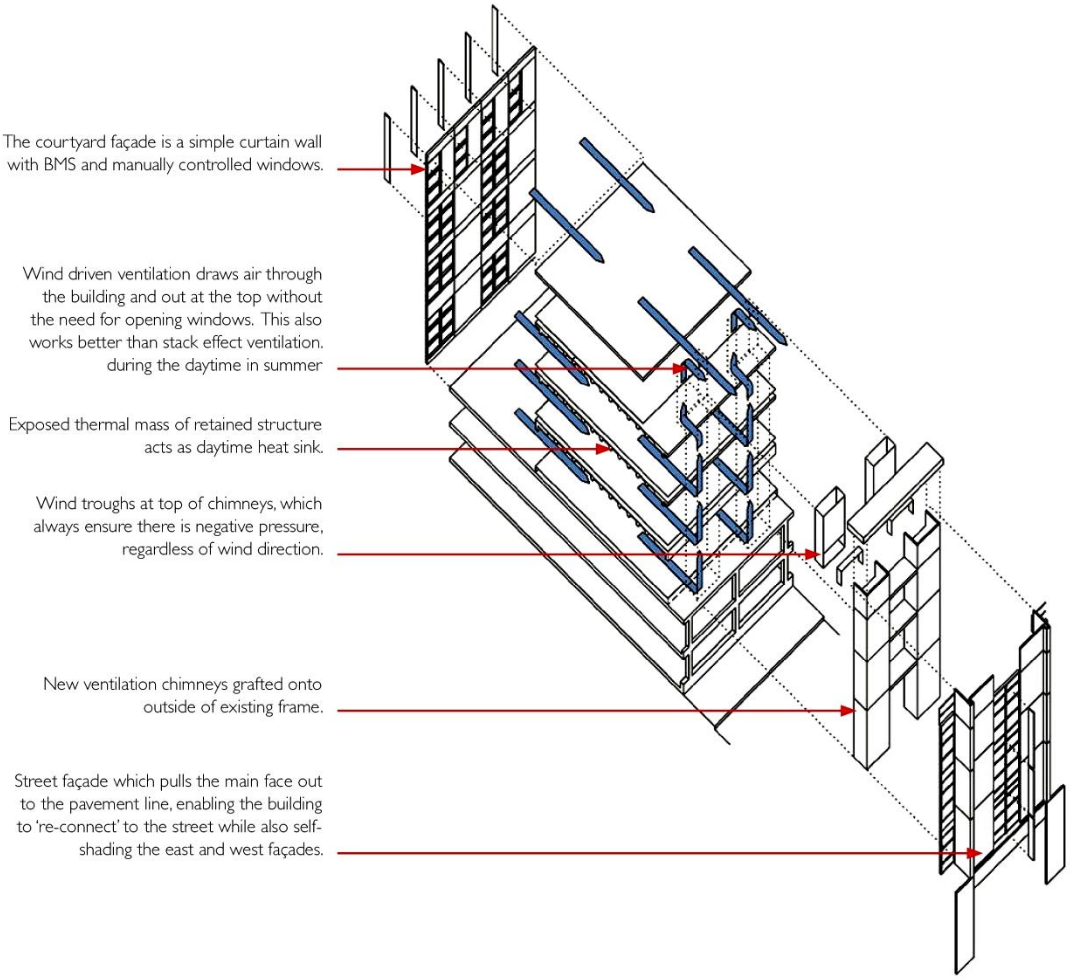

Figure 5.23: The ventilation concept of the Elizabeth II Courts, Winchester

Source: Bennetts Associates (architectural practice of the building) and Riba Architecture website

On the street facing elevation, acoustic studies showed that openable windows were not feasible due to noise levels from traffic. Naturally ventilated air is drawn from the internal courtyards across the floor plates expelled through ducts or chimneys along the street façades. Ducts have devices at the top called wind troughs that use renewable wind energy to create the suction force that drives the system. Certain parts of the office could not be cooled satisfactorily by natural ventilation alone due to their proximity to neighboring buildings so the space planning was adjusted to compensate; in high winds and cold temperatures, windows are shut, thus localised air-handling units provide fresh air to office spaces through swirl diffusers in the floor, operated with rejected heat from the Data Centre.

BMS controls openable windows and chimney vents. At night, building is pre-cooled by opening windows automatically (allowing absorption of the night air by the exposed concrete slab of the original building. Back-up air supply in high winds and cold temperatures, windows are shut and localised air-handling units provide fresh air to office space via swirl diffusers in the roof. The air is tempered by rejected heat from Data Centre mechanical cooling, provided where the suction of chimneys is inefficient (meeting rooms, printing hubs, communal facilities at podium level such as auditorium and restaurant. The café and reception are naturally ventilated). Mechanical cooling comes from a VRF heat pump system and LPHW feeds radiators for heating served by high-efficiency condensing boilers. Waste heat from the cooling plant required to service the Council's Data Centre will be recycled to heat areas of the building in the winter. Lighting is controlled by combined light-level and presence detectors.

5.4 Heating and Cooling Systems Characteristics

5.4.1 Heating system

Four different heating systems have been identified from the case study office buildings shown in figures 5.24-5.27. The key differences between the conventional and the sustainable office buildings is that sustainable office buildings have some automation in controling their heating whereas the conventional office buildings have mainly manual controls and some automatic controls such as on/off controls for the radiators in their central heating system. Also the sustainable office buildings have current state of the art technologies, eg, the Potterrow building has CHP (combined Heat and Power Unit) that provides the building and other buildings on the campus with power, heating and cooling if needed. These technologies have been claimed as highly energy efficient, although their effective usage depends on various factors presented in this section.table ? presents the key characteristics of the heating system on the buildings examined in this study.

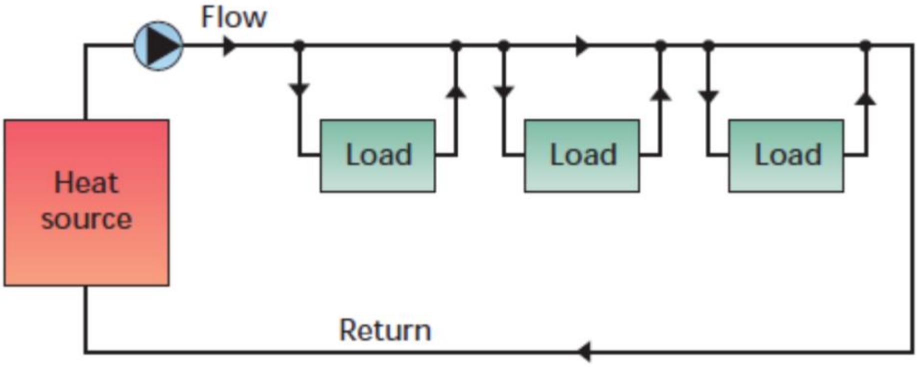

Figure 5.24: One-pipe system example used in the Argyle House

Source: CIBSE 2010, p.42

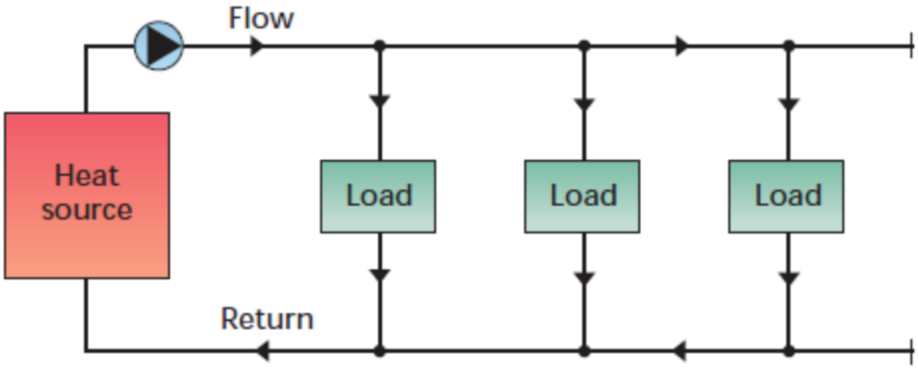

Figure 5.25: Two-pipe system (direct return) example used in Five Ways House

Source: CIBSE 2010, p.42

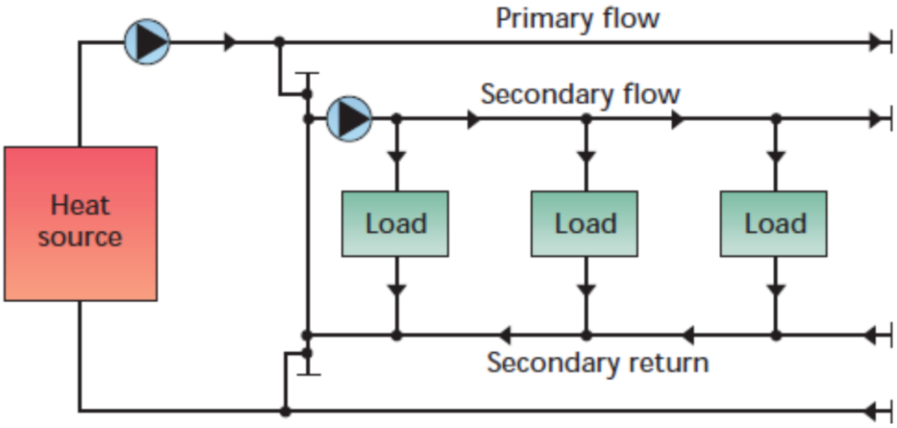

Figure 5.26: Pumped primary/pumped secondary system (direct return) used in the EIIC

Source: CIBSE 2010, p.42

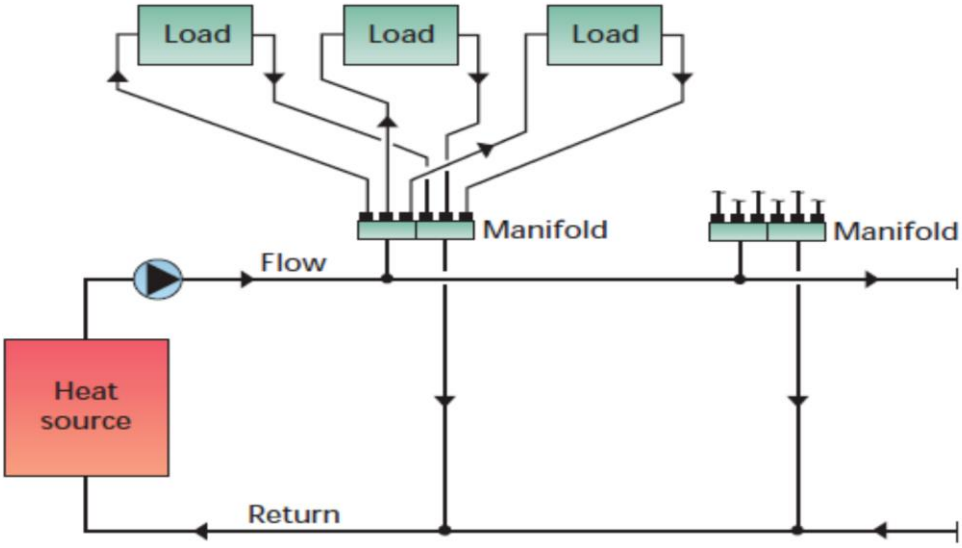

Figure 5.27: Manifold system used in the Potterrow building

Source: CIBSE 2010, p.42

Conventional office building, Argyle House, Edinburgh

The heating system type is central heating, two-pipe return (figure 5.28). Oil is stored in two tanks (figure 5.29) and burned in two large conventional old boilers (figure 5.30) located in the basement floor next to the car parking. A third boiler is used for hot water. LTHW is produced and pumped into the LTHW pipes (figure 5.30) where the temperature becomes lower. When the right temperature is achieved, the water is distributed through pumps in the perimeter radiators in the whole building (figure 5.31). The building has in total 1892 old type radiators and energy efficiency is low as the boilers are 53 years old. In order to find out more about the boilers installed in the building, the manufacturers from the HOVAL company were contacted to comment on the efficiency of the boilers and to provide schematic drawings of the heating system. . The heating system consists of the following equipment:

- 2 oil tanks (since 1960)
- two oil-fired boilers (the date of their installation is not known)
- pumps
- LTHW (low temperature hot water) pipes and ductwork
- a feed and expansion tank (the date of their installation is not known)
- radiators (since 1960)

Figure 5.28: The two oil-fired boilers in the Argyle House plantroom

Source: Site visit

Figure 5.29: Oil tank of Argyle House

Source: Site visit

Figure 5.30: The LTHW pipes of Argyle House in the plantroom

Source: Site visit

Figure 5.31 The perimeter radiators in the office spaces of Argyle House since 1960

Source: Site visit

Sustainable new office building, Potterrow Building, Edinburgh

Heating, cooling and power is provided in the Potterrow building via the CHP[5] (Combined Heat and Power) trigeneration unit (figures 5.32, 5.33), installed outside of the building at the University of Edinburgh campus. This type of energy source can be seen as an alternative to conventional energy production. Figure 5.34 illustrates the typical power distribution process for the heating operation in buildings in the UK. The power is produced by regional electricity grids and transfered through the transmissions lines in the building for the operation of the heating and cooling equipment. Power losses occur through the transmission lines.

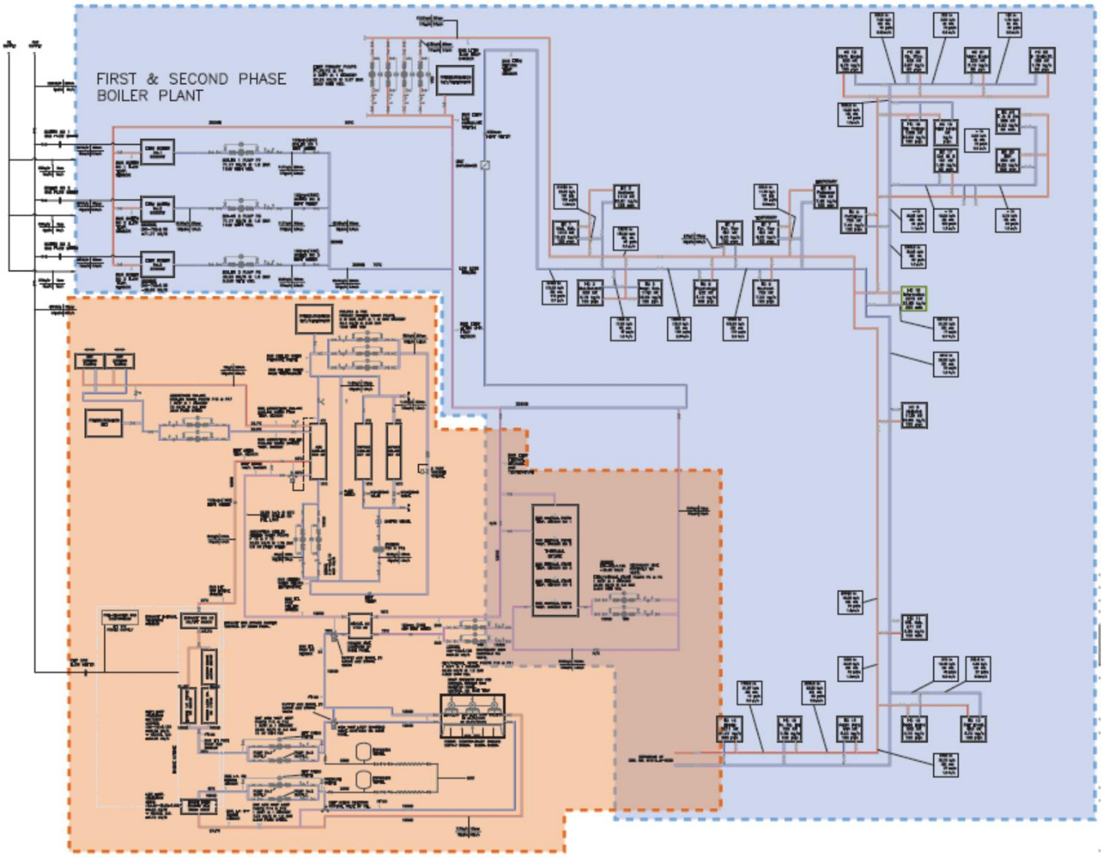

Figure 5.32: Schematic drawing of the CHP network. The blue highlighted area is to show the heating and the red highlighted area is to show the cooling. Source: Burro Happold Engineers (see also appendix 10).

Source: Own interpretations and Burro Happold

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[5] CHP is the simultaneous generation of usable heat and power from the same source. CHP has developed as an established technology and plays a key role in reducing CO_2 emissions. These systems are most suitable for applications where there is a significant year-round demand for heating as well as electricity (CIBSE 2010 p.49).

Figure 5.33: The 12 cylinder Jenbacher Engine in the Potterrow CHP unit

Source: Andrew Witson, Energy manager, University of Edinburgh

On the other hand, the CHP trigeneration unit produces power locally (figure 5.35). This enhances the control of power production for reducing power waste. Surplus electricity is transported in the power grid where thermal energy is released in the combustion process for pre-heating or generating steam. Boilers assist in bridging peak heat demand periods (GE Capital 2011 p.4).

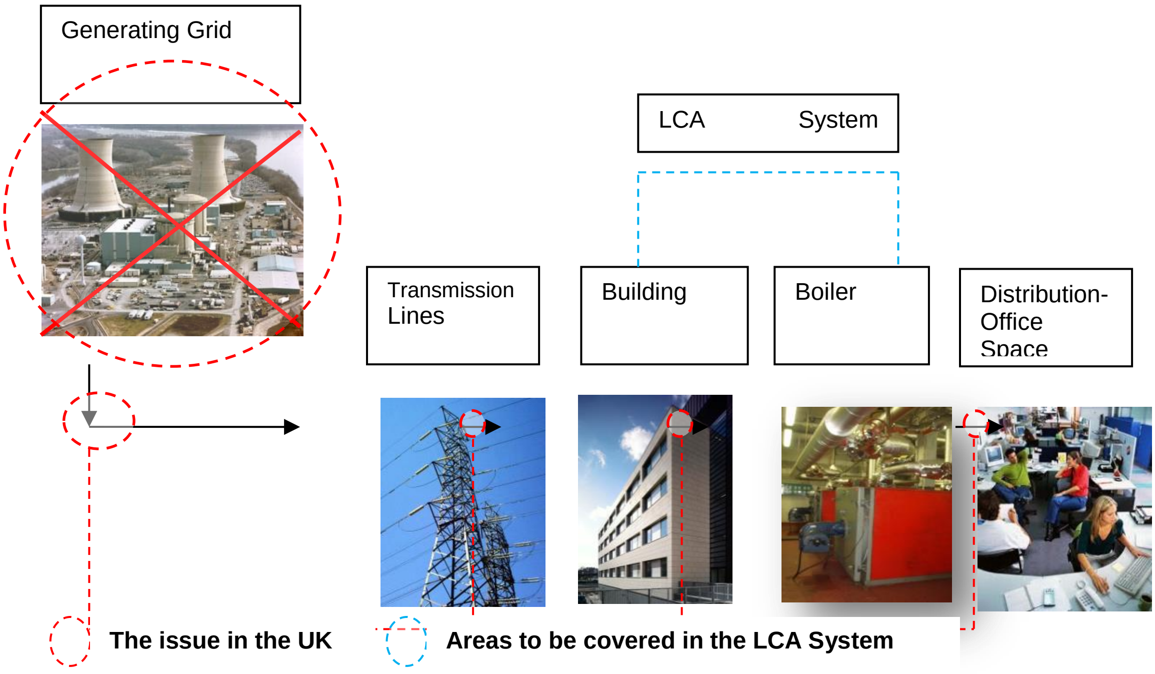

Figure 5.34: Conventional power distribution

Source: Own interpretation

The condensing[6] boilers in the CHP burn natural gas and produce water. LTHW is distributed to heat emitters and air-conditioning systems. Natural gas is combusted and a generator converts the mechanical power to electricity. The provision of heat to the building comes from the University's CHP tri-generation unit. The University network supplies water at up to 90°C but a more typical winter supply temperature is 80°C. The network has variable flows to respond to heat demands from the different buildings on campus (O'Donnell 2010). System pressurisation suitable for the full height of the building, expansion and chemical dosing is provided from the central CHP network (O'Donnell 2010). LTHW is distributed throughout the building through different circuits to serve radiators, trench heaters and over-door heaters (O'Donnell 2010). The underfloor heating circuit is fed from CT (constant temperature) circuits. Each circuit needs to operate on the residual head from the CHP system of 80 kPa; (O'Donnell 2010). Generally, heat emitters are low profile radiators with integral valving. (O'Donnell 2010). Underfloor heating is provided to certain ground floor areas. The system is fed from the CT LTHW circuit into each of the underfloor heating manifolds. The manifold contains a blending valve to mix the water down to the manufacturer's design temperature, a local pump and a flow meter for each loop (O'Donnell 2010). Perimeter trench heating are also deployed. The trench heating system is complete with all ancillary items such as internal and external cover strips, dummy sections and valve boxes to ensure that each run presents a continuous unbroken appearance. Covers are made by anodised aluminium (O'Donnell 2010). The 'waste' heat emitted from the engine is used to provide space heating or hot water. CHP units can achieve efficiencies of around 80% (CIBSE 2010 p. 80). A schematic drawing of the CHP is shown in figure 155. Such systems produce two grades of heat: high-grade heat from the engine exhaust, and low-grade heat from the engine cooling circuits (CIBSE 2010 p.49). For medium and large scale CHP applications, gas turbines are generally used

The CHP unit consist of:

- three low-NOx nature gas boilers with 89% efficiency[7] (see quality assurance appendix 17
    - two of them with heating output of 6000 kW and
    - one of 3000 kW
- an engine (the prime mover) in which fuel is combusted

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[6] Condensing boilers recover the latent heat of vaporisation. The combustion of any hydrocarbon fuel and oxygen will result in the formation of water and carbon dioxide (when the combustion is complete), i.e: $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ + energy . Natural gas is over 90% methane (CH_4), and has the highest carbon-to-hydrogen ratio of the alkanes (common formula $C_nH_{(2n+2)}$). Thus it has the greatest volume of water product, which leaves the boiler as vapour along with the flue gases (CIBSE 2010 p.62).

[7] Efficiency in boilers means the percentage of the total absorption heating value of outlet steam produced by burning gas in the total supply heating value.

- a generator that converts the mechanical power produced by the engine to electricity
- a heat storage unit

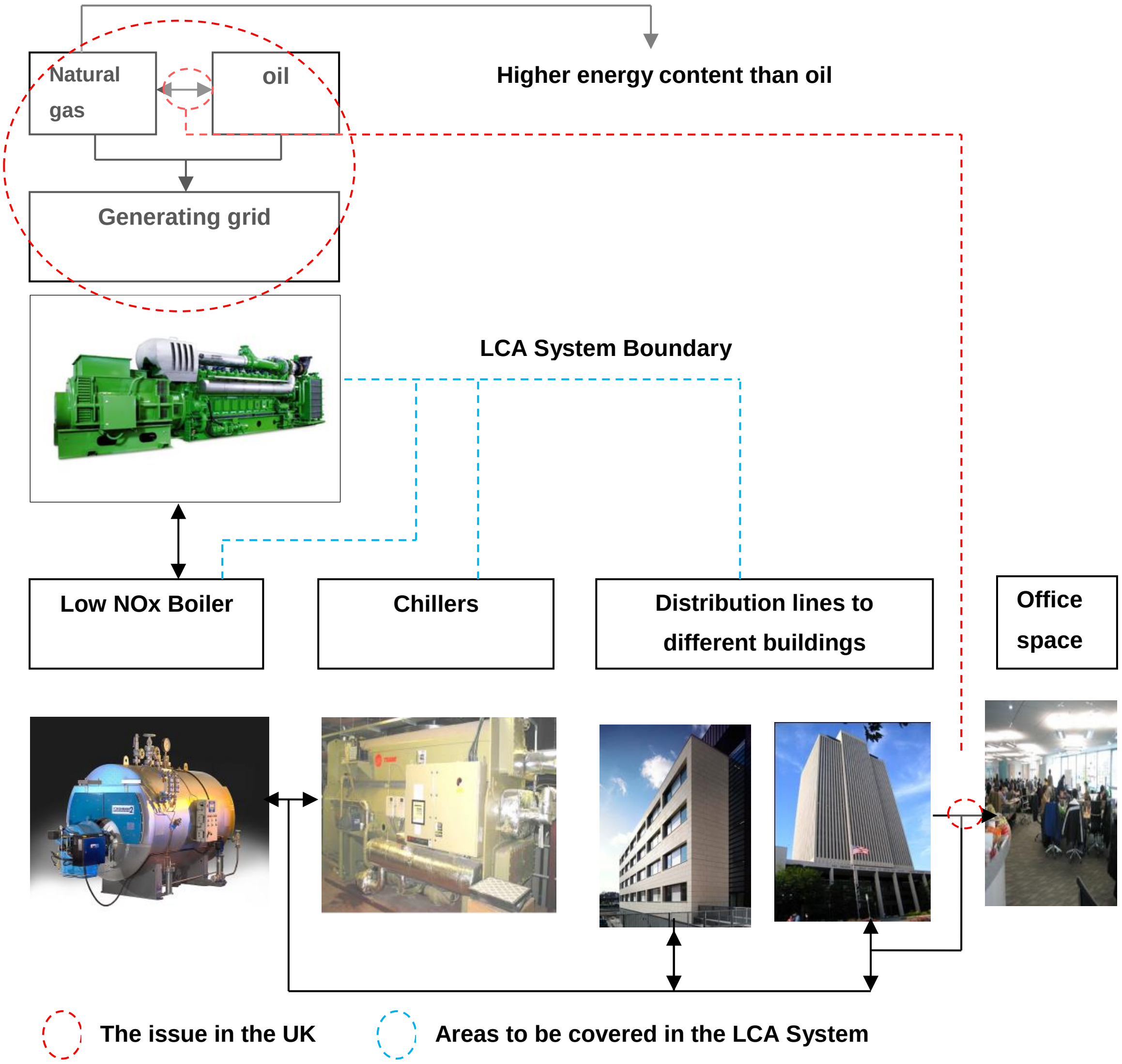

Figure 5.35: CHP power distribution that serves also heating and cooling

Source: Own interpretation

An important point that is significant to draw attention to, is the change of the return temperature in the boiler which plays a significant role for the efficiency of the CHP as well. The senior mechanical engineer, Darius Dabrizi from the University of Central Lancashire, has pointed out that heat is usually produced between 90-110 ^{0}C. The heat temperature in the LTHW pumps drops by 20 ^{0}C and goes down to 80 ^{0}C. This is the temperature of the heat that radiates from the radiators. The remaining radiators not provided to heat the office space, returns to the boilers and goes through a repitable burning process. If the water temperature of the return heat is below 45 ^{0}C, the heat is rejected from the system and flues are relased in the atmosphere (figure 5.36).

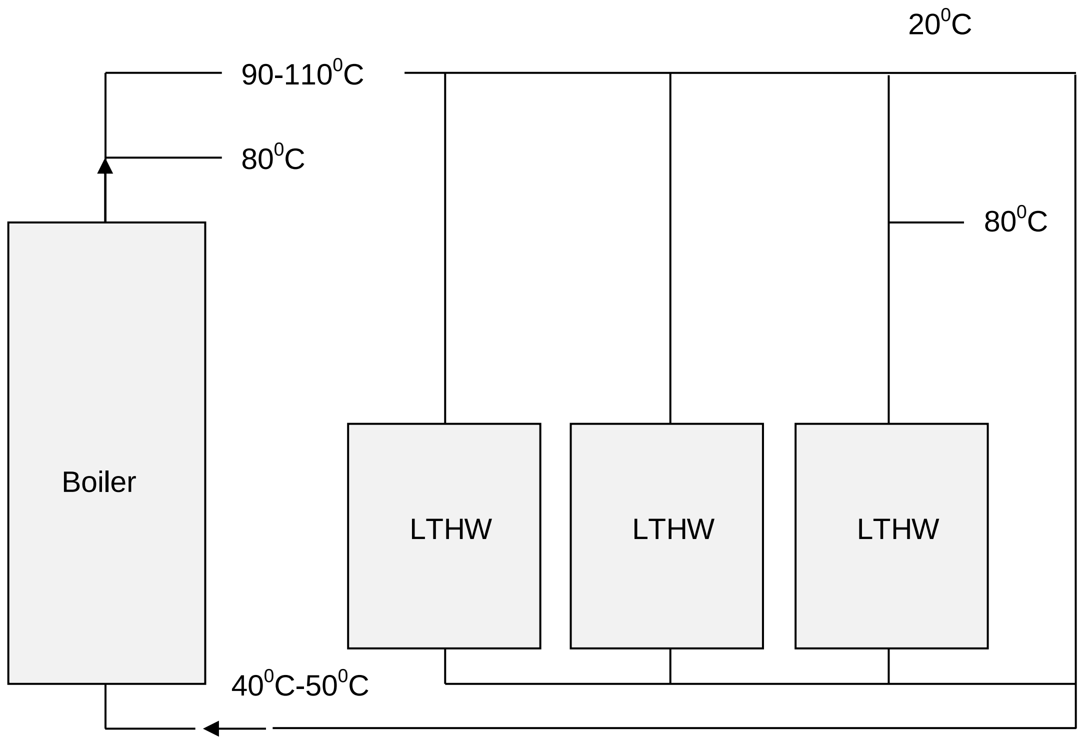

Figure 5.36: Schematic from the temperature change in the CHP

Source: Discussion with Darious Dabrizi, expert in mechanical engineering, University of Central Lancashire, SBNE

Another point of view by CIBSE (CIBSE 2009 p.12) is that low temperature return water enters the condensing heat exchanger and cools the flue gases. If the water is less than about 55°C the water vapour in the flue gases is condensed and latent heat is given up. The lower the return water temperature, the more condensation produced and the greater the efficiency. Therefore, the 45 ^{0}C return water temperature is for non-condensing boilers (CIBSE 2010). The return water temperature is the most possible cause of failure in a CHP unit tripping out, when the return temperature is too high. The solution is to modulate CHP to ''off'' on increase of building water return temprature or transfer heating control to building return water temperature (this could result in flow temperatures lower than allowed (CIBSE 2010 p.140). Other technical characteristics that enhance the efficiency of the CHP are shown in table 40. Further characteristics of the heating system operational are presented in the MATRIX at appendix 8 and in the logbook at appendix 19.

Table 5.6: Technical features that enhance the efficiency of the CHP

Feature	Description	Advantage
Four-valve cylinder head	Centrally located purge pre-combustion chamber, developed using advanced calculation and simulation methods	-minimised charge-exchange losses -highly efficient and stable combustion -optimal ignition conditions
Heat recovery	The heat exchanger can be specified as a two-stage plate heat exchanger	Maximum thermal efficiency even at high and fluctuating return temperatures
Pre-combustion chamber	The ignition energy of the spark plug is amplified in the pre-combustion chamber	-highest efficiency -lowest NOx emission values -stable and reliable combustion
Special gas mixer	Specific version for special gases with low calorific values	-trouble-free operation with special gases with large calorific value differences

Source: GE Energy CHP with Jenbacher gas engines, brochure, technical features.

Another advantage of the CHP in the Potterrow building has to do with the cost reductions (appendix 18). Investmet in conventional building services cost £140,000 while the CHP costs £40,000, ie, a saving of £100.000. The basement construction cost for the conventional system has been estimated at £182,000 and for the CHP £98,000, ie, a saving of £84,000. Therefore the total construction savings are £184,000.

Sustainable refurbished office building, Elizabeth Courts II, Winchester

The heating system includes three natural gas condensing boilers located in the plantroom, provided with modulated-burners (figure 5.37).

LTHW is generated by the three boilers located inside the building (Ashburton Court 2010b) (figures 5.37, 5.38). The LTHW system is topped up with cold water and maintained at a constant pressure by a packaged pressurisation unit located adjacent to the boilers. LTHW is taken from the boilers to serve a number of secondary circuits: the HWS preheat vessel and unit heater located in the plant room, the existing basement heating circuit, the radiator variable temperature circuit and there is also feeding in the air handling unit (AHU) of the ventilation circuit (Ashburton Court 2010b). Radiators, an overdoor heater located over the entrance doors, an overdoor heater, underfloor heating serving the corridor, the break-out area, the auditorium and the restaurant are served from the variable temperature radiator circuit (Ashburton Court 2010b). The plate heat exchangers connected to the condenser heat recovery system to supply the AHU heating coils are served from the constant temperate AHU circuit. VRV air-conditioning has been installed to provide additional heating and cooling to each enclosed office and copy areas (Ashburton Court 2010b). The plate heat exchangers are installed as a duty and standby pair, with LTHW flowing into the primary side at a temperature of 50 ^{0}C and heat recovery condenser water from the dry-air coolers flowing through the secondary side and into the air-handling unit heating coils at a temperature of 40 ^{0}C (Ashburton Court 2010b). A single pump is installed on the secondary flow connection to each plate heat exchanger (Ashburton Court 2010b). The heating system consists of the following equipment:

- 3 main boilers
- 1 pressurisation unit
- 16 pumps
- 1 heat exchanger
- 434 radiators
- 1 overdoor heater
- 1 underfloor heating
- 1 unit heater

Figure 5.37: The three natural gas boilers in the plantroom of Elizabeth Courts II from the site visit.

Source: Site visit

Figure 5.38: Plantroom of Elizabeth Courts II showing LTHW pipes connected to the boilers

Source: Site visit

The heating process is similar to Argyle House with the difference that this system has three natural gas condensing boilers and heat exchangers. Additional VRF[8] mechanical equipment from electricity operate for heating in meeting rooms. The heating process explained is shown in figure 5.39.

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[8] Variable refrigerant flow (vrf) also known as variable refrigerant volume (vrv). This type of system consists of a number of air handling units (possibly up to 48) connected to a modular external condensing unit. The refrigerant flow is varied using either an inverter controlled variable speed compressor, or multiple compressors of varying capacity in response to changes in the cooling or heating requirement within the air conditioned space.

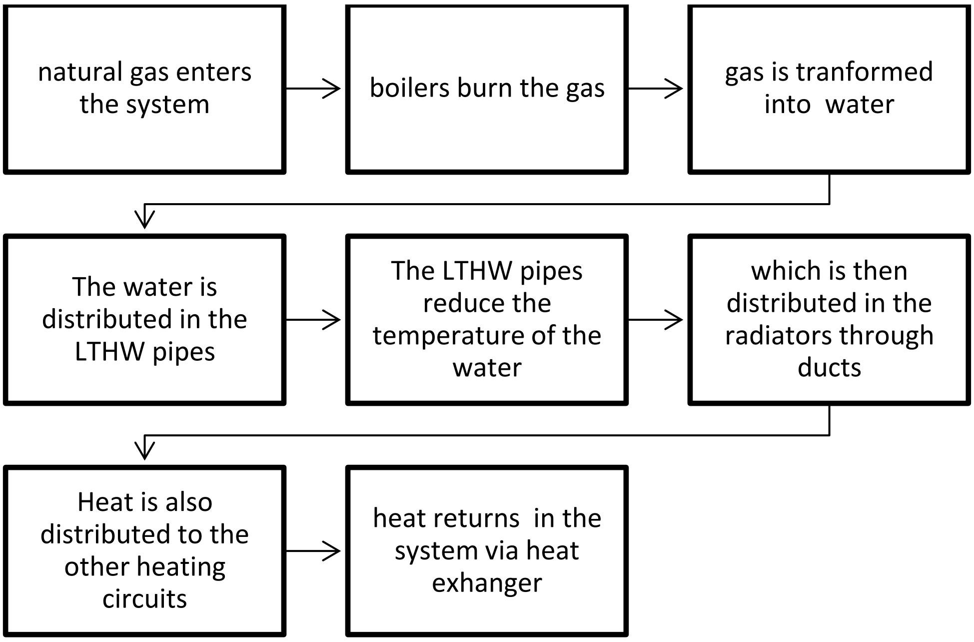

Figure 5.39: Description of the heating process

LTHW boilers produce hot water at 90^0C. Condensing boilers use heat exchangers when the heat returns in the boiler to reduce the heat temperature so that most of it condenses. This process defines the 89% efficiency (Carbon Trust 2006 p.4). The advantage of the condensing heating system is that exhaust gases are recovered through the use of the heat exchanger (Carbon Trust 2006 p.9). Increasing the temperature of the combustion air by 20^0C, it improves the overall efficiency of the boiler by 1% (Carbon Trust 2006 p.9). Insulation on boiler and pipework is important to avoid heat losses (Carbon Trust 2006 p.8). Maintenance is expected to be yearly for the full system and quarterly for the flue gas and the life expectancy is for about 15 years (Carbon Trust 2006 p.15,16). According to Carbon Trust guidance, the efficiency of the heating systems depends on (Carbon Trust 2006; Carbon Trust 2008 p,1;Centre for Alternative Technology 2010):

- Good combustion of fuels
- Good heat transfer to the hot water
- Low losses
- Use of large heat exchangers to extract as much heat from the flue gases as possible
- Right size of boiler
- Proper installation
- Heat exchanger should be made from non-corrosive material
- Getting radiators and pipes flushed out
- A' rating boilers
- Building insulation

- Heating system insulation
- Compatible with low-temperature applications

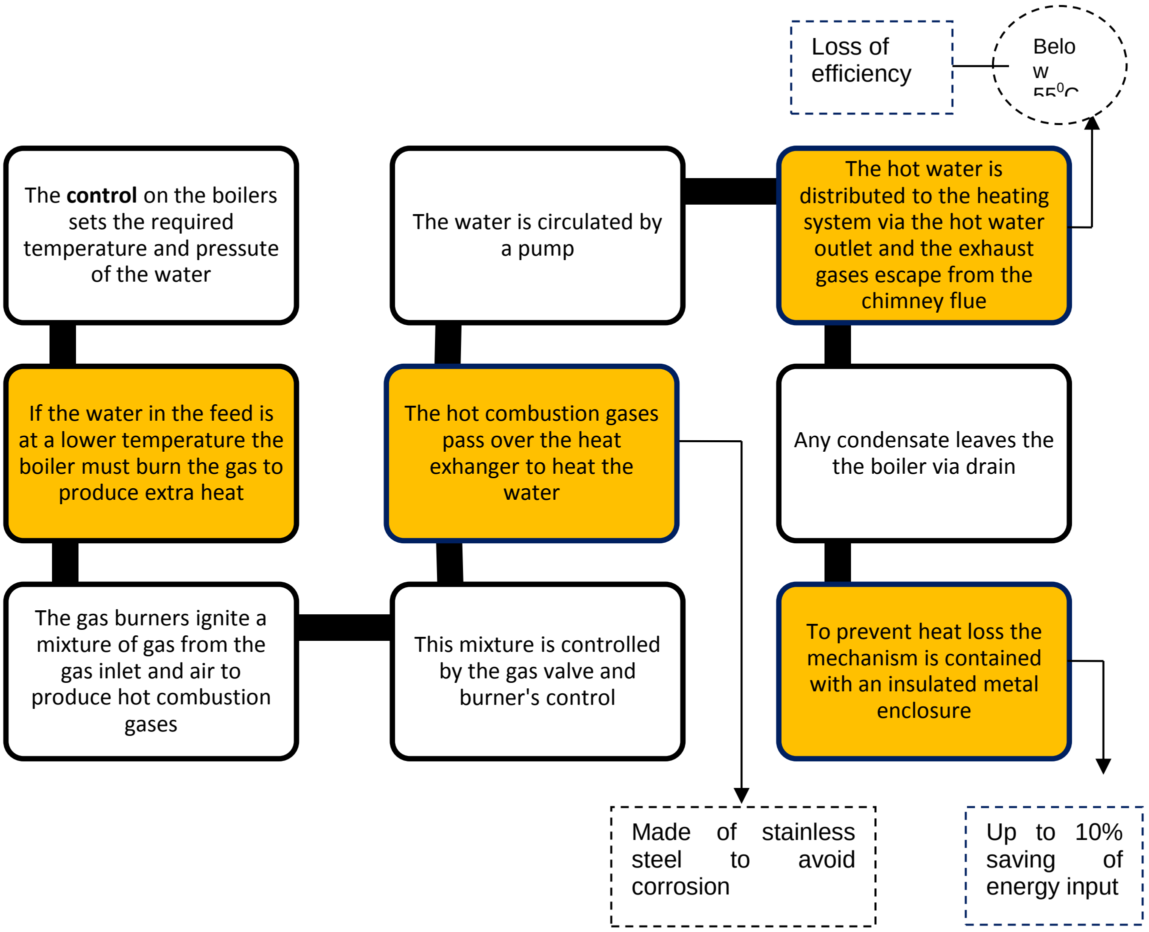

Figure 5.40: Emerging areas for consideration in order to enhance energy efficiency. The amber highlighted areas play an important role in energy efficiency.

Source: Own interpretation

Conventional office building, Five Ways House, Birmingham

The system is a two pipe flow and return central heating system (figure 5.41). The three boilers are used directly for the central heating of the site (figure 5.42). They are rotated on a weekly basis for optimum use and asset longevity. The old boilers used to run on a 24/7 basis with no BMS control over operation. When these three boilers were installed with associated BMS controls, usage and temperature controls could be revised and set to achieve optimum performance and a reduction in energy consumed. There is an exchange system in boilers only in the way that they are rotated on a weekly basis to maximize asset performance and life expectancy and minimize maintenance costs (Colin 2010)

Figure 5.41: The three natural gas boilers in the plantroom of Five Ways House

Source: Site visit

Figure 5.42: The radiators were installed in 1990s inside the office enclosed rooms

Source: Site visit

Gas fuel consumption is based on natural gas with a gross calorific value of 38.6 MJ/m^3 (Potterton Commercial 2010 p.3). The Potterton NXR4 is a cast iron sectional boiler available in outputs from 320 kW to 800 kW. The heat transfer surfaces of the NXR4 have been specially designed to maximise boiler efficiency and the large combustion chamber capacity ensures environmentally sound combustion reducing CO_2 and NOx emissions. Specially designed and pre-wired control panels allow full boiler control and flow and return manifolds have facilities to fit sensor pockets for boiler management. The NXR4 is an overpressure type with 5-pass reverse flame design. The first two passes are in the combustion chamber the rest in the convection tubes where turbulence to achieve high heat transfer is generated by the extended surface area achieving efficiencies of 92% (net), 86% (gross) (Potterton Commercial 2010 p.5). The controls on the boiler set the required temperature and pressure of the water. If the water in the feed (the return water) is at a lower temperature than required, the boiler must ‘fire’ to produce heat, i.e. it must burn fuel. The gas burners ignite a mixture of gas (from the gas inlet) and air (from the boiler surroundings) to produce hot combustion gases. The precise mixture of gas and air is controlled by the gas valve and burner controls (this is covered in further detail later). The hot combustion gases pass over the heat exchanger (a network of pipes) to heat the circulating water within. This water is circulated by a pump. The resultant hot water is distributed to the heating system via the hot water outlet and the exhaust gases escape to the atmosphere via a flue or chimney . Any condensate leaves the boiler via a drain . To prevent heat loss from the boiler, the whole mechanism is contained within an insulated metal enclosure (Carbon Trust 2006 p.4).

All the heating systems mentioned above are summarised in table 5.7 below.

Table 5.7: Characteristics of the heating system on the conventional and on the sustainable case study office buildings

	Argyle House (conventional)	**Potterrow building (sustainable new)**	**Five Ways House (conventional)**	**Elizabeth Courts II (sustainable refurbished)**
				
Types	-Central heating -Oil tank supply -Oil fuel -One-pipe LTHW system	-District CHP heating -Gas pipes supply -Natural gas condensing -Manifold LTHW system	-Central heating -Gas pipes supply -Natural gas -Two-pipe LTHW system (direct return)	-Central heating -Gas pipes supply -Natural gas condensing -Pumped primary/pumped secondary LTHW system (direct return)
	-one heating circuit and one meter	-Variable flow -Different heating circuits, and sub-meters	-one heating circuit and one meter	-Variable flow -Different heating circuits and one meter -Back up heating supply via VRF/VRV air conditioning
	-control switching on/off -no insulation on pipes -no ducts	-insulated pipes -use of ducts (appendix 10)	-MBS control -no insulation on pipes -use of ducts	-insulated pipes -use of ducts (appendix 10)
Energy efficiency	Poor	High	Good	High
Space requirements	-moderate to low plant space in the basement	-low plant for heating as CHP district is located outside of the building -high use of space by ducts (appendix 10)	-moderate to low plant space in the basement -moderate use of space by ducts	-moderate plantroom space for heating in the basement - moderate use of space by ducts (appendix 10)

Source: Own interpretation and guidance from (Saulles 2002a).

5.4.2 Influential factors for energy efficiency

The selection of different heating/cooling equipment in office buildings must meet certain strategic criteria related to planning, sustainability, occupancy, building use and thermal comfort.

In terms of the sustainability criteria what is considered is (CIBSE 2010):

- Delivery of required indoor temperature within client budget
- Efficiency in costs and emissions
- Sustain performance in the long run with limited need for maintenance or replacements
- Compliance with legal requirements

In terms of the occupancy and the building use the considerations are (CIBSE 2010):

- Period of occupancy
- Heat gains from occupancy
- Requirements in all building areas (zones)
- Adaptation to re-allocation of space

The building considerable influential parameters are (CIBSE 2010):

- Building form-orientation
- Building layout (window, thermal mass, radiation, convection, fabric insulation, volume of space, size of the building)
- Building air-tightness and ventilation
- Requirement for heating space and hot water
- Pre-heat time

For instance, the large office building Argyle House has been designed with long office open plan spaces (up to 50 m^2), with different building blocks. In order for the heating to heat the whole building, a central heating system was selected in the 1960s with perimeter radiators. Argyle house talks longer to pre-heat (see daily hours of heating operation in MATRIX table, appendix 8). All the above characteristics play a significant role in decision making for the selection of heating/cooling technologies; such as their size, heating/cooling capacity, space requirements inside or outside of the building, the type of heating/cooling, the amount of equipment needed.

Another important parameter of energy efficiency of the heating/cooling system is the control system; in the Potterrow building, radiators and trench heaters have been divided into zones, controlled by thermostats with indoor set temperature at 21 ^{0}C and underfloor heating controlled through wall mounted temperature sensors.

One of the most significant areas for consideration that influences the efficiency of heating systems is the practical use of the CHP used in the Potterrow office building (hours of daily and seasonal operation), the return temperature, the type of fuel as well as the set temperature parameters. In order to rate which factors most influence the energy efficiency of the CHP for heating, an online survey was used (appendix 21). The participants rated as most important the following factors:

- Set temperature paremeters
- Fuel type
- Heat exhanger type
- Operational hours
- Return temperature
- Constant use of heat
- Alternative use of excess heat

In the same question about the energy efficiency of the CHP for cooling, the participants rated as most important the following parameters:

- Set temperature parameters
- Return temperature
- Operational hours
- Constant use of stored heat-excess heat
- Type of fuel

Another important question is about how the energy efficiency of the CHP can be enhanced in the summer period. The participants rated as most important the following approaches:

- Switch off the CHP
- Operation of the CHP only when needed
- Add renewables
- Use of the excess heat from another building on the site
- A seasonal flexible approach is needed
- Weekend controls may be different
- Systems should anticipate and provide optimum conditions

Back up heating is also provided via the VRV/VRF heating and cooling system that is further discussed in the following section.

The energy efficiencies of each building are different according to the building context. The most efficient heating system is the manifold system and the pumped primary/pumped secondary system as they give the possibility for direct heat in the areas needed. The CHP network is the most current state of the art technology in terms of energy efficiency and environmental impact reductions but its efficiency depends on several factors, as explained previously. Its efficiency can be significantly influenced in the summer days when there is no need for heating and if there is no need for cooling. The benefits and limitations of the heating systems are presented in table 5.8.

Table 5.825: Characteristics of the heating systems identified from the case study buildings

	Heating system types			
	Argyle House (conventional)	**Potterrow building (sustainable new)**	**Five Ways House (conventional)**	**Elizabeth Courts II (sustainable refurbished)**
	One-pipes oil fired systems	**CHP district natural gas fired-condensing/ Manifold system**	**Two-pipe direct return natural gas fired system**	**Pumped primary/pumped secondary LTHW system (direct return)**
Benefits	-moderate use of plantroom space	-reduces primary energy consumption -high energy efficiency -simultaneously generates both its thermal and electrical energy providing cooling as well -reduction in NOx and SO_2 and CO_2. -independence in control -condensing boilers that use latent heat -moderate building plantroom space as the CHP unit is located outside of the building -different heating options according to the building room and side needs -half size of total heating equipment compared to a conventional office building -use of thermostats and sensors for heating when needed wherever needed	-moderate use of plantroom space -condensing boilers -1185 radiators can be directly switched on/off through radiator valves -BMS control	-The primary pump run all the time, and the secondary pumps can be cycled on and off to create independent zones -independent control -less heating consumption through better control and secondary pumped system -back up heating from VRF/VRF

	Heating system types			
Limitations	-two old boilers with low efficiency -oil fuel consumption has higher contribution to CO2 emissions - 1892 radiators that demand an increased number of un-insulated pipes also continuous heat output from boilers –more operational hours and high -heating is provided gradually which means more times for other building areas to be heated. -waste of heat production in unoccupied areas -frequent maintenance -set point parameters for heating for different building zones -low unused water return temperature -no back up heating supply	-increased number of pipes for CHP connection with the building services -increased number of pipes for different heating circuits to serve different technologies -sub metering can be problematic if not done properly -efficiency of the CHP depends on several factors like the water temperature return, practical use of the CHP in the summer -constant operation of the CHP unit to serve different or sometimes low heating demand in the building	-set point temperature parameters for heating different building zones -no back up heating supply Occupancy complaints about the indoor set temperature comfort and parameters	-higher plantroom space -different heating circuits require more space and more pipes which they need additional space

Source: Own interpretation and guidance from (Saulles 2002a)

5.4.3 Cooling system

In terms of the cooling system, different types of cooling system have been identified across the case study buildings, as shown in table 43:

Conventional office building, Argyle House, Edinburgh

In the cooling system of Argyle House, there is a large quantity of equipment used, ranging from outdoor heat pumps and indoor air-conditioners (figure 138, 139). In the archives, there is no information about the exact amount of operated cooling equipment. The building schedules provide a list of the air-conditioners installed in the building and their location, although mechanical specifications giving sizes and particular information on the equipment's characteristics does not exist. Therefore, a recording-measurement survey was conducted of the installed outdoor and indoor equipment during one of the site visits (appendix 20). It was found that some equipment does not operate, due in tome part to age and in some part to technical/mechanical faults and due to the fact that the occupancy number since 2004 has decreased. Most of the equipment recorded is located mainly in the server rooms and in the comms rooms. After a walkthrough of the building it was observed that the large server room in the plantroom area of the basement is fully operational with all the air-conditioners installed. Apart from that, for each floor and for each block, air-conditioners are installed in separate small server rooms. The negative aspect of the cooling equipments relates to the refrigerant types used since the equipment was first installed in the building

Figure 5.43: Air-conditioner recorded in the IT server rooms

Source: Site visit

Figure 5.44: Air-conditioner recorded in the meeting room

Source: Site visit

Sustainable office building, Potterrow Building, Edinburgh

Cooling energy is provided to Potterrow in the form of chilled water supplied from the CHP campus network (figures 5.32, 5.45 and appendix 16).

Figure 5.45: A 600 kW Absorption chiller in the Potterrow building in Edinburgh

Source: David Barratt, engineering operations manager, E&B Works Division, University of Edinburgh

A water cooled chiller in the basement allows for the peak summer CHW load for the building, as well as providing resilience for the server room and to rooms with expected high heat gains such as labs or meeting rooms. The primary provision of chilled water for cooling to the building comes from the University's central network. This network provides 150 mm diameter flow and return CHW pipes to the Potterrow site. The network is variable flow to respond to cooling demands from the different buildings on campus. Incoming CHW pipework has been insulated in phenolic foam and route in the basement corridor to the Phase 1 CHP Room (Kilpatrick 2009).

In the Potterrow building it forms a main header from which the following supplies are taken off (Kilpatrick 2009):

- Phase 1 CHW Circuit (figure 178)
- Phase 2A CHW Circuit (figure 179)

The Phase 2A circuit initially only provides chilled water to Phase 2A, but it has been sized to allow for future Phase 2B loads. System pressurisation, expansion and chemical dosing are provided from the central CHP network (Kilpatrick 2009). As a backup to this supply, a water to water chiller is installed in the Phase 1 Basement. This rejects heat to a dry air cooler mounted at roof level. This primarilys act to provide 100% redundancy of supply in the Phase 1 server room; although it has been available to provide cooling to the server rooms in peak summer conditions to allow the main incoming CHW supply to provide peak lopping to the AHUs. This chiller has been installed on an independent secondary circuit, complete with its own pressurisation unit, expansion vessel, dosing set and run / standby pumps (Kilpatrick 2009).

BMS monitors the temperature of the incoming and outgoing chilled water through stats located in a normally active area of pipework. If the temperature indicates that the supply from the central campus has been interrupted or is not sufficient for the building's needs, the backup chiller and associated plant is enabled. The flow and return temperatures are compared against the external ambient temperature to determine whether central CHW plant is operating in summer or winter mode (changeover at 10 degrees). A 2 degree margin has been allowed for sensor variation. This plant operates until normal CHW supply resumes or until the building load reduces sufficiently for a half hour period (Kilpatrick 2009).

In the case where the backup chiller fails and the CHPc supply is not sufficient for the whole building's needs, the motorised valve in the CHP room closes, ensuring that all chilled water is reserved for the server room until the demand reduces (Kilpatrick 2009).

CHW circuits are metered and submetered with main incoming heat meters capable of giving pulsed output. CHW circuits have been provided to serve the Air-Handling Units' cooling coils and local cooling devices throughout the building. Each coil and main cooling device is controlled by a 2 port valve ensuring that the system operates in a variable flow mode, in sympathy with the central campus network. Each main CHW branch includes a differential pressure valve in the riser to ensure that CHW flow rate can be modulated without pressure fluctuations adversely affecting upstream plant. Local fan coil units have generally been concealed in floor voids (Kilpatrick 2009).

The Phase 1 server room is served by 4 close control downflow units (run/ run /run/standby) located in the room to provide temperature and humidity control. This is typically served from the main CHW network. However, under designated conditions the 2 port valves on this section of the circuit activates and allows chilled water to be provided from the backup chiller. The Phase 2A server room is similarly served by 2 downflow units but is not backed up by a standby chiller and instead relies upon the resilience provided by the central campus cooling system (Kilpatrick 2009).

In general, absorption chillers provide an economic and environmental alternative to conventional refrigeration. Combining high efficiency, low emission power generation equipment with absorption chillers allows for maximum total fuel efficiency, elimination of HCFC/CFC refrigerants and reduced overall air emissions (GE Energy 2011).

Chillers produce chilled water by heating two substances, refrigerant water and lithium bromide salt to achieve temperatures between 4-12^{0}C. To achieve lower temperatures (-60^{0}C) , ammonia refrigerant with water absorbent are used (GE Energy 2011 p.2). Combining a cogeneration plant with an absorption refrigeration system allows utilization of seasonal excess heat for cooling. The hot water from the cooling circuit of the cogeneration plant serves as drive energy for the absorption chiller. Up to 80% of the thermal output of the cogeneration plant is thereby converted to chilled water. In this way, the year-round capacity utilization and the overall efficiency of the cogeneration plant can be increased significantly (GE Energy 2011 p.2). In addition to the simultaneous production of heat and power, CHP can also be used to provide cooling for air-conditioned buildings. This process, known as ‘trigeneration’ or ‘combined cooling, heat and power’ (CCHP), combines CHP with a heat driven absorption chilling plant to extend the base load heat demand in the summer months to meet cooling loads that are economic and help to reduce CO_2 emissions. Trigeneration makes effective use of heat for large air-conditioned buildings that were previously unsuitable for CHP alone (CIBSE 2010 p.49).

Sustainable refurbished office building, Elizabeth Courts II, Winchester

The cooling system of the Elizabeth II Court consists of a chilled water system and of an indoor VRV air-conditioning system. The cooling equipment installed in the building is:

- 3 chillers
- 1 pressurisation unit
- 8 pumps
- 1 buffer vessel
- 3 dry coolers
- 40 air-conditioners

Chilled water is generated by 3 chiller units located in the basement plantroom (figure 5.46). The chillers are water-cooled units with duplex refrigeration circuits, semi-hermetic twin-screw compressors with BMS controls to receive on/off and set point adjustments signals and providing monitoring information (Ashburton Court 2010a). The chilled hot water (CHW) system is topped up with cold water and maintained at a constant pressure by a pressurisation unit located in the plantroom, and mechanical drawings appendix 15) (Ashburton Court 2010a) .

Figure 5.46: The 3 installed chillers in the plantroom of Elizabeth Courts II.

Source: Site visit

Figure 5.47: Water tank. Hot Water and partial cooling only in the Data Centre

Source: Site visit

CHW from the chiller is pumped by a primary twin head pump installed in the return connection, from where it is taken to serve conditioning units in the Data Centre (figure 5.47) and Uninterruptible Power Supply (UPS) Room (Ashburton Court 2010a). Cooling in the chillers is fed by 3 adiabatic air chillers located on the 4th floor roof plant area (Ashburton Court 2010a). The condenser water system is topped up with cold water and maintained at a constant pressure by a pressurisation unit located in the roof plantroom and it is pumped by a primary twin head pump (Ashburton Court 2010a).

A connection has been taken from the heat recovery condenser plant to serve heating coils installed within air handling units (AHU) with additional heat provided via the plate heat exchanger located in the basement plantroom (Ashburton Court 2010a).

VRV air conditioning has been installed (see schematic figure 5.48) to provide additional heating and cooling to each enclosed office and the Level 3 copy area, with cooling only VRV air conditioning provided in the copy areas at podium, 1st and 2nd floor levels and the IT hub rooms, and cooling only DX[9] air conditioning systems serving IT hub rooms (Ashburton Court 2010a). The VRV air conditioning units serving partitioned office areas are floor-mounted units which draw air from the floor void (Ashburton Court 2010a). The air is filtered and heated or cooled as necessary before being discharged back in the room (Ashburton Court 2010a). Cooling to the VRV units is by external condenser units located at roof level with on unit designed to serve each zone of the building. The IT hub rooms are provided with wall-mounted VRV unit and a wall-mounted DX split system air conditioning of similar construction to the VRV unit (Ashburton Court 2010a). This arrangement provides a standby backup in the event of unit failing and allows the VRV to be shut down outside of occupied ours when heat gains are likely to be small (Ashburton Court 2010a). Air conditioning is provided to the Data Centre and UPS room by 8 downflow air conditioning units. The units draw air through an intake grille mounted at the top, where it is cooled by a cooling coil connected to the building CHW system, then discharged into the space through a low-level grille (Ashburton Court 2010a).

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[9] In the DX system the air used for cooling the room or space is directly passed over the cooling coil of the refrigeration plant (Khemani 2009).

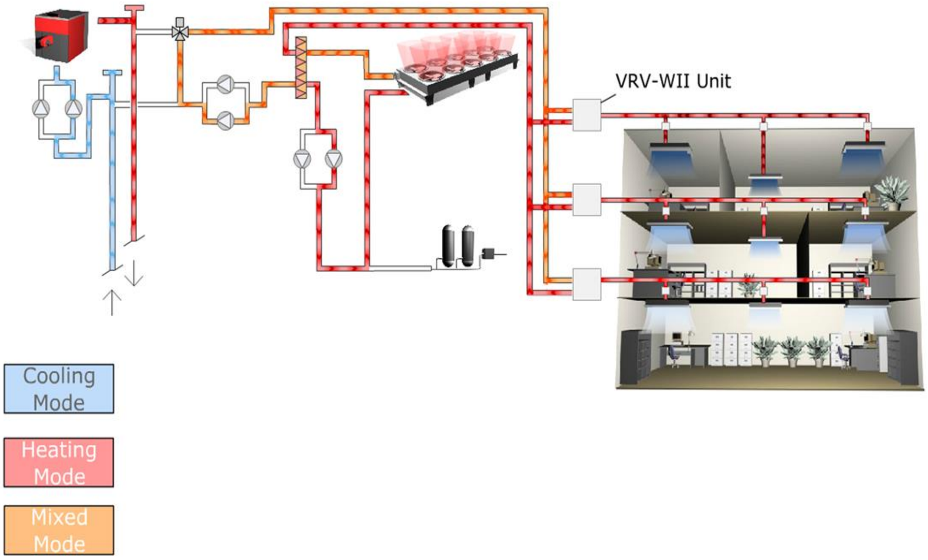


Figure 5.48: VRV air conditioning schematic

Source: Daikin, water cooled VRV-the next generation of VRV

A standby pump is also provided in the event of the duty pump failing. To maintain a minimum chilled water system content, a galvanised mild steel buffer vessel has been installed in the return water pipework prior to the pumps.

Conventional office building, Five Ways House, Birmingham

In terms of cooling, typical single and double heat pumps are located outside the building and in the roof of the building, which supply air to the air-conditioners inside the building (figures 5.49, 5.50). The air-conditioners have been installed for approximately 15 years and they are installed on each floor inside the server rooms.Two different types have been isntalled, the one is wall-mounted and the other is wall and floor-mounted over the door. In total 12 air-conditioners have been installed in the server rooms in the 6th floor building. Schmatic drawings of the cooling system do not exist.

Figure 5.49: Outdoor heat pumps

Source: Site visit

Figure 5.50: Indoor air-conditioners

Source: Site visit

The above cooling characteristics are presented in table 5.9 below.

Table 5.9: Characteristics of the cooling system in the conventional and the sustainable case study office buildings

	Argyle House	**Potterrow**	**Five Ways House**	**Elizabeth Courts II**
				
Types	1)Local System: -Split system air conditioning -Provides cooling in the immediate space where they are located	1)Centralised air system: -Displacement ventilation - variable flow to respond to cooling demands from the different buildings on campus -All plant located in a single area -One or more AHU condition the air supplied by ductwork through floor spaces -Chillers provide chilled water for cooling coils of the AHU through insulated phenolic foam pipework in phase 1 circuit and in phase 2 circuit (Hot water for heating coils is provided by boilers) -water to water chiller is installed in phase 1 basement which performs as a back up to the other chiller supply (above) -in case the backup chiller fails and the CHP supply is not sufficient the motorized valve in the server room closes	1)Local system: -Split system air conditioning -Provides cooling in the immediate space where they are located	1)Local system: -VRV air conditioning - waste heat from indoor units in cooling mode can be re-used to produce hot water or provide heat to other rooms - Used in buildings with multiple zones to match the particular cooling/heating demands of each zone -DX split air conditioning system 2) Centralised system: - CHW supplied by chillers located in the basement to feed air conditions in the Data Centre and UPS rooms. Cold water is provided in the chillers and in the condenser unit of the AHU

	Argyle House	**Potterrow**	**Five Ways House**	**Elizabeth Courts II**
Energy efficiency	Poor	Very good	Poor	Good to average
CO_2	75kgm^2/y	No data	50 kgm^2/y	75 kgm^2/y
Space requirements	-Low plant -None/moderate occupied area None ducts	-Low plant -None/moderate occupied space Moderate ducts	-Low plant -None/moderate occupied area	-Low plant -None/moderate occupied area

Source: Own interpretation and guidance from (Saulles 2002a).

Table 5.10 presents the benefits and the limitations of these systems as well as a summary of the basic components used in these systems (see also MATRIX, appendix 8).

Table 26: Characteristics of the cooling systems identified from the case study buildings

	Cooling system types		
	Split Units	**Partially centralised/centralised**	**VRF/VRV**
Benefits	-they do not require any form of centralised plant space within the building	-the size of the ductwork installation and associated air handling plant is smaller than that required by the centralised air system. (This is because, unlike a centralised air system, air is only required for ventilation and consequently the high volume of air necessary to provide the building's heating/cooling is avoided).	-provides simultaneous cooling -doesn't require plantroom area -relatively energy efficient due to the ability to reduce the speed of the supply/extract fan(s)
Basic components	-indoor room cooling unit -outdoor refrigeration unit which dumps heat taken from the building -linked by pipes	-chilled water is pumped around 1 or more cooling coils in central AHU as well as in fan coils if installed in the building. -separate chiller and heat rejection plant linked with pipework -heat rejection takes the form of evaporative cooling tower (see schematic appendix 9)	-concealed indoor fun coils types can be configured to provide fresh air -heat rejection via dry air cooler
Limitations	-can serve a single internal zone -it can't provide simultaneous heating or cooling -recirculation of room air (they don't act as ventilation)	-low cooling capacity, although displacement systems are normally used in conjunction with another cooling system, such as chilled ceilings. Ventilation terminals can be large and take up floor/wall space.	-space requirements are high in both the plant room and ceiling voids -significant amount of refrigerant passes through occupied space. (if leaks occur that will be a problem) -system must be of high standard to ensure good performance and reliability

Source: Own interpretation and guidance from (Saulles 2002).

The cooling system in the conventional office buildings is a local system with split indoor air conditioners and outdoor heat pumps that serve only the server rooms 24 hours/day and the meeting rooms only when needed. The office spaces are natural ventilated. This type of cooling does not require plantroom space, no further and large equipment is installed in the plantroom and no ductwork has been used. Also refrigeration risks are less due to the split air-conditioning systems (refrigerant does not pass through occupied space).

One of the limitations of the split units is in the control of the system, which means no switching on/off is provided and serving different zones with different temperature in the building is not possible as with the VRV cooling system in the Elizabeth Courts II. Also a split unit system means that each air conditioner has its own heat pumps outside of the building/roof, which is not good for the aesthetics.

In terms of comfort the occupants seem to be satisfied with openable windows. The FM manager has explained that *''comfort is perception''* (see interview remarks, appendix 22). Occupants see the thermometer and they are influenced by what they see. The set point parameters of Argyle House for cooling are 24^{0}C and for heating 21^{0}C, which are, “outrageous temperatures”, according to the occupants (appendix 21). In UK the summer outside maximum temperatures are comfortable so that natural ventilation is assumed to be just enough for cooling the indoor office spaces but when someone actually spends time inside the conventional buildings, in different zones, the differences in the indoor temperature can be realised, therefore the need for cooling. If just in case mechanical cooling is needed in the office space, this need cannot be served and this is a limitation.

5.5 Discussion

The discussion of this chapter is upon two key thematic areas unfolded from this chapter:

1. The differences between sustainable and conventional office buildings
2. Influential factors and parameters that influence the two environmental performance indicators examined in this study; energy efficiency and raw-material efficiency and finally discussion

5.5.1 Key differences between sustainable and conventional office buildings

Argyle House and the Potterrow building are located in the Old Town of Edinburgh within a close distance to each other, although Argyle House is oriented to the South and Potterrow building to the West. Argyle House is surrounded by other traditional commercial buildings, by fences and by other structures that shadow parts of the south and the west side of the building and the east side completely. The Potterrow building is also surrounded by other commercial buildings although the building design-shape has been made considering the surroundings.

Even though both buildings are in the same location their difference is that Argyle House was built in 1960s where local temperatures were different from the local temperatures considered in designing the Potterrow Building. This is the reason that the functional unit of the LCA comparison is for two years of operation in 2009 and 2010. In terms of the building construction, pre-cast concrete has been used in both cases but with difference in the design and texture and with key differences in the U-values and the surface pattern and installation. This is a key characteristic of the Potterrow building and can be recognised from the facades. The pattern used in the stoned-pre-cast concrete panels and in the windows is to allow flexibility for future changes in the interior layout as well as to maximise heat gains from the sun. Thus the shape and the size of these structures, U-values and insulations are within the passive building principles.

In contrast, the window pattern of the Argyle House is the same parametrical, covering about 70% of the building surface, installed in a high position close to the ceiling, without considering heat gains from the different sides of the buildings. The structural exterior walls and the interiors have no insulation. Double glazing from PVC is not enough to protect the office spaces from outside temperatures. Another highly important difference is the layout of the indoor office spaces and the occupancy pattern. In Argyle House the ceiling height is about 3.5 meters with most of the office area open-plan and unoccupied. About 30% of the building is currently occupied. What has been realised from looking at the office building benchmarks in the literature (ECG19, 2003), the benchmark for the heating consumptions for instance is taken by m^2 however it is the volume of space that has to be considered in heating a room. If a room has a higher volume of space then it will demand more heating output. If the heating volume of space is large, if doors are not properly sealed and if there are unoccupied large areas in a building, such as those in Argyle House, heat tends to escape and the occupied office spaces will constantly lose their temperature (figure 5.51). Thus the building zones will need different set point temperature parameters. Buildings with several unoccupied rooms are more vulnerable to the external climate.

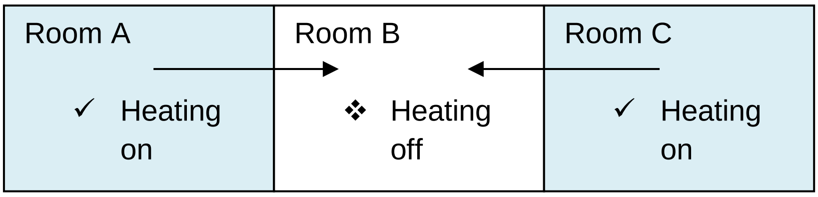


Figure 5.51: Escape of heat in the area that is not heated

Source: Own interpretation

It must also be considered that it is within the principles of design (Roaf, Fuentes, & Thomas 2009) that warm air goes up and the cold goes down and that the temperature on upper floors depends on outside temperatures and the temperatures on lower floors depend on the temperatures on the ground (figure 5.52) (Roaf, Fuentes, & Thomas 2009).

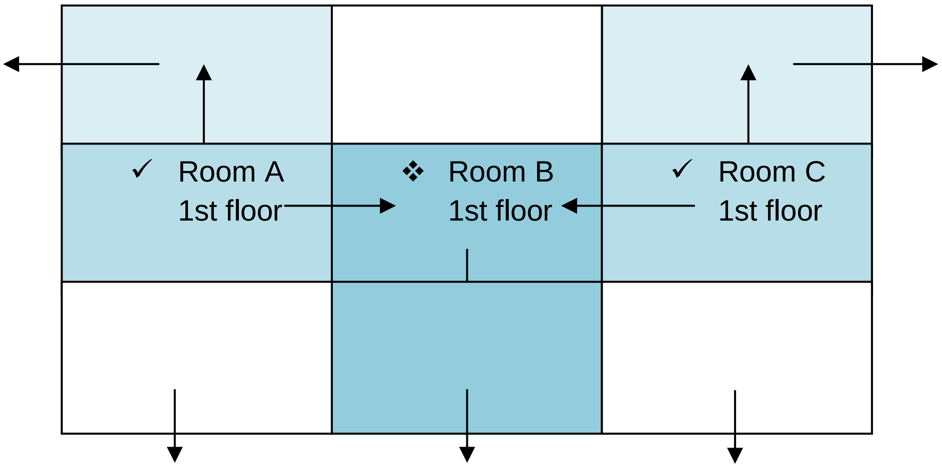


Figure 5.52: Heat escapes to unheated rooms on the first floor. Heat moves to the upper floors and cold temperatures move to the lower. The temperature in the upper rooms depends on the outside temperatures and that lower than the ground.

Source: Own interpretation

These big differences between the sustainable and the conventional office building are mainly due to the buildings being built in different periods. The Potterrow building has been built to achieve high carbon emission reduction targets according to building standards. The sustainable office building should be of higher concern than the conventional because the new building built now and in the last 4, 5 years there will be existing buildings in the 25 years.

In case study two, Five Ways House is located in Birmingham in the West Midlands and Elizabeth Courts II is located in Winchester, in the South East. Therefore there is some temperature difference. Five Ways House is oriented to the North while Elizabeth Courts is oriented to the West, as is the Potterrow building. Five Ways House has some issues with shadows from the surrounding buildings (commercial buildings) and structures from the South. Elizabeth Court is surrounded by lower residential buildings to the West, East and North at the height of the car parking of Elizabeth Court so the rest of the occupied building is not shadowed.

In terms of the temperature difference, apart from the location, Five Ways House was built in the 1950s when seasonal temperatures were lower than seasonal temperatures in 2009-2010 (section 5.4.4). Although temperatures were lower, the building was constructed without insulation, single-glazed with a window surface of about 80% and with windows installed parametrically close to the ceiling.

The two buildings also have differences in the office layout (see drawings in appendices). Five House Ways has an open plan office space apart from some meeting rooms with ceilings of approximately 3.5 meters, ie, a large volume of heating space to serve large and long office spaces on each floor. The building is fully occupied, meaning that heat from IT, lighting and body heat is increased, which is not the case in the conventional offices in Argyle House. This heat plus the heat produced from the central plant is not efficient considering the heat losses that this building can suffer (evaluated with thermography in chapter 6). Both buildings are naturally ventilated but a backup plan is provided in Elizabeth Court for extra cooling comfort whenever and where needed. The south facing aspect of Elizabeth Court is protected from the direct heat and glare with a shading system, whereas the south face of Five Ways House is partly exposed. The key difference between the two buildings is that in the construction of t Elizabeth Court, an environmental approach has been used with key features the exposed thermal mass, ventilation ducts and wind-troughs. Based on the key differences discussed between the case study buildings, table 5.11 ranks the building characteristics pros and cons which also demonstrate what has or has not been considered.

Table 5.11: Ranking of the sustainable and of the conventional office buildings according to the passive design building characteristics. One * indicates a bad example, three * indicates an average example and five ***** indicates a very good example. This data could also be translated as pros/cons and as the participants rated as most important the following factors considered/not considered.**

Ranking on building efficient performance factors	Potterrow Building	Argyle House	Elizabeth Courts II	Five Ways House
🟥 *				
🟨 **				
🟧 ***				
🟦 ****				
🟩 *****				
Passive Solar Principles-Factors				
Location				
efficient use of the planning grid/building shape	🟩	🟨	🟩	🟧
Orientation				
main orientation 30 degrees of the south	🟩 west & south	🟦 south	🟧 west	🟨 north
south facing slope		🟦		
neighbouring buildings to the east and west	🟩	🟨 shadowed	🟩	🟧 south side is shadowed
trees to the north (protection from wind)	🟧 west	🟨 south	🟨 west & east and south	🟨 east
roads run east and west	🟩	🟨 west only	🟩	🟧
orientation to the east-west to ensure a long side faces the sun	🟩	🟨	🟩	🟨
Shadows and surroundings				
optimize solar gain in winter-south facing windows not to be over-shadowed between 9am-3pm	🟩	🟧	🟦 shading system in the south	🟧
Weather conditions				
(t) on upper floors depends on the outside (t)	🟩	🟥	🟩	🟧
(t) on lower floors depends on the ground (t)	🟩	🟥	🟩	🟧
(t) depends from the between un-occupied/unheated rooms	🟩	🟥	🟩	🟧
warm air goes up, cold goes down	🟩	🟥	🟩	🟧
Building characteristics				
the bigger the volume the bigger the heat loss or heat gain	🟩	🟥	🟦	🟨
building shape	🟦	🟨	🟦	🟧
minimise the building surface to the volume area	🟦	🟨	🟦	🟨

Ranking on building efficient performance factors	**Potterrow Building**	**Argyle House**	**Elizabeth Courts II**	**Five Ways House**
🟥 *				
🟨 **				
🟧 ***				
🟦 ****				
🟩 *****				
Passive Solar Principles-Factors	🟩	🟨	🟩	🟨
insulation	🟩	🟥	🟩	🟥
Doors & floors				
air-tight doors	🟩	🟨	🟩	🟨
insulated floors	🟩	🟥	🟩	🟥
raised floors-solid/void	🟩	🟥	🟩	🟥
Overall building insulation	🟩	🟥	🟩	🟥
Indoor office space layout				
open-plan (large volume)	🟩	🟨	🟧	🟧
office rooms (smaller volume-longer heat retention-faster heating)	🟩	🟨	🟦	🟨
Occupation				
fully-occupied	🟩	🟨	🟩	🟩
Life span	🟩	🟨	🟦	🟧
Heating/cooling system efficiency	🟩	🟨	🟦	🟧
CHP	🟩			
Condensing natural gas boilers			🟦	
Natural gas fired/non-condensing				🟧
VRF/VRV cooling			🟦	
Split Units cooling		🟥		🟥

According to this rating, it can be seen that the EIIC has the highest ranking in all areas in terms of actually having those building characteristics that can better define a building as sustainable (as this building was certified by BRREAM). This actually agrees with the BREEAM score of excellence, considering that the building was certified with the 2006 BREEAM assessment scheme. However, to what extent these characteristics-criteria can determine that the EIIC in-use is a BREEAM excellent, has been discussed in the following chapters. This ranking system has been used as a reference in chapter 10 under the application of the indicator to one of the office buildings that was evaluated in the thesis. This is a key contribution of the new sustainability indicator.

5.5.2 Influential factors and parameters for the environmental performance of the case study office buildings

This study unfolds two key influential parameters for building energy performance:

- The external parameters (location-related)
- The internal parameters (building-related)
- Further, the internal parameters have been sub-categorised in:

- Building parameters
- Occupancy parameters
- Facility Management (FM) parameters

These parameters discussed have been prioritised according to their significance in influencing the energy and environmental performance of office buildings (figure 5.53). These are important considerations for the integration of the new sustainability indicator in the BREEAM assessment or as an individual environmental performance evaluation tool (see more in chapter 9).

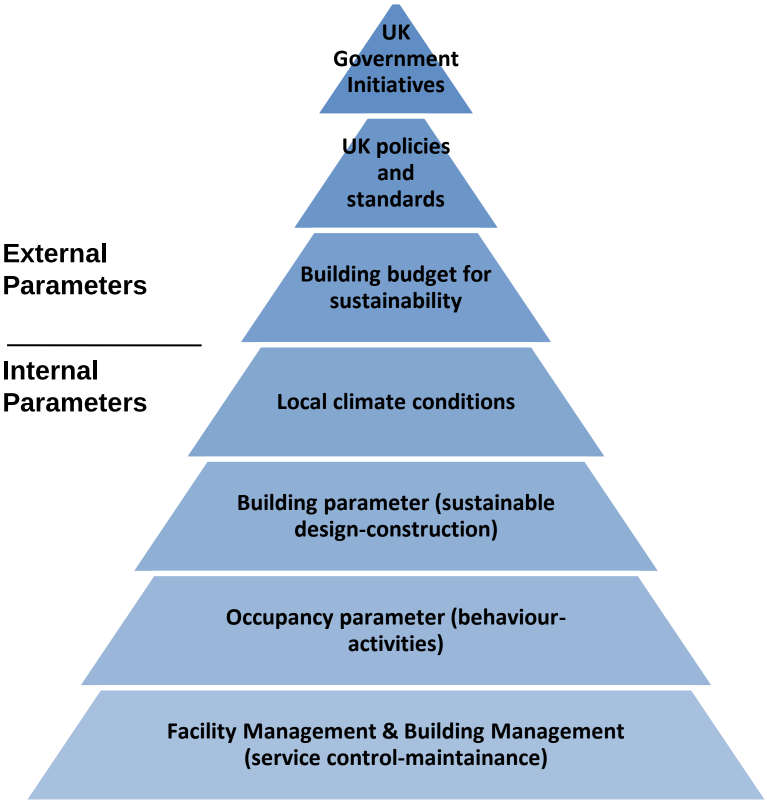


Figure 5.53: External and internal parameters in a hierarchy of importance

This study also unfolds the key influential parameters for heating and cooling environmental performance, considering the building requirements for heating and cooling and the technological features needed. Reducing volume of space for heating or cooling is a highly significant consideration and depends on building design. The technologies within the buildings have been selected mainly for their energy efficient features rather than their aesthetics and also according to the space requirements for heating. The building thermal mass plays a significant role in the space requirements of heating and cooling systems as well as building design and building layout. During operation, their life span and efficiency will also depend on occupancy comfort and requirements for heating and cooling. If there is more effort to improve

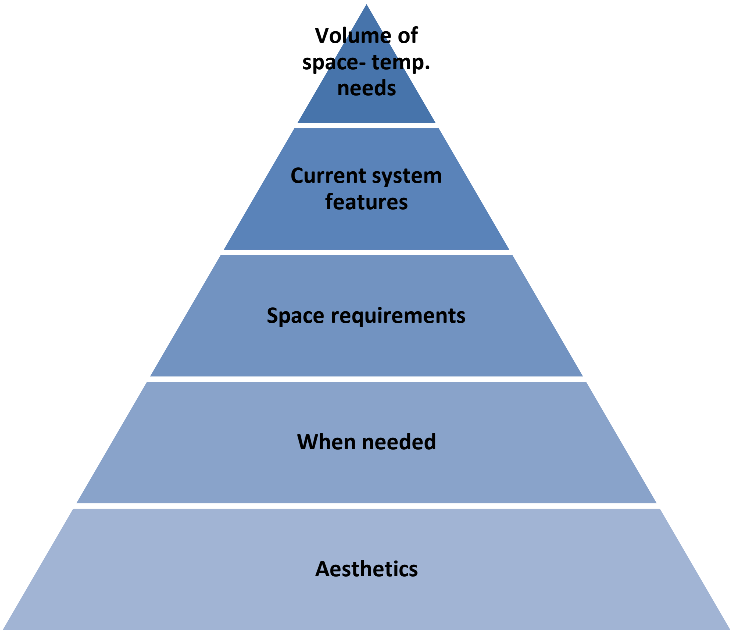


Figure 5.54: Hierarchy of benefit and limitation factors emerged from the cooling system

Source: Own interpretation

From the ranking table it can be seen that if there is more effort in improving the building fabric characteristics and in creating a technological system within the building (see example with the wind through and exposed thermal mass of the EIIC), that could reduce the amount of heating equipment needed to heat the building efficiently. However, gas consumption and energy consumption for cooling are two different things and when it comes to reducing energy consumption of the whole building, a CHP package with underfloor heating and trench systems could actually be better.

The above-mentioned parameters can make a significant contribution to the increase of the raw-material embodied emissions, as more technologies within a building means more raw-material consumption and more emissions to be manufactured.

5.6 Summary

This chapter has presented the key characteristics of the four office buildings that have been evaluated with the new sustainability indicator, and has also presented their heating and cooling system characteristics. Further, it has rated their features showing best practices on different features as well as what needs to be considered in case of future refurbishments in conventional office buildings. Furthermore it has discussed the key influential parameters of the environmental performance of the two indicators, energy and raw-materials, of this LCA study. Basically, it can be said that building design plays the most significant role for influencing energy consumption and raw-material consumption. It is pointless to have low-carbon technologies installed in buildings that have poor building fabric features. Besides, an energy effective building structure can reduce the demand for mechanical equipment operation by reducing at the same time energy and gas consumption and the amount of technologies installed in a building for heating and cooling.

CHAPTER 6: POE ON ENERGY AND BUILDING FABRIC THERMAL PERFORMANCE OF OFFICE BUILDINGS

6.1 Introduction

The previous chapter explained that the building design and its building characteristics can play a significant role in the energy and environmental performance of the office buildings. An improved passive design office building could help in limiting the operation of the mechanical services while providing a better indoor environmental comfort for the occupants. This chapter evaluates the energy and building fabric thermal performance, using POE methods, in an attempt to explore to what extent the BREEAM office buildings perform as excellent as well as to identify areas where improvements can be made. The outcome of the POE evaluation is linked to the environmental performance evaluation (chapter 7), looking at how low energy efficient and improperly-sealed building fabric of office buildings can have a significant impact on the environment in the long run. This forms a fundamental component for the development and application of the new sustainability indicator (discussed in detail in chapter 8).

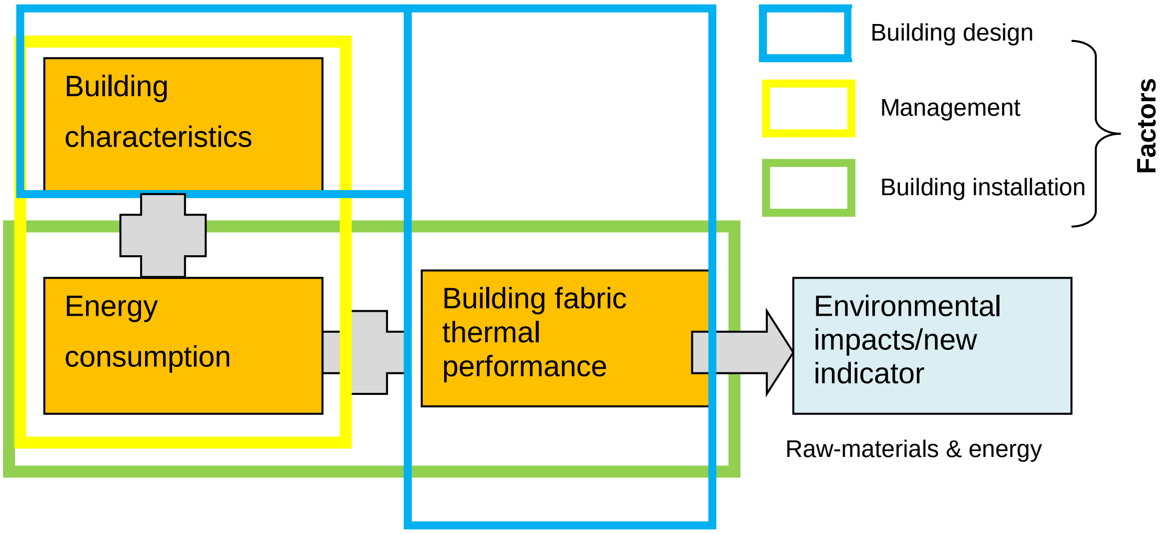


Figure 6.1: Relationship of the key POE investigative methods for the development of the new sustainability indicator

6.2 Energy consumption for heating and cooling

6.2.1 Case study 1

Electricity consumption

The electric power of Argyle House is a conventional type which happens through transmission lines to the building (section 7.1.2). This electric power is for lighting, for mechanical cooling in the comms rooms and for the IT server rooms. The annual electricity since 2004 and until the end of 2010 is presented in figure 6.2. The figure shows a significant increase from 2004 to 2005 and a decrease of around 20-30% each year from 2005 to 2010.The facility management team explained (see interview remarks appendix 22) that this has to do with the decrease in the level of occupancy each year, resulting in lower electricity consumption for the use of IT equipment-server rooms, lighting, heating water (for tea-coffee), elevator, and photocopier machines. The building is going through an evacuation plan which is happening gradually. The building will remain occupied for the next 5-7 years from 2010, with a gradual occupancy reduction. The occupancy decrease is mainly related to the running and maintenance costs as the building is too low, with poor building fabric, modest style with low energy efficiencies. Apart from the economical aspects, the waste heat issue in unoccupied areas and the oil waste, as well as the low-efficient energy boilers, contributes to causes of environmental impact in the outdoor environment. Electricity figures for 2009 and 2010 are shown in figures 6.3 and 6.4. Electricity consumption follows the same pattern between 2009 and 2010 with higher consumption in the winter months.

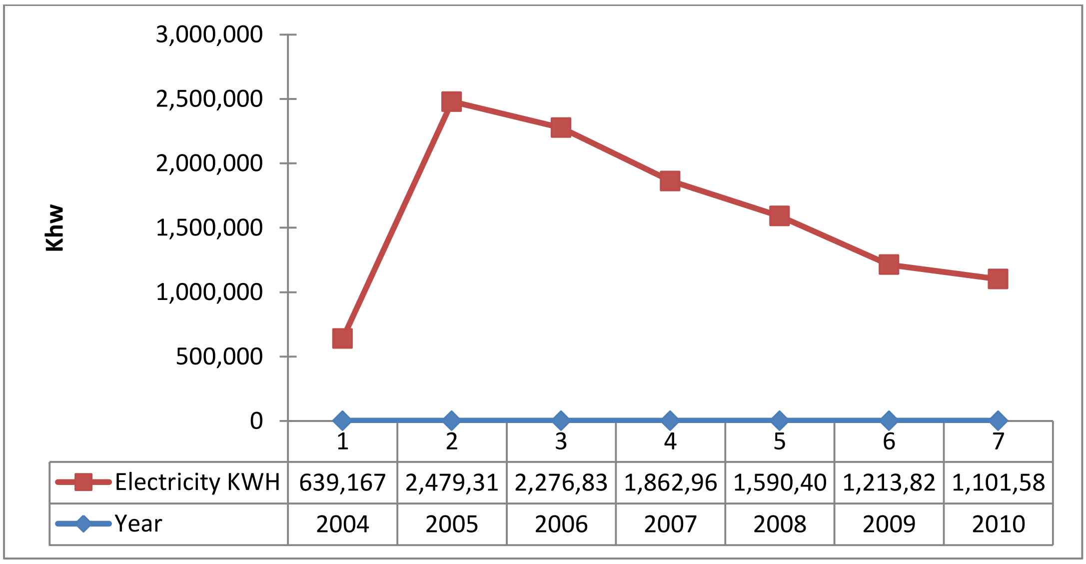


Figure 6.2: Electricity consumption, KWh/year

Source: FM team of Argyle House

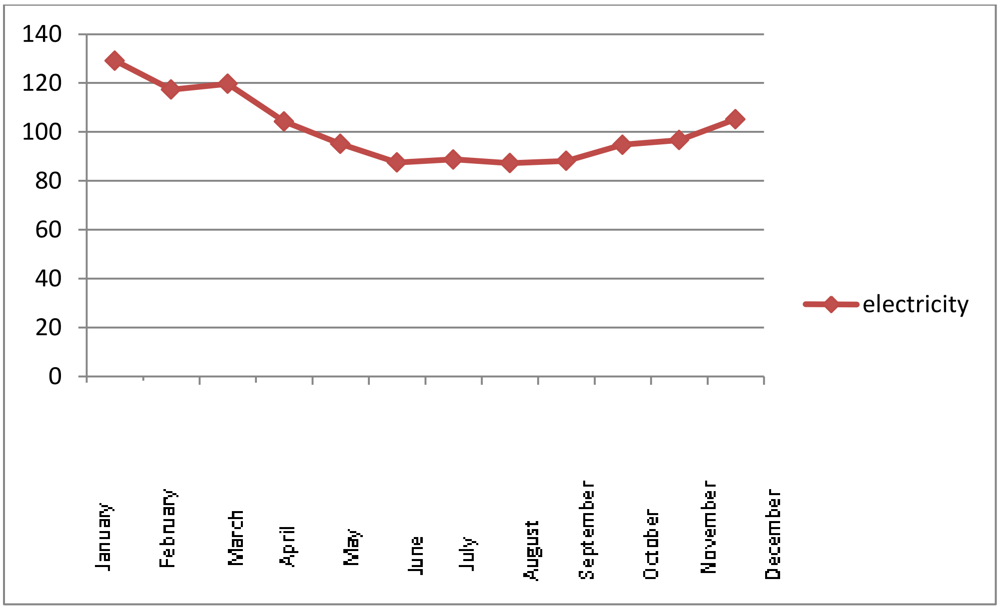


Figure 6.3: Electricity consumption, kWh/month in 2009

Source: FM team of Argyle House

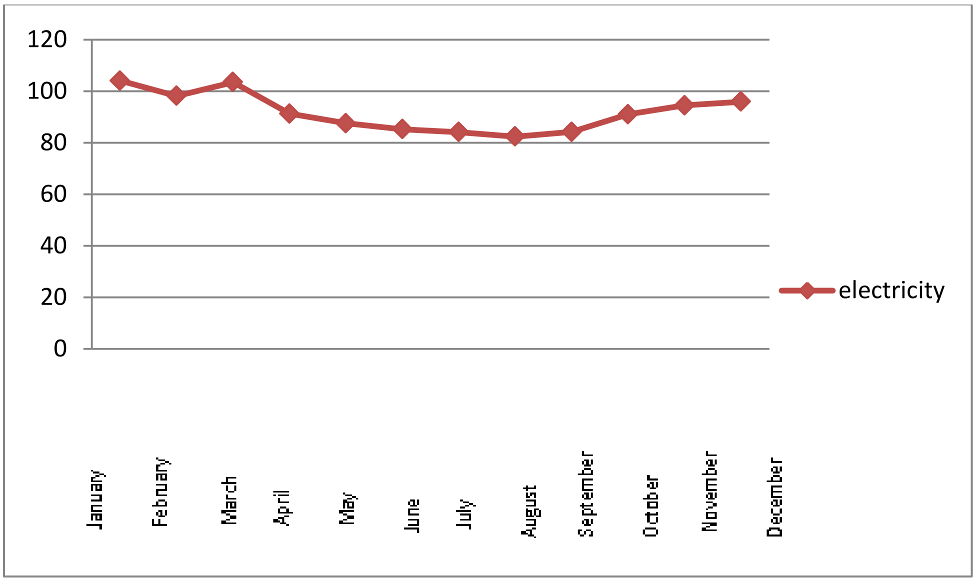


Figure 6.4: Electricity consumption, kWh/month in 2010

Source: FM team of Argyle House

In the Potterrow building, electric power is produced locally in the CHP regeneration unit located in the network campus. This is the alternative of the conventional power generation. It has a heat output is of 1730 kW. The power generated in 2010 was 13167 MWh and the power exported was 6025.1 MWh (figure 6.5).

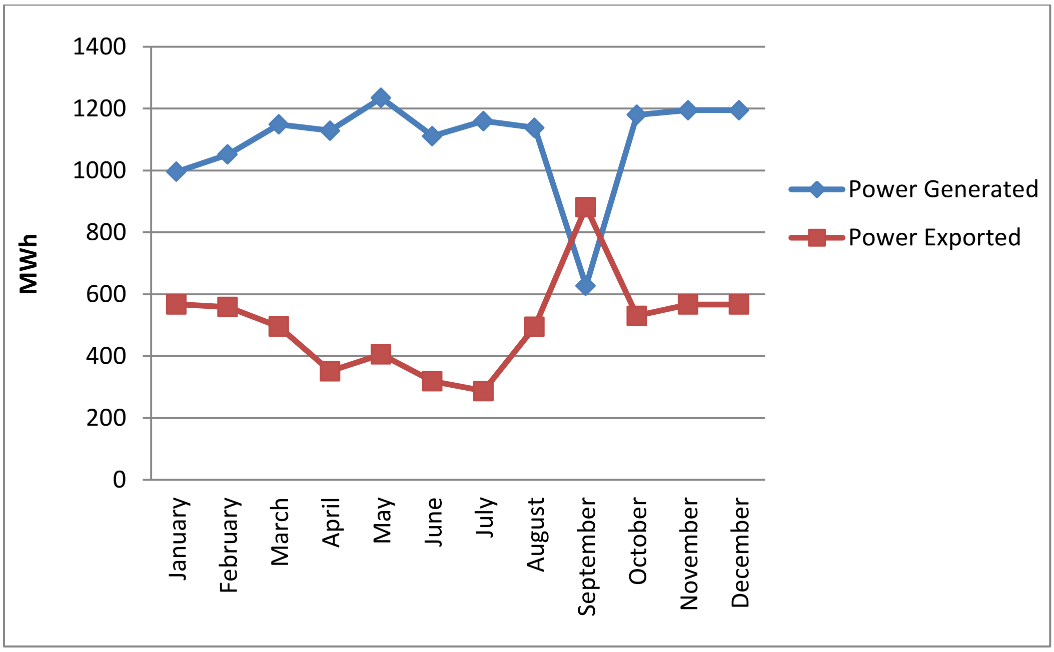


Figure 6.5: Power imported and exported from the CHP for the Potterrow building in 2010

As can be seen, the Potterrow building's electricity consumption is much higher than that of Argyle House. This may also happen due to the fact that the cooling system in the office spaces in Argyle House is naturally ventilated.

Heating consumption

Argyle House has a poor building fabric and old type central heating, which are the most significant influential parameters, as discussed in sections 6.5 and 7.5 (see also MATRIX table in appendix 8). In terms of the building it is oriented to the south which means that it could be over heated over the summer months if UK temperatures are about 30^0C. The building is double glazed and has no insulation at all, which does not suffice for the building to perform passively. Also the building is located on a sloping site to its west side which means that sunlight gain is not maximised, most significant in winter. The building has many blocks and angles that do not help in its being properly lighted. In combination with the low energy-efficient oil-fired boilers, the building consumes a large quantity of oil for heating; each of the two boilers in the system produces 1500 kW heat output. The amount of oil ordered depends on the time of the year; it can be ordered every two to three months but in the height of the winter it is usually ordered every 10 days (3 times/month). Usually the oil order covers 16000-18000 litres (see interview remarks, appendix 22) to achieve set point indoor temperature parameters of 21^0C. The heating on/off hours per season presented in table 6.1 show that the pre-heat time of the heating system is at 6:00 am so that the building can be at 21^0C by 9:00.

Table 6.1: Daily/Monthly/Seasonal oil demand

Seasonal	Monthly	Daily
Fall/Winter	October to February	ON 06:00am OFF 16:00pm
Spring	February to March / April	ON 06:00am OFF 15:30pm NOTE: as weather warmer just now (has been done in previous years / as needs) heating switched off at noon & back on 14:00 for last few hours as a "boost"
	March / April to May – as above (Feb – Mar)	but switch off at lunchtime and remain off unless afternoon "boost" required
Towards summer	End May	heating plant switched OFF

According to the heating time and set temperature indoor parameters the heating consumption of the building for 2009 is shown in figure 6.6 (this is the same for 2010). In total in 2009, 342,000 litres of oil were consumed, ie, 90346.8419 gallons (of gasoline) which means 2135.859147 MWh. During the summer months the heating is off (figure 6.6).

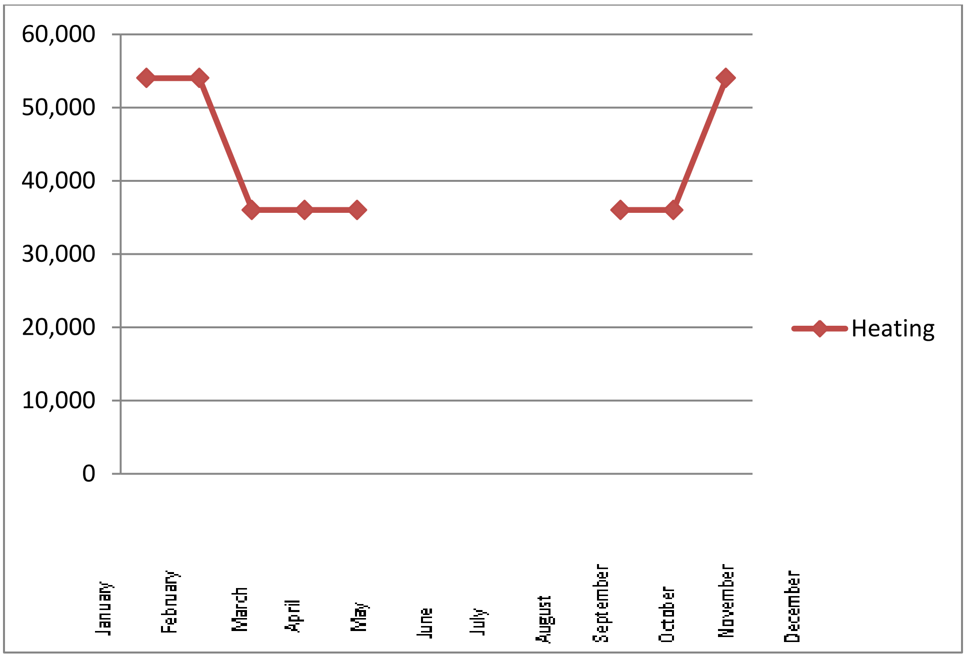


Figure 6.6: Heating consumption, kWh/month in 2009. The same figures assumed to be in 2010 as well

The Potterrow building, on the other hand, is oriented to the west, maximizing through this the daylight gain and thermal mass through different construction material, with different window patterns and with its insulation. These are important parameters for influencing heating consumption (section 7.5.1). Figure 6.7 presents the heating consumed in the whole building for heating the office space, with indoor set temperatures at 21 ^{0}C in 2010. The CHP operates throughout the year 24 hours per day although the daily operational office hours are from 9:00 am to 5:00 pm. In the CHP unit 3 boilers are installed. The overall natural gas consumption in 2010 was 47273 MWh (figure 6.8). Boiler 1 of 3000 kW consumed 46.4MWh, boiler 2 of 6000 kW consumed 4546 MWh and boiler 3 of 6000 kW consumed 1692.9 MWh of gas. Boiler 2 seems to be the lead boiler which means that it operates more hours from the other two boilers. Boiler 3 operates in the summer period to feed the cooling system in the building. Figure 6.8 shows also low gas consumption in the summer months as heating and cooling demand was low. Power generation during the summer period and until the end of September decreased in 2010, probably due to a summer holiday period where less staff and students used the building.

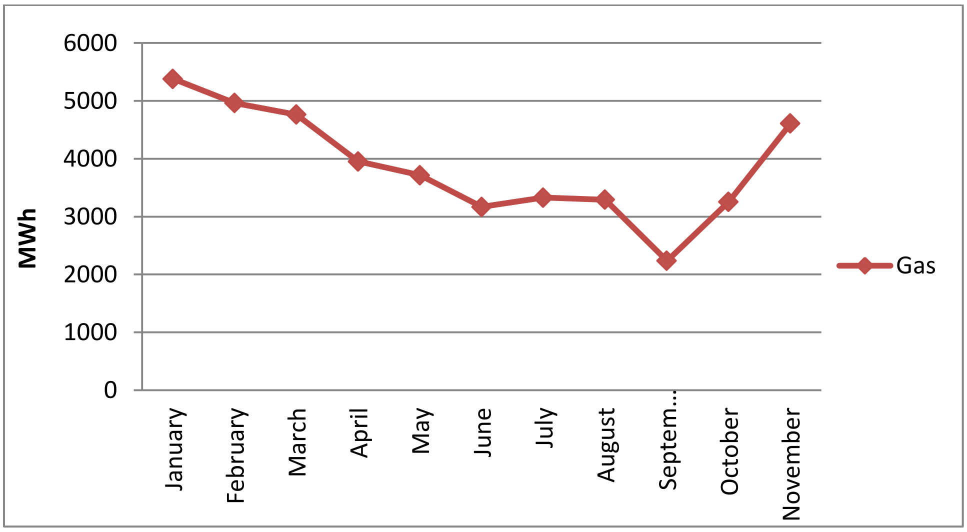


Figure 6.7: Gas consumption 2010

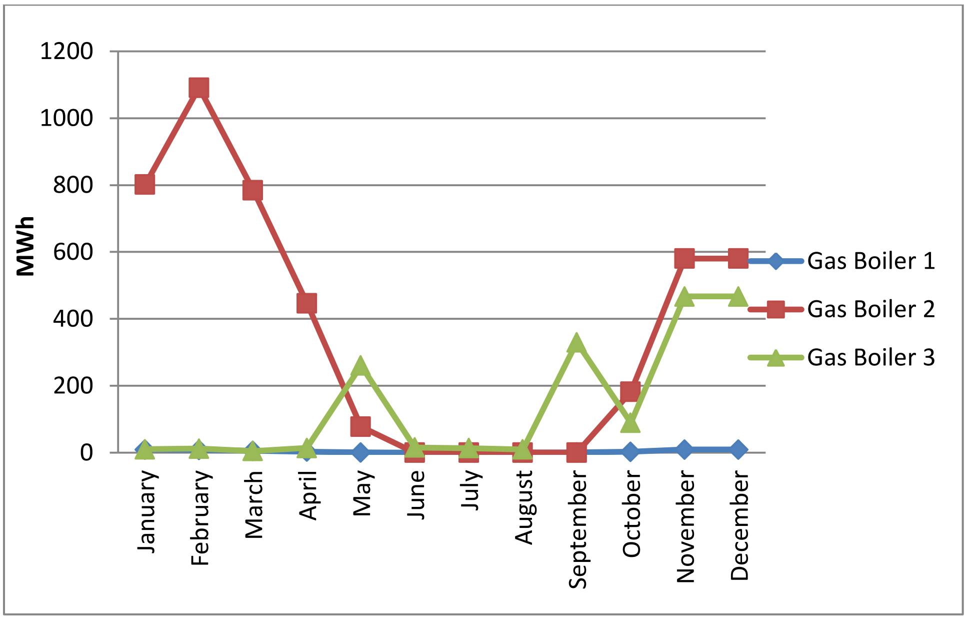


Figure 6.8: Gas consumption per boiler in 2010

As explained already in the previous chapter, the CHP provides heating in the building through different heating circuits for heating space and heating water. The heating circuits included are the primary heat meter, the heating circuit for the Informatics and DHW for the Informatics, DHW for the Dugald Steward, and heating circuit for the Dugald and VT (volume temperature) heating for Dugald (figures 6.9, 6.10). In terms of the heating consumption figure 6.10 illustrates that more heating was consumed in 2009 compared to 2010.

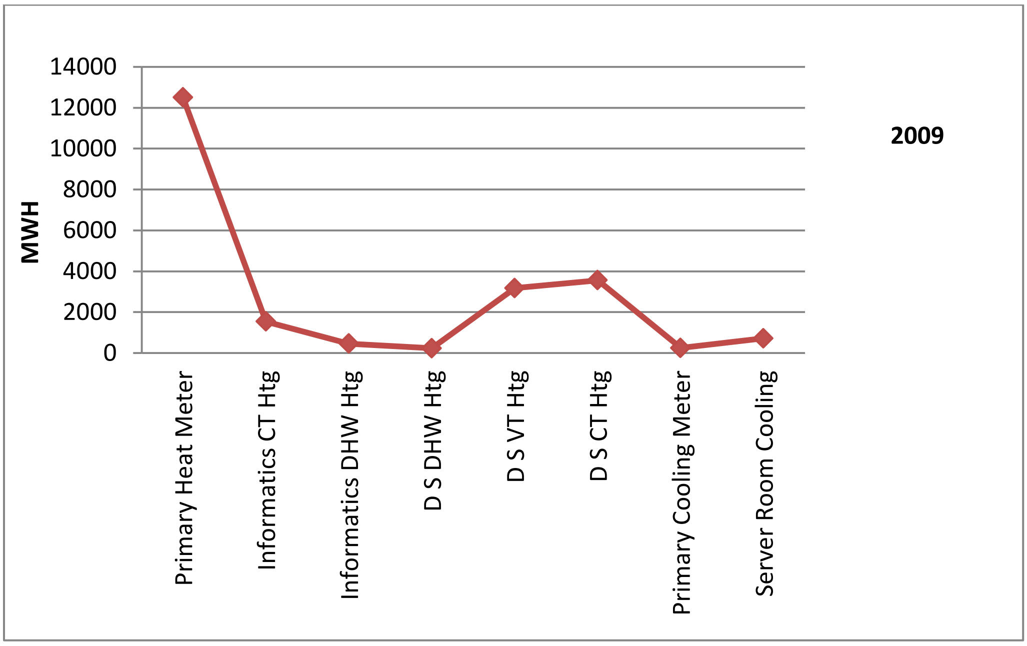


Figure 6.9: Heating consumption 2010

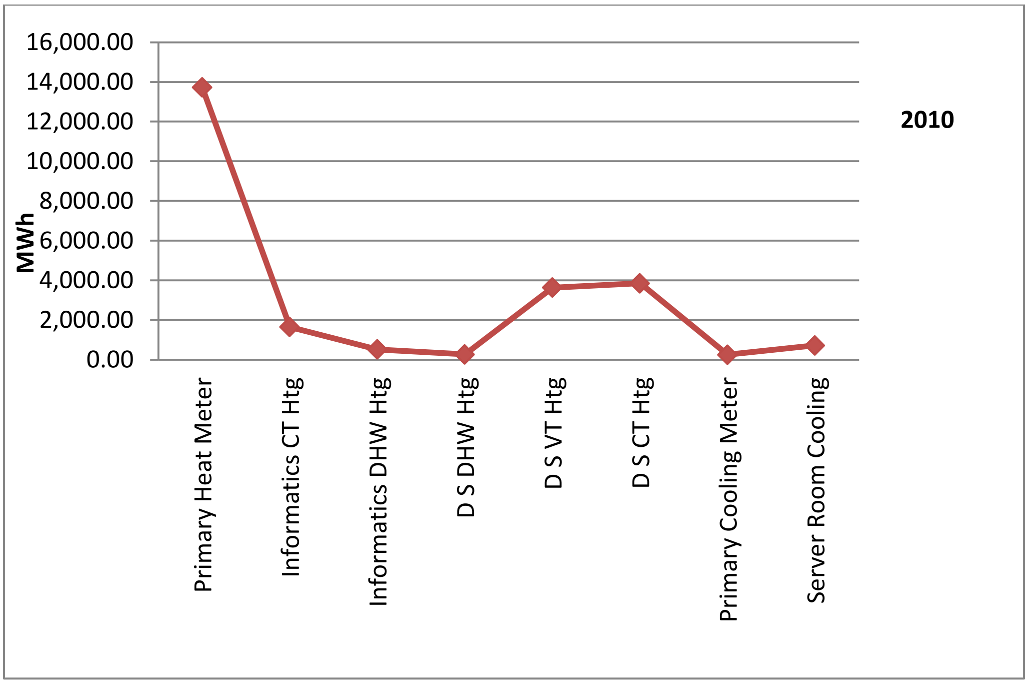


Figure 6.10: Energy meters for heating and cooling

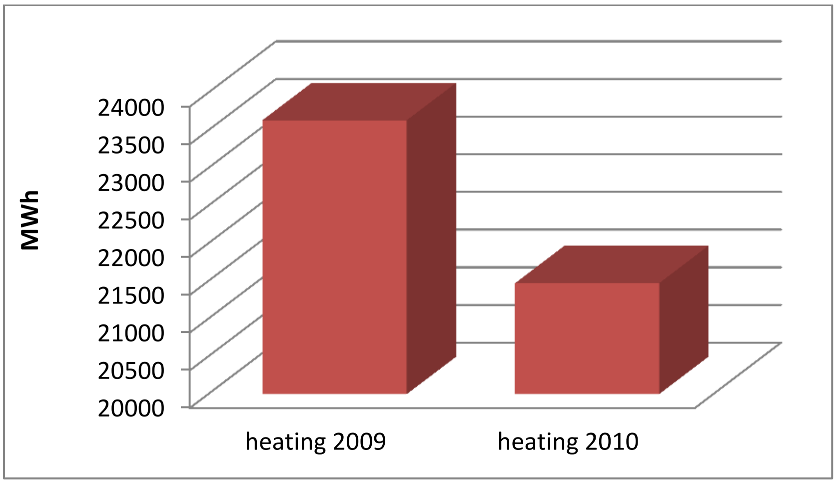


Figure 6.11: Heating consumption in 2009 and 2010

Cooling consumption

As Argyle House is naturally ventilated it has been assumed that maximum 10% of the total electricity has been consumed for cooling. It is believed that the cooling contribution of this particular building might be even less than 10% but this maximum parameter is used for the conventional office buildings. Therefore figures 6.12 and 6.13 present the cooling consumption for 2009 and 2010. It can be seen that mechanical cooling was consumed to a greater extent in 2010, due to the cooling provided in comms rooms. The winter months that show cooling consumption is the cooling provided in the server rooms 24 hours/day.

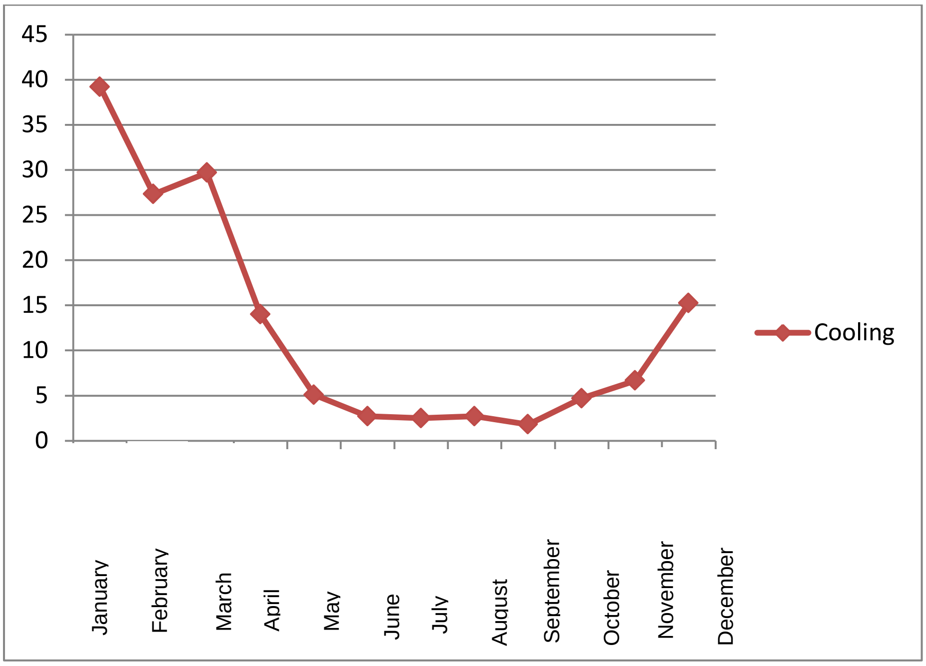


Figure 6.12: Cooling consumption, kWh/month in 2009

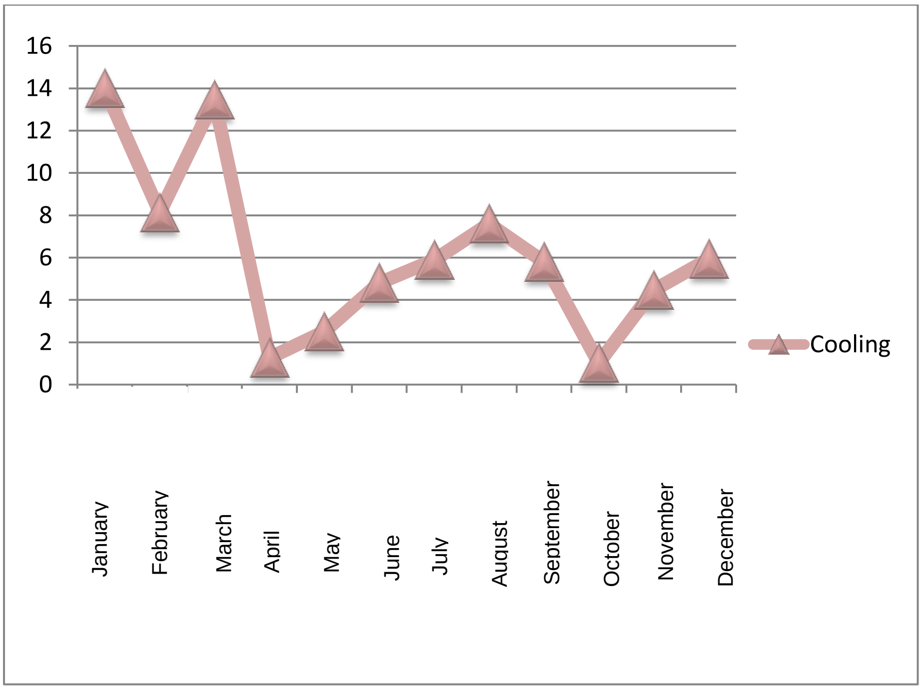


Figure 6.13: Cooling consumption, kWh/month in 2010

Cooling in the Potterrow building is provided from the CHP trigeneration unit through two different cooling circuits, the primary cooling meter and the server room cooling meter. The cooling consumption of the centralised air system in 2010 was 700 MWh (figure 6.14).

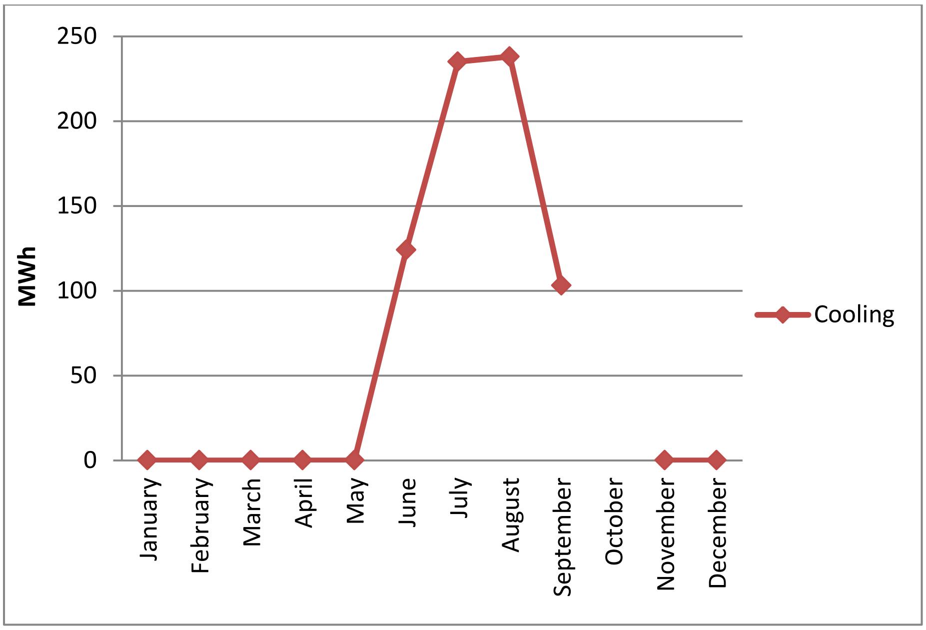


Figure 6.142: Cooling consumption

6.2.2 Case study 2

Electricity consumption

As with Argyle House, Five Ways is powered through national grids. The building is also naturally ventilated and mechanical cooling is only on in the comms rooms and in the IT server rooms. The rest of the electricity is consumed mainly for lighting and IT equipment. The building has a north orientation which does not benefit from sunlight. This can have an impact on the electricity consumption for lighting. Therefore, the total electricity consumption in 2010 was 148741.0965 kWh (figure 6.15).

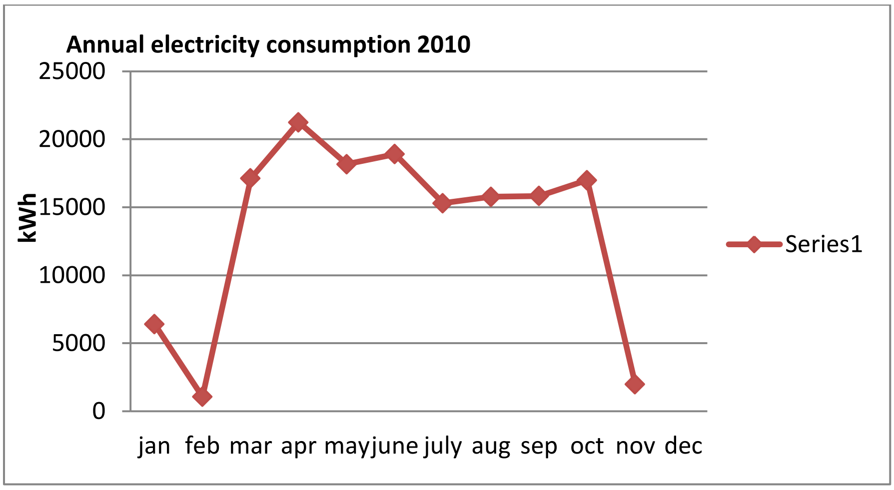


Figure 6.15: Annual electricity consumption 2010

Heating consumption

Five Ways House has a poor building fabric (section 6.4) and an upgraded heating system with non-condensing natural gas-fired boilers which are supposed to be over 80% efficient (section 7.2.2) with BMS control. Although energy efficiency is claimed to have improved, due to the poor building fabric, Five Ways House consumes in total 3323.384 kWh of natural gas burned in non-condensing low NOx boilers (figure 6.16).

The annual kg of CO_2 emissions in 2010 were 610.107 kg (figure 6.17). The year 2011 is excluded from the evaluation, although here it is used to show the difference in the total gas consumption from 2010, which was 2838.814 kWh, and total CO_2 emissions of521.149 kg. Separate data on the actual heating consumption does not exist. To calculate the consumption assumptions have been used, as presented in the methodology chapter. This assumption considered the heating output kW, the daily and seasonal heating demand. Further it has to be considered that the indoor set temperature is at 28^0C, which is too high compared to what is normal as a set temperature, being 21^0C for office buildings in UK, and also that the efficiency of the non-condensing boilers is net 92% and calorific 83%. On this basis the total heating consumption in 2010 was 2696 MWh and in total for 2009 and 2010, 5392 MWh

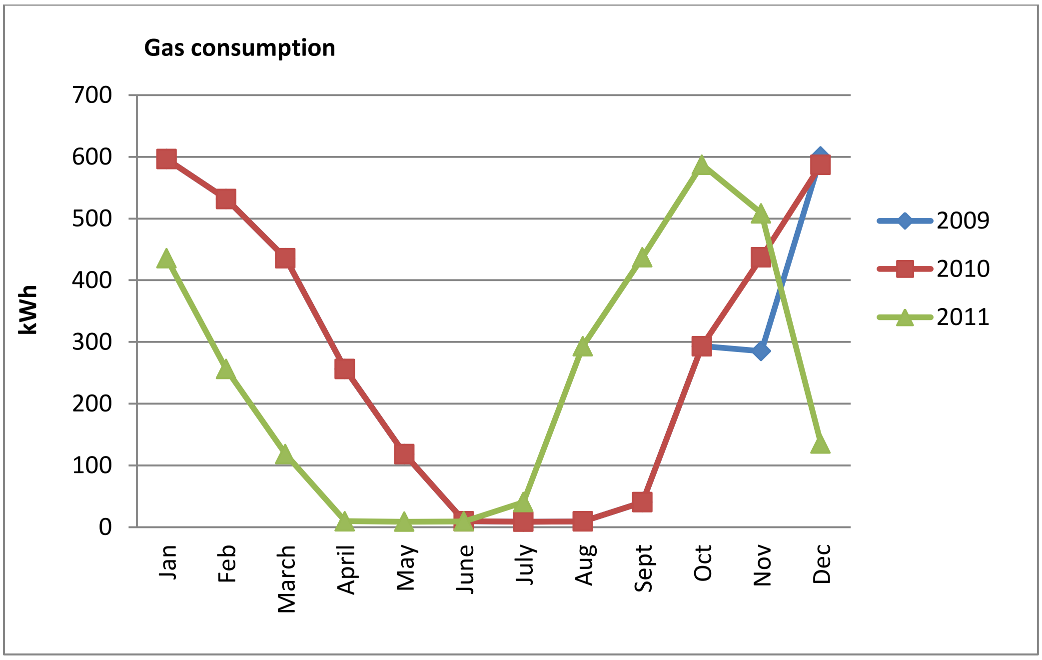


Figure 6.16: Total gas consumption for the years 2009, 2010, 2011

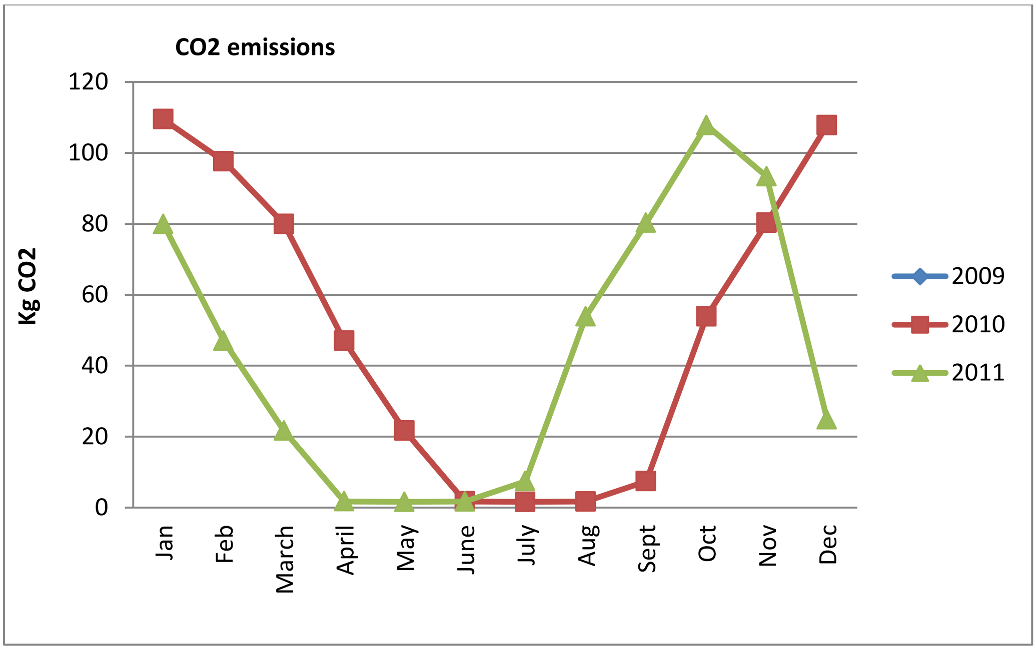


Figure 6.173: Total CO2 emission from gas consumption for the years 2009, 2010, 2011

The EIIC which is west oriented, fully insulated with double glazing and energy efficient condensing boilers, benefits also from the sub-metering. Different circuits are fed from the central heating system. The data that has been calculated included monthly numbers of kWh for heating space, for the waste heat and the recovery heat. The boilers are energy efficient, condensing with heat exchangers to recover the waste heat. The total heating consumption in 2010 and in 2009 was 177442 kWh. The annual heat waste in 2010 was 51059.95141 kWh (figure 6.19) and the annual heat recovery in 2010 was 222903 kWh (figure 6.20). Figure 6.21 presents the overall annual energy consumption in 2010.

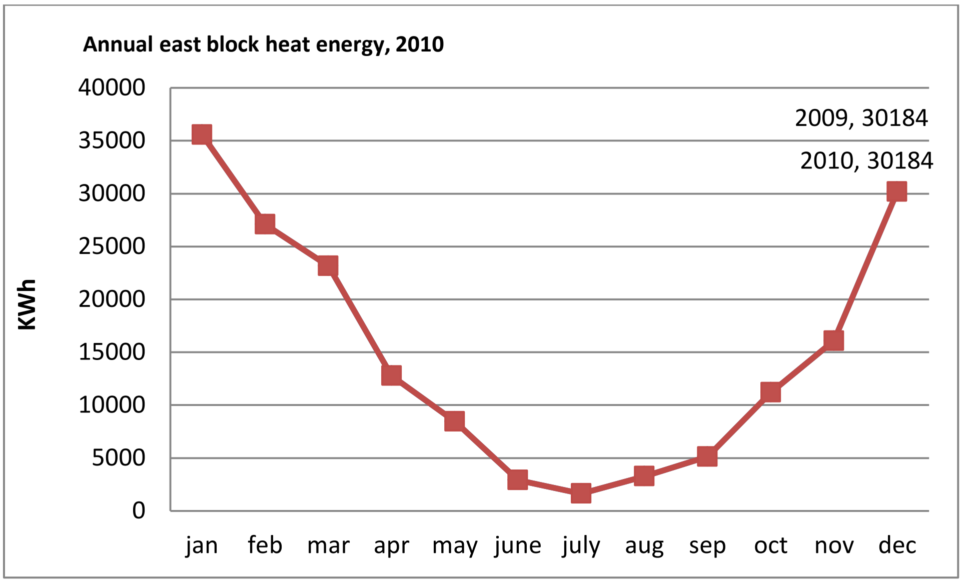


Figure 6.18: Annual heat consumption in 2010

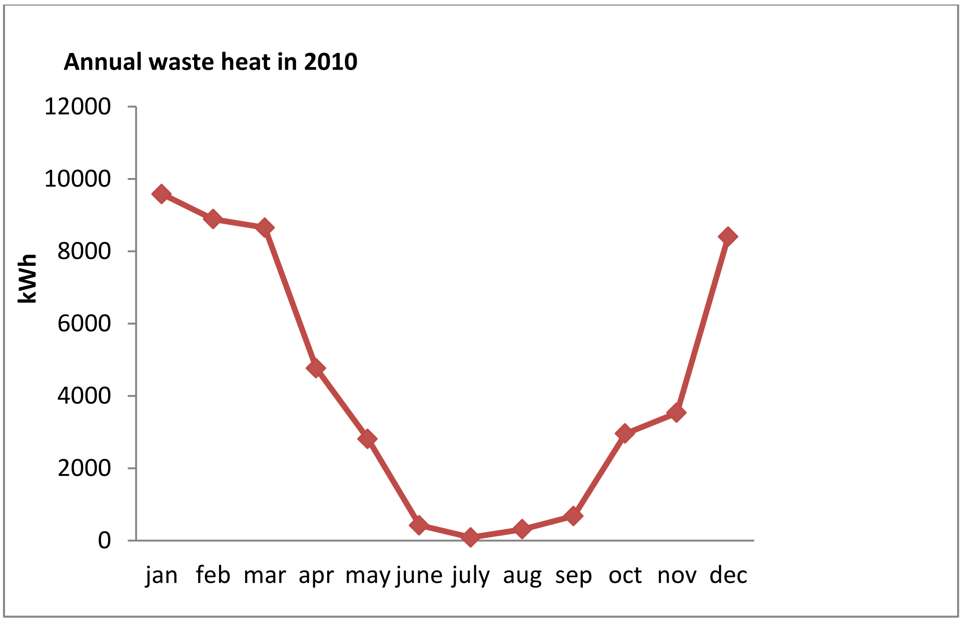


Figure 6.19: Annual heat waste in 2010

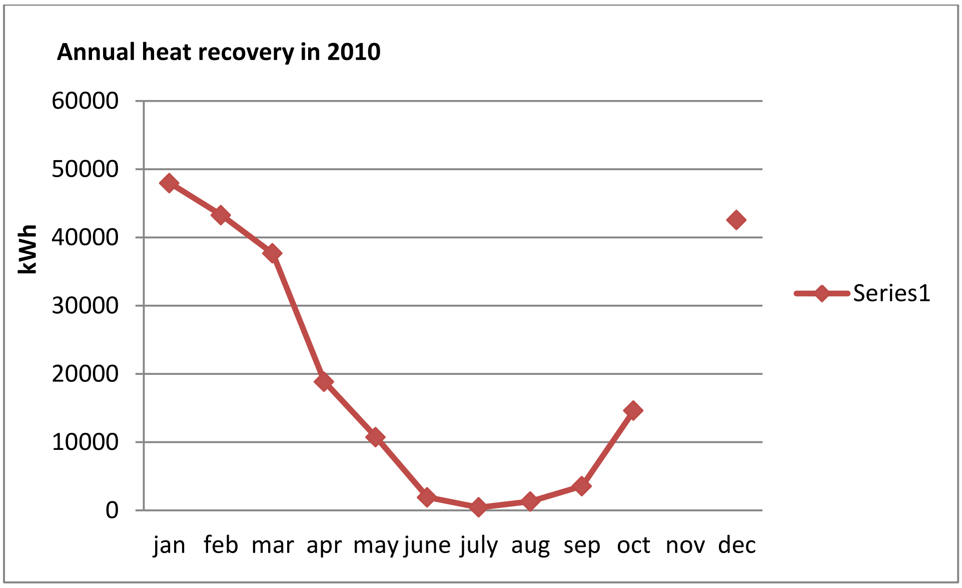


Figure 6.20: Annual heat recovery in 2010

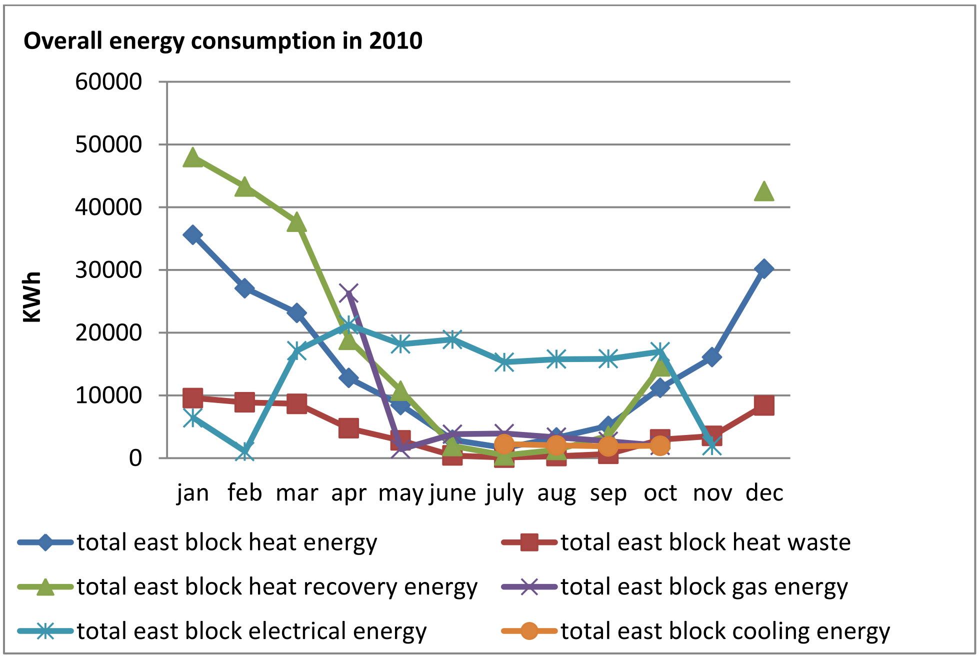


Figure 6.214: Overall energy consumption in 2010

6.3.3 Cooling consumption

The annual energy consumption for the VRV air-conditioning system in the EIIC in 2009 and 2010 was 8080.8 kWh (figure 6.22). Here it has to be considered that the office spaces of the building are naturally ventilated.

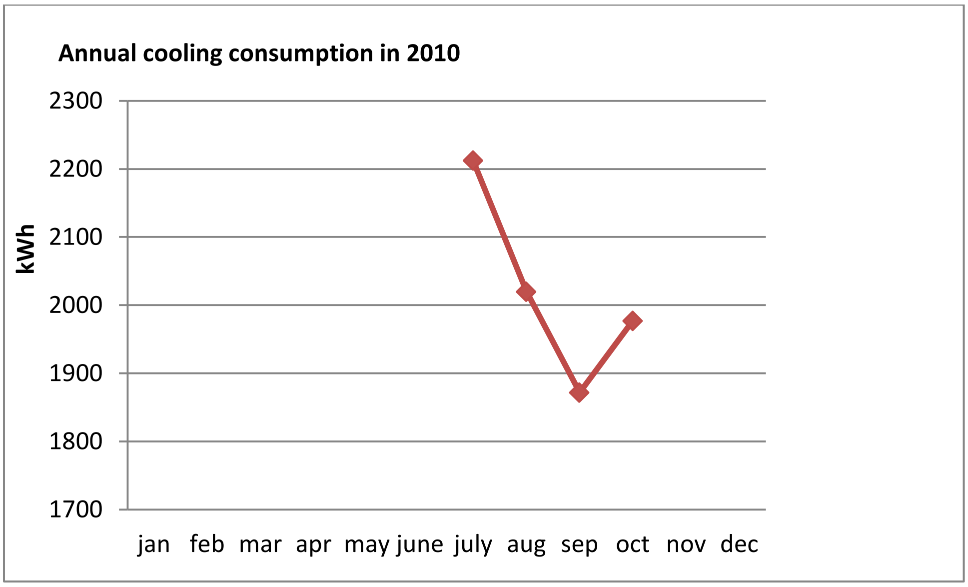


Figure 6.225: Annual cooling consumption in 2010

The annual energy consumption for the split-air-conditioning system in Five Ways House was considered to be less than 10% of the total electricity consumption. In two years 409.5 kWh of electricity were consumed (figure 6.23).

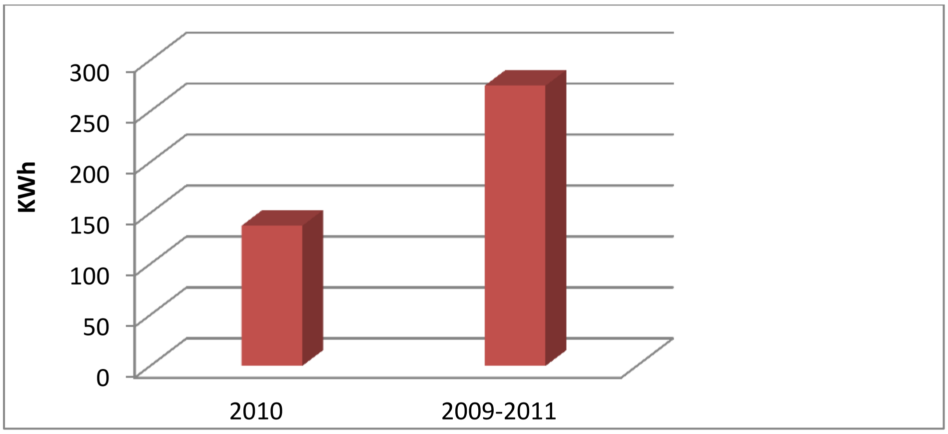


Figure 6.236: Cooling consumption

6.3 Benchmarking

The original office building Ashburton Court, produced 36 $kgCO_2/m^2$/year for heating 18 $kgCO_2/m^2$/year for office equipment, 13 $kgCO_2/m^2$/year for lighting and 5 $kgCO_2/m^2$/year for fans and pumps, higher than the ECON19 Type 3 office good practice. The design target was supposed to achieve 8 $kgCO_2/m^2$/year from heating and 28 $kgCO_2/m^2$/year from the total electricity. The metered performance of the total $kgCO_2/m^2$/year from the refurbished office building Elizabeth Courts II, is higher than the ECON19 Type 2 office good practice with reduction only in the heating consumption from 15 $kgCO_2/m^2$/year to10 $kgCO_2/m^2$/year (figure 6.24).

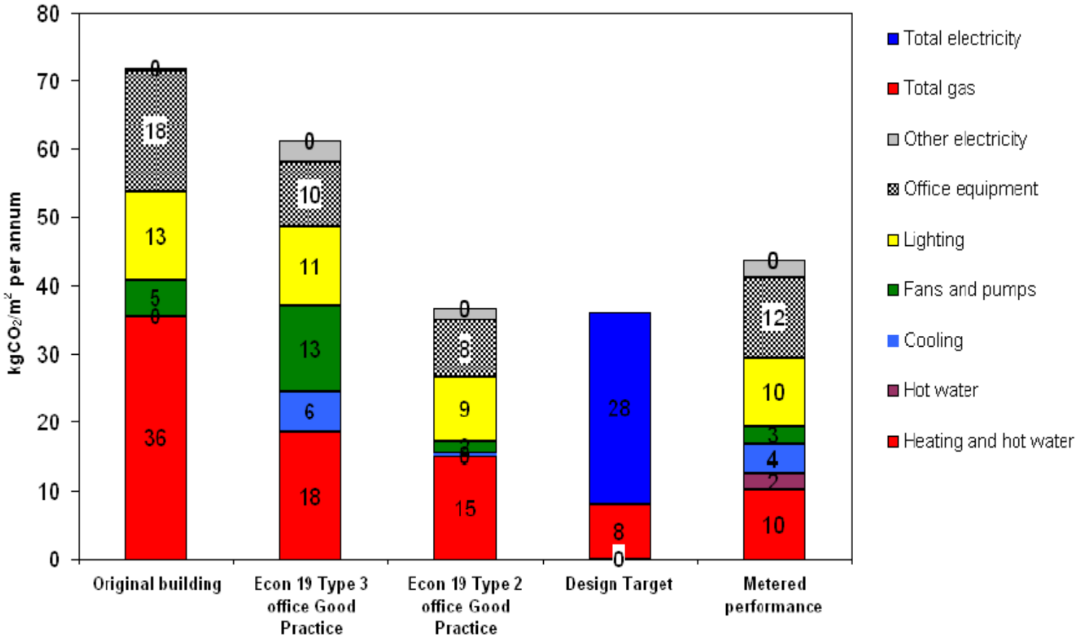


Figure 6.247: Benchmarking of the Elizabeth II Court in Winchester. The carbon dioxide emissions for the East block at Elizabeth II Court, based on data in figure 1. The carbon factors used to calculate emissions were 0.194 for fossil fuel (gas) and 0.422 for electricity. The treated floor area is 3185 m2.

Source: Bunn Roderic (2011).

According to the occupancy satisfaction survey conducted by ARUP, most of the before variables (former Asburton Court) were significantly worse than the UK benchmarks; uncomfortable both in summer and winter, too much artificial light and not enough natural light, too noisy, poor control of heating, not a pleasant image for the visitors. It had a very high dissatisfaction level with overall comfort rated at 71% dissatisfied. The refurbished building has certain variables higher than the UK benchmark; design, needs and image to visitors. Approximately 9 variables are no different from the UK benchmarks; temperatures in summer overall, noise overall, temperature in winter overall, air in winter overall, lighting overall, noise overall, comfort overall, health and perceived productivity. Considering 46 variables 12 are classed as green, 19 as amber and 15 as red. The red results show that the building is perceived as draughty in both winter and summer with too little control over conditions, too much artificial light and temperature variation. Therefore the building is a ‘typical’ UK office example for most variables but mostly for the comfort level. Twelve principle variables are the same or better from the UK benchmark (table 6.2).

Table 6.2: Principal variables. From the 46 variables 12 are classed as green, 19 as amber and 15 as red. The red indicates that the building is perceived as draughty in both winter and summer with too little control over conditions, too much artificial light and with too much temperature variation.

Green	**Amber**	**Red**
Air in summer: odourless/smelly Air in winter: odourless/smelly Cleaning Design Do facilities meet needs? Furniture Image to visitors Lighting: glare from sun and sky Needs Noise: noise from outside Personal safety in building and its vicinity Temperature in summer: hot/cold	Air in summer: dry/humid Air in summer: fresh/stuffy Air in summer: overall Air in winter: dry/humid Air in winter: fresh/stuffy Air in winter: overall Comfort: overall Health (perceived) Lighting: glare from lights Lighting: natural light Lighting: overall Meeting rooms: overall Noise: noise from colleagues Noise: overall Noise: unwanted interruptions Productivity (perceived) Space in the building Temperature in winter: overall Temperature in summer: overall	Air in summer: Air in winter: Control over cooling Control over heating Control over lighting Control over noise Control over ventilation Lighting: artificial lighting Noise: from other people Noise: other noise from inside Space at desk Storage space: overall Temperature in summer: stable/varies Temperature in winter: stable/varies

Source: Occupant Satisfaction Survey, provided by Neil Broadman, FM of the EIIC

The occupancy survey showed that even though the building was certified as excellent by BREEAM, there is still dissatisfaction in certain areas and still need for improvements in terms of the heating/cooling comfort. Occupancy plays the most significant role in the environmental performance of buildings in terms of how the building and its technologies are used to satisfy the comfort of the occupants. According to environmental claims the assets of the Potterrow office building have achieved a 70% reduction in CO_2 emissions compared to ECON 19 Type 3 Good Practice asset emissions (figure 6.2). A post-occupancy evaluation survey took place in 2012, which was out of the time of the agreed fieldwork data collection.

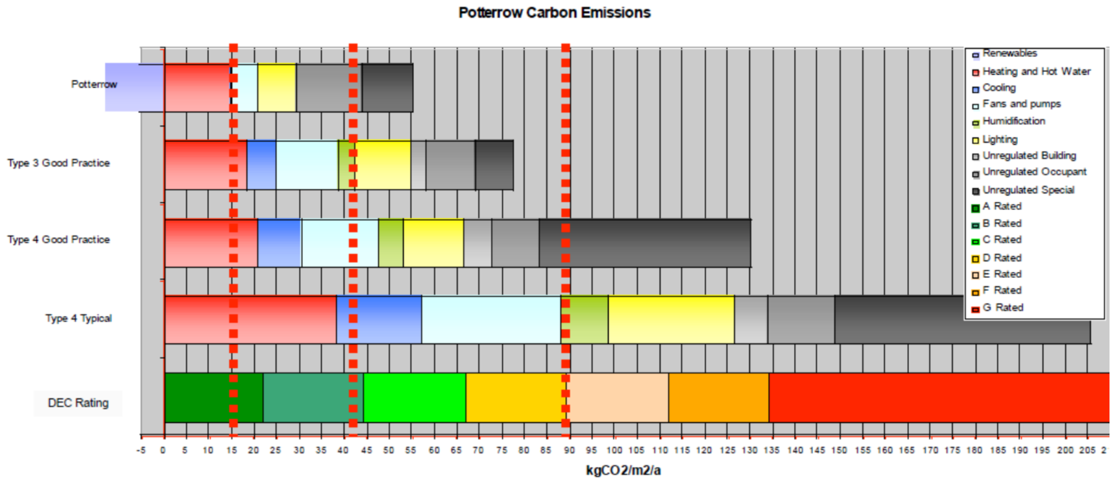


Figure 6.25: Benchmarking of Potterrow building

Source: Clark Gary, Feedforwards: POE studies, Bennetts Associates

According to the benchmarks provided in the guide ECON19, (Action Energy 2003) for energy consumption in office buildings, a type 3 Typical Practice A/C office consumes 341 KWh/m^2/y, from which 178 KWh /m^2/y belongs to heating, 31 KWh /m^2/y for cooling and 60 KWh /m^2/y for fans and pumps, where a Type 3 Good Practice A/C office building consumes 174 KWh /m^2/y from which 97 KWh /m^2/y is for heating, 14 KWh /m^2/y / for cooling and 30 KWh /m^2/y is for fans and pumps. Based on that, the conventional office building in Edinburgh consumes three times the electricity of a typical type 3 benchmark office building.

The Display Energy Certificate in Five Ways House (appendix 23) shows that compared to the typical energy efficiency, which is 100, the building has been rated with C 57 and with a few improvements the building could achieve rating B 26-50, although the target should be A' rating. The technical information explains that the total useful floor area of the building in m^2 was 29971.25 and that the annual energy use for heating was 119 kWh/m^2/year compared to the typical energy use of 135 kWh/m^2/year. If per m^2 the heating consumption was 119 kWh for 29971.25 m^2 the heating consumption would be 3566.5 MWh and for two years (2009 and 2010) it would be 7133.1 MWh, which is not a significant difference from the calculations based on the previous assumptions. This is a typical type 3 benchmark office building.

6.4 Heating Degree Data (HDD) Evaluation

6.4.1 Case study 1

The average base degree temperature for Argyle House, with no insulation and other passive measures, is 15.5 ^{0}C. Through investigation of the metering readings, the energy metering is taken at the end of each month, as suggested by the Degree Days for energy management guide by Carbon Trust (2012). The scatter graph from 2009 indicates the correlation between the energy metering and the weather degree days (figure 6.26). The straight line with intercept on the degree-day axis shows that the building requires no heat until a certain level of degree days is reached. This could be because heat gains from equipment are high Carbon Trust (2012).

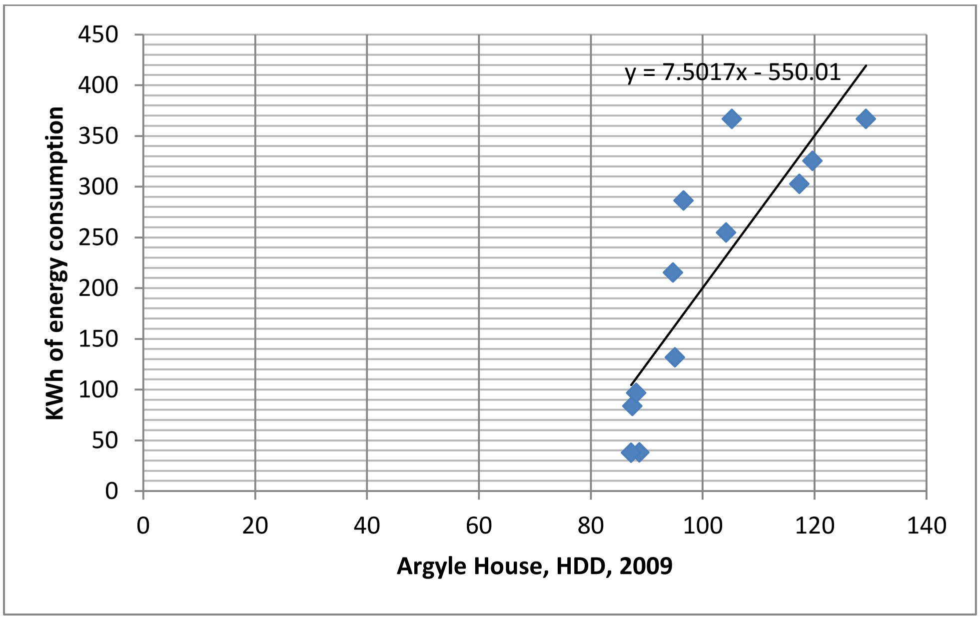


Figure 6.268: HDD evaluation, Argyle House, 2009. The ''y'' corresponds to the kWh of energy consumption, the ''x'' corresponds to the degree days, the figure that multiplies the X (7.5017) represents the gradient of the trend line and the constant at the end (550.01) is the intercept. This represents the base load energy consumption. The ''r^2'' shows how good the correlation is. It is better if it is close to 1. This is the same for all the scatter diagrams in this section.

Wide scattering indicates that meter readings were not taken reliably; missing the start or end of the month by three or four days (which may happen if readings are only taken on Mondays for example) and could account for +/-10% of the monthly fuel consumption Carbon Trust (2012). The HDD counted for 2010 (figure 6.27) show a better correlation between the energy consumption and the degree days, which means that energy has been consumed according to the cold days below 15.5 ^{0}C.

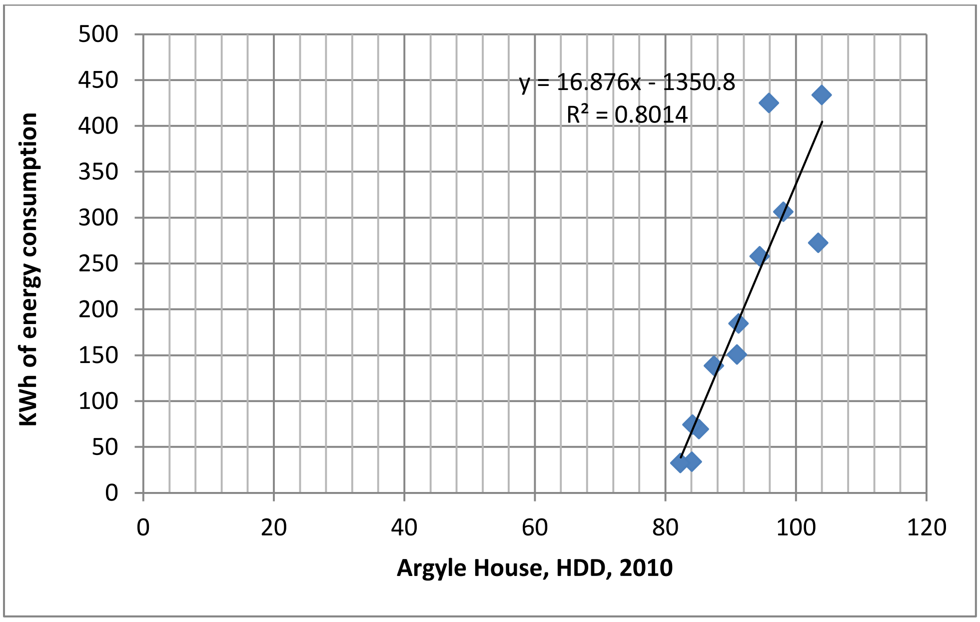


Figure 6.27: HDD evaluation, Argyle House, 2010

The scatter graph for the HDD of the Potterrow Building shows a straight line with intercept on the energy axis. Wide scatter points indicates metering readings taken at different dates in each month both in 2009 and 2010 (figures 6.28, 6.29).

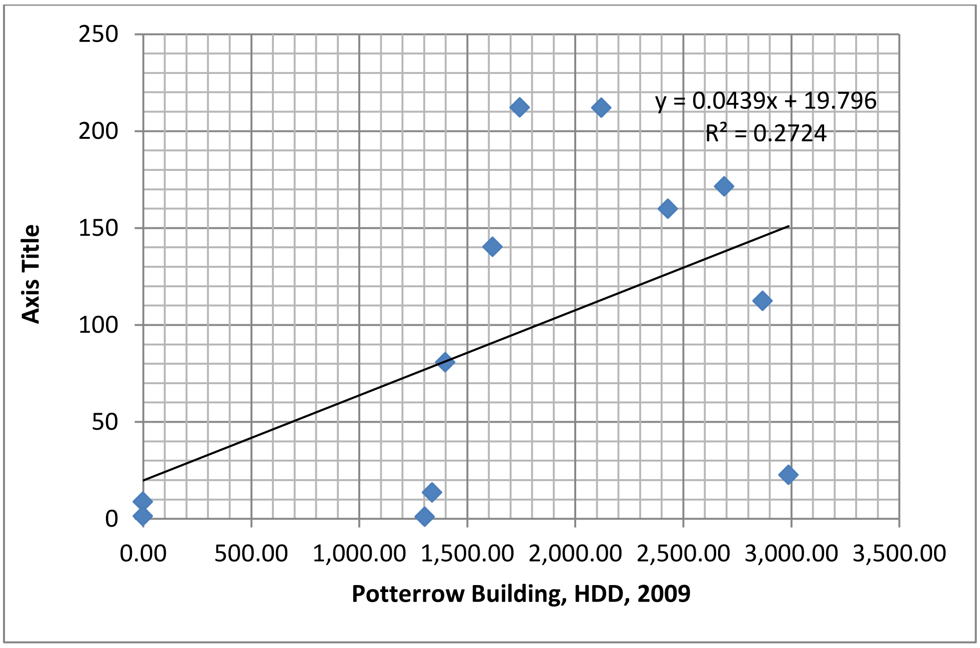


Figure 6.28: HDD evaluation, Potterrow Building, 2009

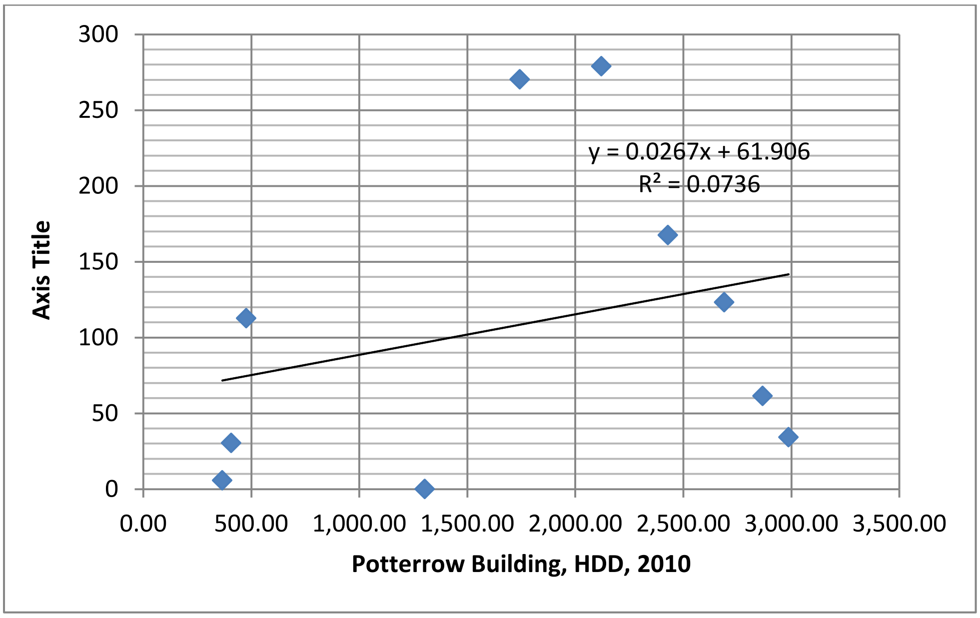


Figure 6.299: HDD evaluation, Potterrow Building, 2010

6.4.2 Case study 2

The HDD of the EIIC shows both in 2009 and in 2010 correlation of the heating consumption with the HDD base temperature (figures 6.30, 6.31). The 2010 scatter diagram (figure 6.31) shows a better correlation (see R^2 value) compared to 2009.

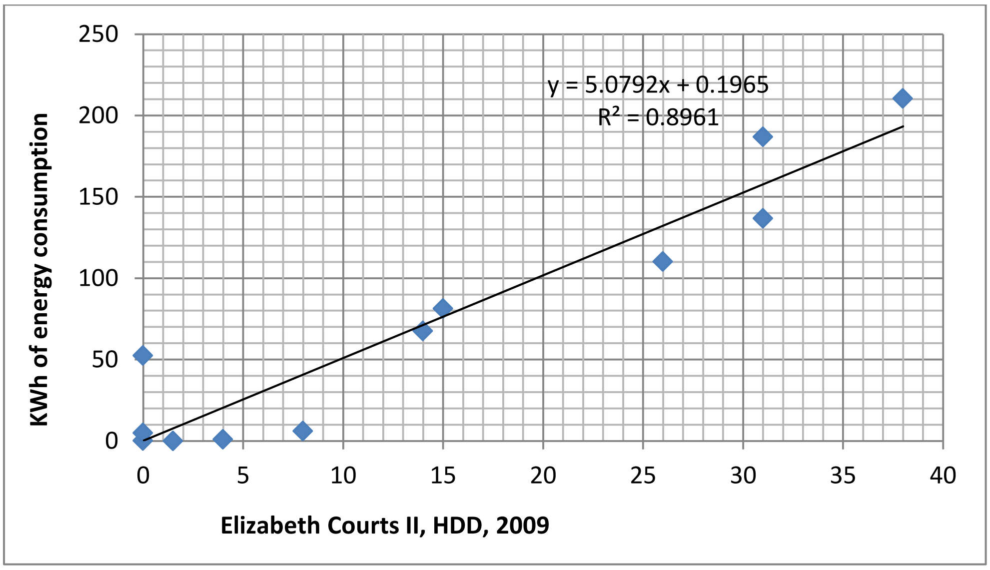


Figure 6.30: HDD evaluation, Elizabeth Courts II, 2009

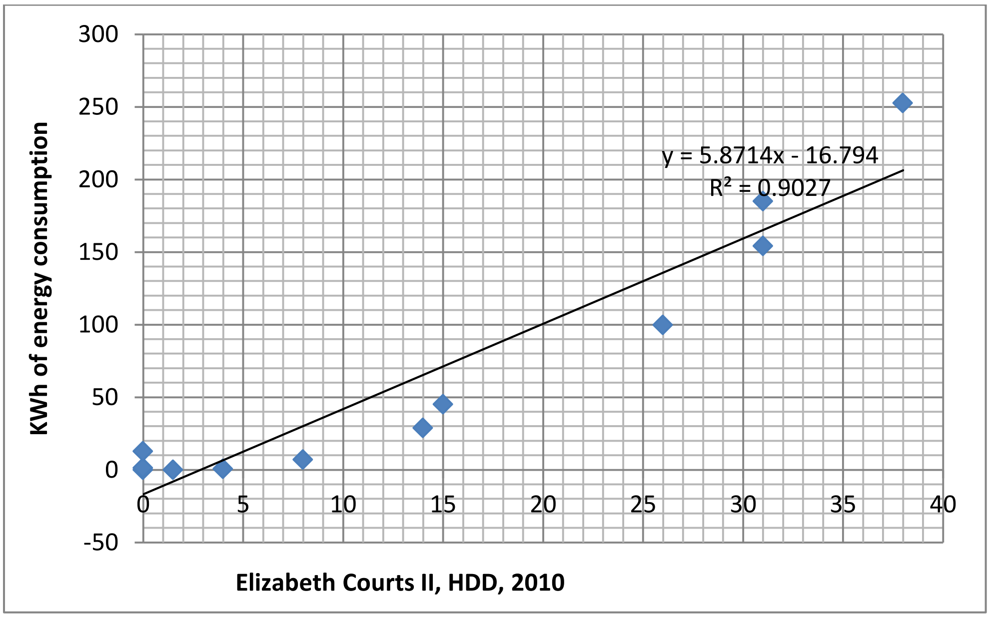


Figure 6.31: HDD evaluation, Elizabeth Courts II, 2010

The scatter diagram of Five Ways House in 2009 (figure 6.32) shows a straight line with a positive intercept on the energy axis and modest scatter. This means that there is some correlation between the energy consumption and the degree days, illustrating that metering readings are not taken reliably. The scatters also indicate wide control dead bands (the difference in temperature between which a thermostat switches a heating system on and off). Additionally there could be lack of weather-related controls, activities of the occupants such as opening and closing of windows and doors, and variations in the length of the working day. It could also mean control faults (Carbon Trust 2012b). Here the scatter is observed to be less wide than in the previous office building cases. The base temperature is considered as 15.5^{0}C based on the building fabric which has no passive measures to it, as advised by Carbon Trust’s guide 2012.

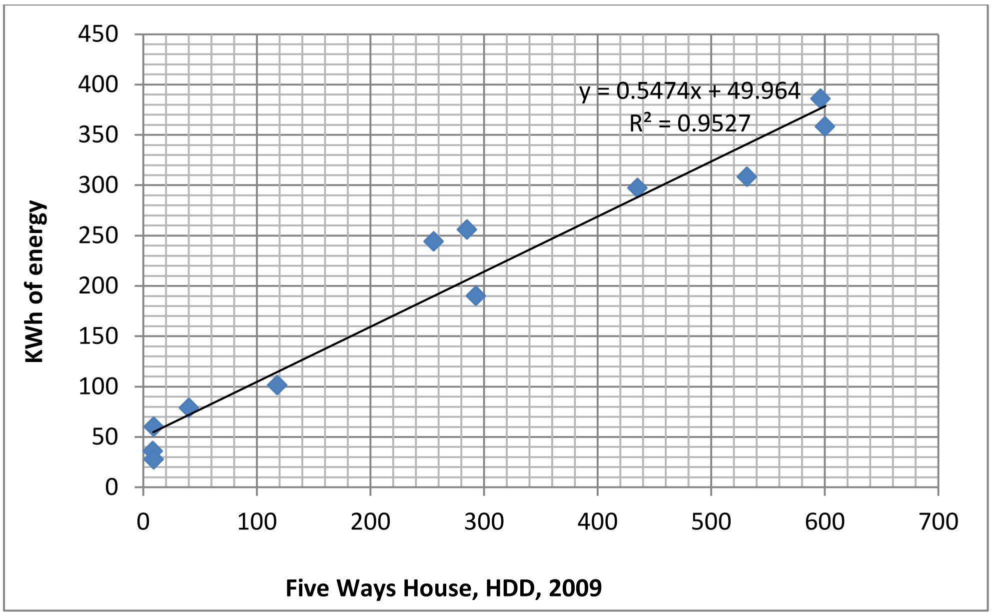


Figure 6.32: HDD evaluation, Five Ways House, 2009

Similarly the scatter graph from 2010 (figure 6.33) shows a straight line with a positive intercept on the energy axis; however the scatter points are wider which means that the above-mentioned issues must be considered in order to ensure proper energy consumption. The positive intercept may also be a result of the Life Cycle Review process, undertaking frequent audits, where several stakeholders are involved to ensure low energy consumption costs.

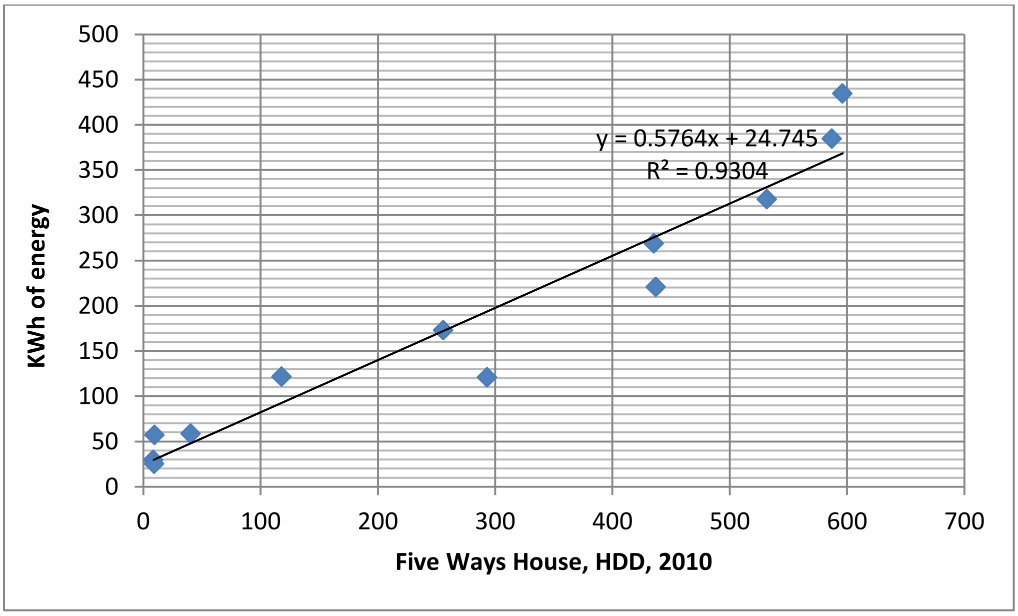


Figure 6.33: HDD evaluation, Five Ways House, 2010

6.5 Building fabric thermal performance evaluation

The thermographic survey using thermal imaging is a highly significant instrument to identify heat losses, air-leakages and insulation gaps from buildings. It is part of the POE's building monitoring methods (section 5.1.1). In this study it is used to compare the thermal performance between the BREEAM excellent office buildings and the conventional office building in the selected case study office buildings. Through this survey the different design approaches used in the different sides of the buildings (south, west, north, east) can be seen. Therefore this survey evaluates the building design and the building fabric parameters unfolded in section 2.9 and 4.2.1 and it further justifies their selection for the case study selection criteria. Also through this survey it can be understood to what extent sustainable offices are different from conventional office buildings in terms of their design. Further, this survey raises questions about whether conventional office buildings are worth keeping for renovation since their building orientation to the sun and their design are wrong. This survey also explains the difference in heating and cooling consumption, which is closely related to the design, but also to the way buildings are operated. From the infrared images it can also be seen that while heating was on at the time of the survey, some windows on different sides of the building were open, allowing heat to escape. In this survey, the role of full occupancy and the heat-temperature movement to unoccupied rooms, as discussed in the discussion section in chapter 6, becomes more clear. This information highlights further the significance for developing a new sustainability indicator which can link through all these different areas. Following the building description about office building orientations in chapter 6, the two BREEAM certified office buildings are west oriented while Argyle House is south oriented and Five Ways House north oriented. This is important for understanding the building design and the thermal performance. For the surrounding shadows, which had little impact on the results of the survey, see shadow images in chapter 5.

6.5.1 Case study 1

Argyle House is south oriented while the Potterow building is west oriented. The building design is different comparing the two buildings and their orientations. The longer facades of Argyle House face the north and the south while the longest facades of the Potterow building face the west and the east. There is also structural difference between them in terms of the materials used on each side of the building; Argyle House is made entirely from pre-cast concrete with no wall insulation and the Potterow building has different stone pre-cast concrete from the west to the east to enhance thermal performance (see characteristics in MATRIX, appendix 8 and case study 5).

The impact that the building design parameter has (sections 4.2.1 and 5) in the energy performance of a building is evaluated using infrared analysis between the conventional and the conventional building. The weather conditions at the time of the survey are shown in table 6.3.

Table 6.3: Weather conditions at the time of the thermographic survey in Edinburgh

Date of thermal imaging				19th March 2012			
Time				5:30pm-6:30pm			
Weather							
Source: The Weather Channel							
Day		**Avg. High**		**Avg. Low**		**Mean**	
19-03-2012		9		2		6	
Sunset/Sunrise							
Source: The Weather Channel							
Day		**Sunrise**		**Sunset**		**Daylight Hours**	
19-03-2012		06:17		18:25		12h, 8min	
Hourly Weather Observation							
Source: The Weather Channel							
Time	**Conditions**	**Feels Like**	**Dew Point**	**Humidity**	**Visibility**	**Pressure**	**Wind**
17:20	11 Light rain	11	6	71%	10km	1.023.03 mb	WSW 35 kmph
17:49	10 Partly Cloudy	7	6	76%	10km	1.023.03 mb	SW 32 kmph
18:19	10 Partly Cloudy	6	6	76%	10km	1.023.03 mb	SW 34 kmph

South side of Argyle House and the Potterrow building

The infrared image of the south side of Argyle House shows the heat losses from the window frames and the heat retention around the window structure (figure 6.34, 6.35). The infrared image of Potterrow's south side shows well sealed-insulated windows and panels with low heat losses on the south facing facade that captures the heat and generates it naturally during the course of the day (figure 6.36, 6.37).

Figure 6.3410: Argyle House south side

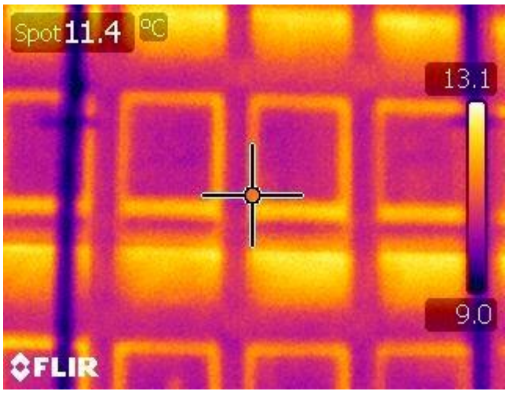


Figure 6.3511: Infrared image of Argyle House south side

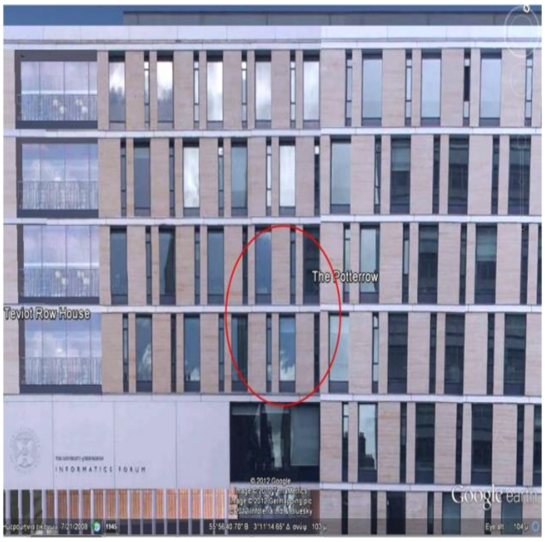


Figure 6.36:Potterrow south side

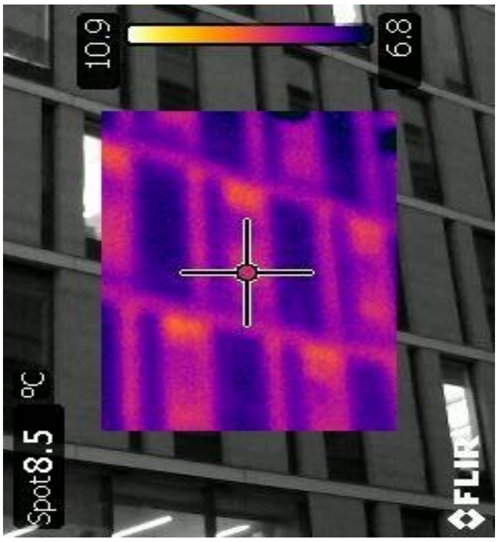


Figure 6.37: Infrared image of Potterrow south side

South-west side of Argyle House and the Potterrow building

The digital image of Argyle House (figure 6.38) shows shadows on the middle and lower parts of the south-west facade of the building, due to the angle of the sunset. The infrared image (figure 6.39) shows heat absorption and retention in the concrete structure and heat losses from the window structure. This side of the building is unoccupied but heating is on in all of the building. The glass on the staircase shown in the middle part of this facade presents some heat losses which could be from the heat retention around the glass.

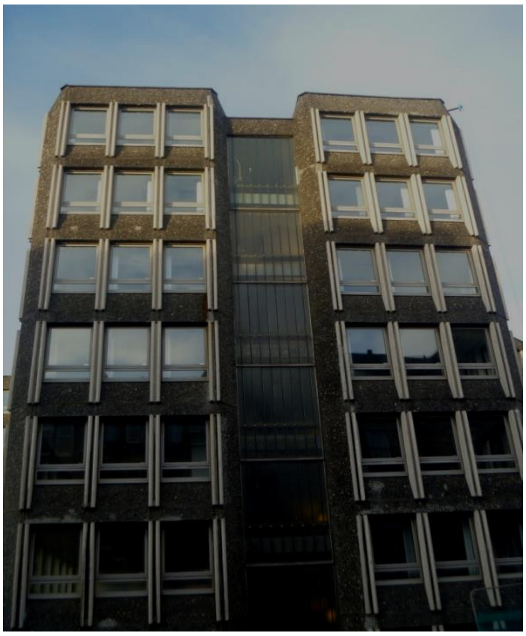


Figure 6.3812: Argyle House south-west side

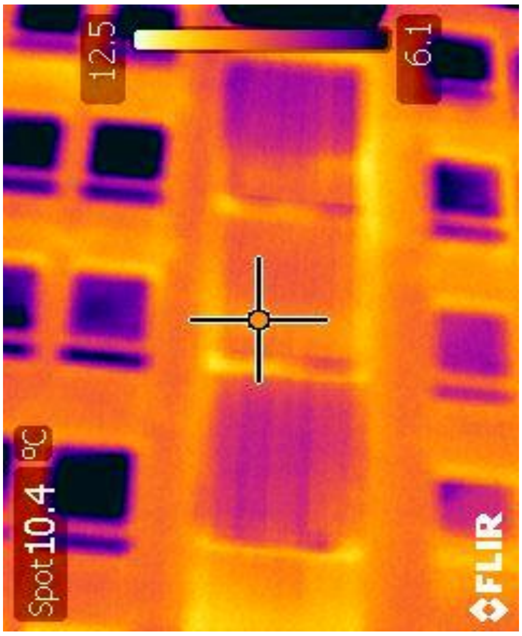


Figure 6.3913: Infrared image of Argyle House south-west side

West side of Argyle House and the Potterrow building

This west side of the building (figure 6.40) is not occupied, although heating is on due to the central heating system. Figure 6.41 shows heat movement around the window frames and in the concrete structure which does not last for long in evening hours as the building has sufficient thermal mass.

Figure 6.4014: Argyle House west side

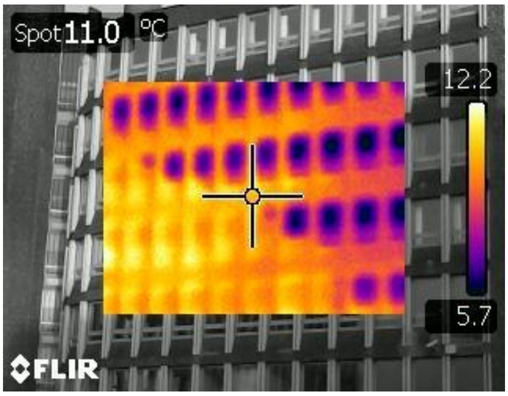


Figure 6.4115: Infrared image of Argyle House west side

Figure 6.42 shows the stone facade precast panels that face west and the infrared image (figure 6.43) shows low heat losses from the window frames facing west.

Figure 6.42: Potterrow building west side

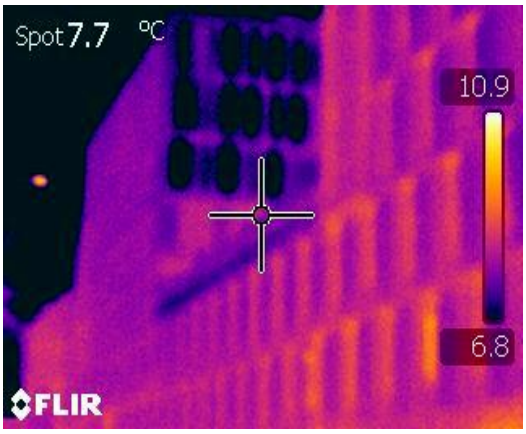


Figure 6.4316: Infrared image of Potterrow Building, west side

Figure 6.44 shows the large surface glass from a meeting room on the first floor of the building in the west side, were a trench heater was on. The infrared image (figure 6.45) on the double glass shows no heat losses. This shows the interaction that the energy-efficient heating systems have in relation to the building fabric.

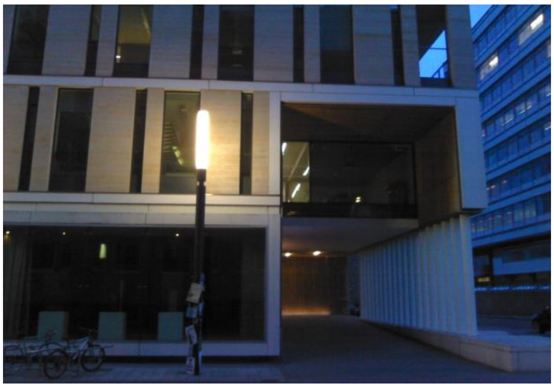


Figure 6.44: Potterrow building west side

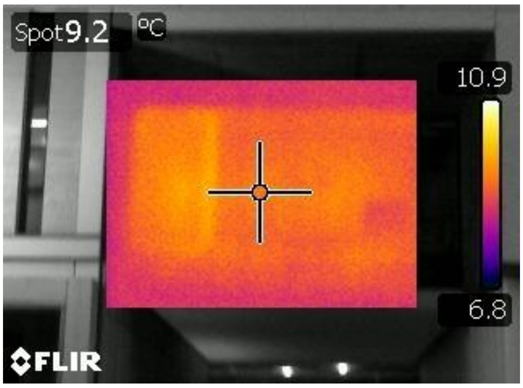


Figure 6.45: Infrared image of Potterrow Building, west side

East side of Argyle House and the Potterrow building

The sun rises from the east and sets in the north/west. According to that the east facades of Argyle House are not that warm since the sun remains longer on the west side of the building where the sun sets. Apart from that the east side of the building (figure 6.46) is surrounded by other buildings, at a close distance, causing large surface shadows. The infrared image (figure 6.471) shows heat losses from the glass strip windows through its frame on the staircase.

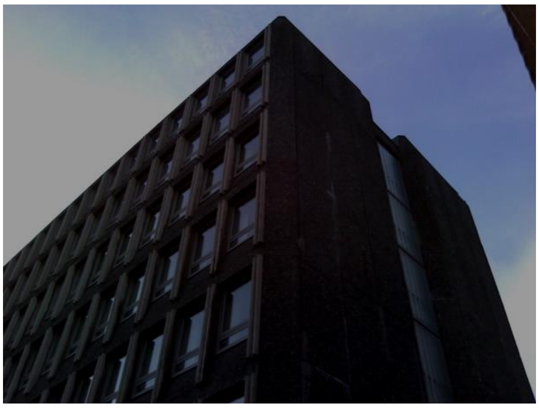


Figure 6.46: Argyle House east side

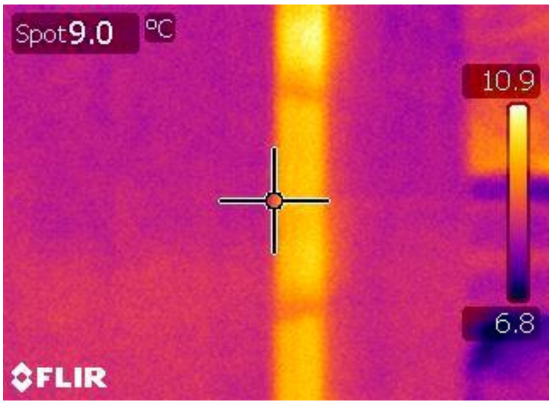


Figure 6.47: Infrared image of Argyle House, east side

All the north-east facing facades of the Potterrow building in the large courtyard (see more perspective images in appendix 8) are made from white polished precast panels (figures 6.48, 6.50). The infrared image from the east side of the building shows low heat losses (figures 6.49, 6.51).

Figure 6.48: image of Potterrow building, east side

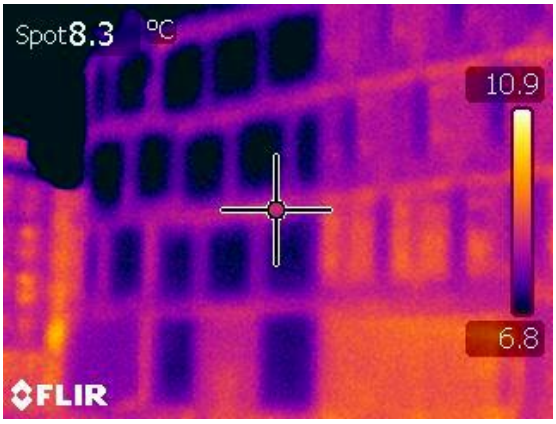


Figure 6.4917: Infrared image of Potterrow building, east side

Figure 6.50 Image of the Potterrow building, east side

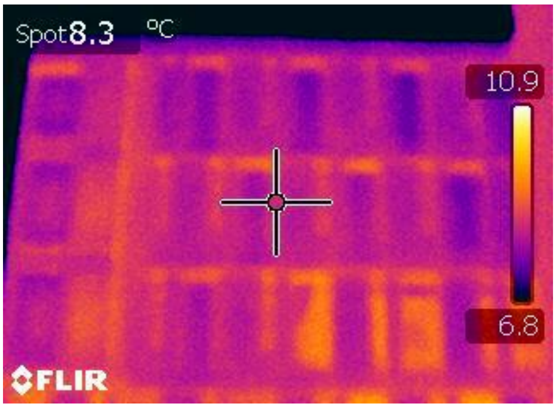


Figure 6.5118: Infrared image of the Potterrow building, east side

Existing thermographic survey

The existing thermographic survey conducted by BSRIA only in few areas of the building, shows air-leakages and thermal bridging throughout the building (see figures 6.52-6.60).

Figure 6.52: A digital image of an external window

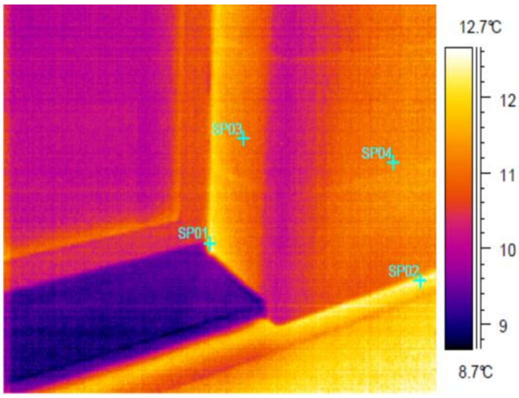


Figure 6.53: A thermal image of an external window

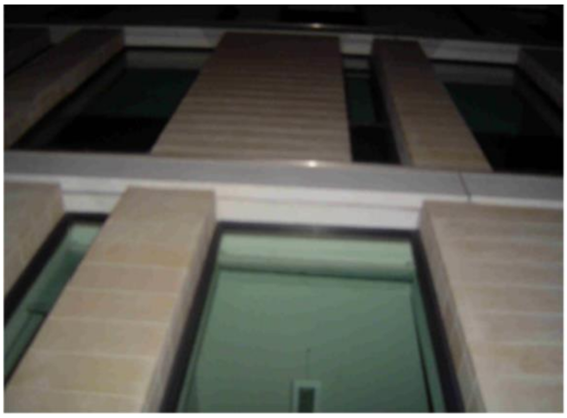


Figure 6.54: A digital image of an external window

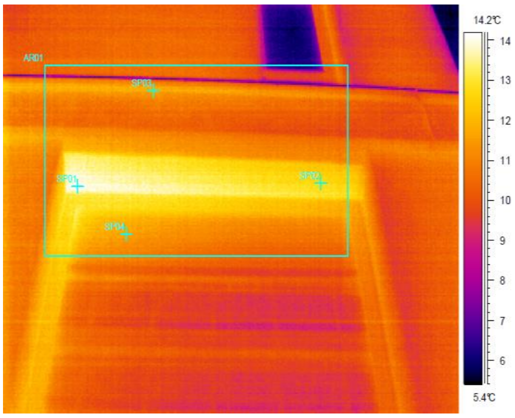


Figure 6.5519: A thermal image of an external window

Figure 6.5620: A digital image of the upper part of an external window frame due to the conduction of heat from the interior of the building.

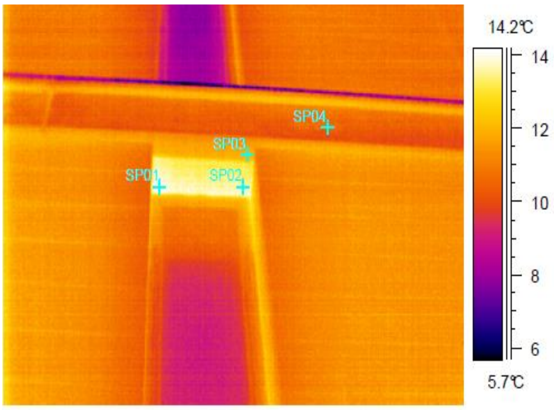


Figure 6.57: A thermal image of the upper part of an external window frame due to the conduction of heat from the interior of the building.

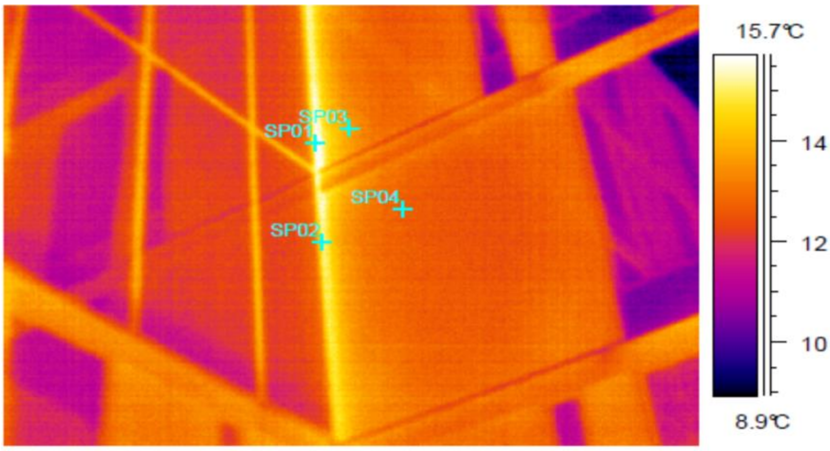


Figure 6.58: A defect involving the join between two external walls. Air may be leaking through the join.

Figure 6.59: An optical and digital image of the plant room external wall. Evidence of air-leakage through a possible gap in the joints. Heat may also be conducting through one of the support beams creating a thermal bridge between the interior of the plant room and the exterior.

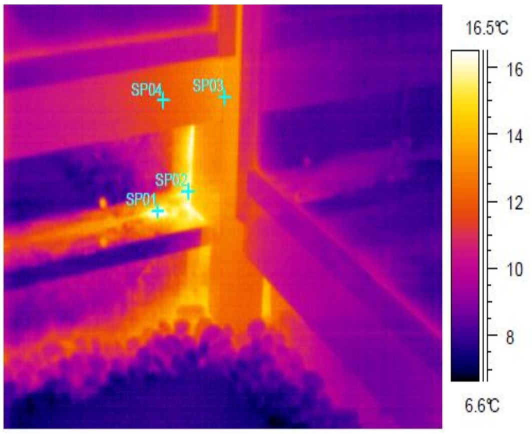


Figure 6.60: An optical and thermal image of the plant room external wall. Evidence of air-leakage through a possible gap in the joints. Heat may also be conducting through one of the support beams creating a thermal bridge between the interior of the plant room and the exterior.

6.5.2 Case study 2

Similar to the explanation on the orientation of case study 1, Five Ways House is north oriented while the EIIC is west oriented like the Potterrow building. So this is a common sustainable feature or criteria for low carbon office buildings. The longest facades of Five Ways House face the north and the south with a relatively long facade facing the east and only a small part of the building facing the west. Five Ways is built within a slightly sloping site where the upper part is the west. On the other hand the longest facades of the EIIC are in the west and east. There is also a structural difference between the west-east and the north-south facades of the EIIC. Brick wall exposed mass in the west and east through to the windthrough suction ducts that are installed within the facade (see section 6.4.9). There is a shading system on the south facing facades of the EIIC while there is shading in Five Ways House. In order to find out the difference in building fabric performance between the two, infrared analysis was used. It also has to be considered that the two buildings have a small difference in local temperature which influences to a certain extent the outcome of the analysis (see weather condition at the time of the survey in tables 6.4, 6.5):

Table 6.427: Weather conditions at the time of the thermographic survey in Birmingham

Date of thermal imaging	15th March 2012
Time	6:00pm-8:00pm

Weather

Source: The Weather Channel (uk.weather.com

Day	**Avg. High**	**Avg. Low**	**Mean**
15-03-2012	11	4	n/a

Sunset/Sunrise

Source: The Weather Channel (uk.weather.com)

Day	**Sunrise**	**Sunset**	**Daylight Hours**
15-03-2012	06:18	18:10	11h, 52min

Hourly Weather Observation

Source: World Weather Online (worldweatheronline.com)

Time	**Conditions**	**Feels Like**	**Cloud**	**Humidity**	**Visibility**	**Pressure**	**Wind**
18:00-20:00	Sunny 8^0C	7^0C	3%	83%	n/a	1024mb	6mphs

Table 6.5: Weather conditions at the time of the thermographic survey in Winchester

Date of thermal imaging	16th of March 2012
Time	6:00pm-8:00pm

Weather

Source: The Weather Channel

Day	**Avg. High**	**Avg. Low**	**Mean**
16-03-2012	9	1	6

Sunset/Sunrise

Source: The Weather Channel

Day	**Sunrise**	**Sunset**	**Daylight Hours**
16-03-2012	06:19	18:14	11h, 55min

Hourly Weather Observation

Source: World Weather Online

Time	**Conditions**	**Feels Like**	**Cloud**	**Humidity**	**Visibility**	**Pressure**	**Wind**
18:00-20:00	Part cloudy/part sunny 10^0C	8^0C	54%	88%	n/a	1016mb	10mph SW north/east

South side of Five Ways House and the EIIC

The infrared from the south facing facades of Five Ways House (figures 6.61, 6.62) indicate heat losses from the single-glazed windows. The surface temperature is no different from the air indoor temperature, which is 10^{0}C.The concrete horizontal rows have absorbed the air temperature and retained that during the survey. Again it can be said that concrete changes temperature slowly, although due to no insulation and not very thick exterior walls, the concrete walls adapt easily to the inside and outside temperatures and lose temperature rapidly also. The infrared also shows anomalies with thermal losses and thermal resistance. Where the window blinds are closed the infrared detects lower heat retention from the windows with open blinds. Surrounding buildings create some shadows (see section 6.4.3) in the lower floor however the middle-top floors are exposed to the direct sunlight. The fact that there is no insulation, thicker walls and single-glazed windows, contributes to poor envelope thermal performance.

Figure 6.61: Five Ways House south side

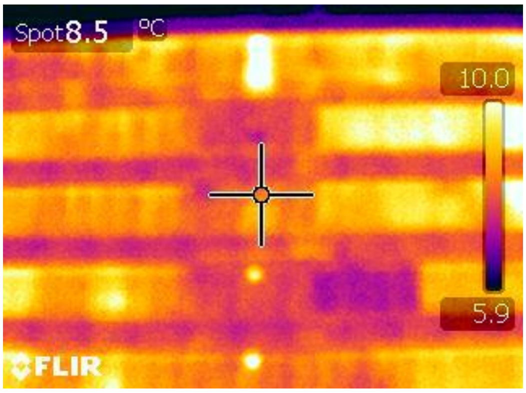


Figure 6.6221: Infrared image of Five Ways House, south side

The south courtyard facing elevations are finished with new fenestration and lightweight cladding with timber solar shading in certain locations (figure 6.63). The infrared image (figure 6.64) shows the heat that is retained from the shading system. Therefore this south facing area gets plenty of sunlight over the day due to different angles of the sun in different seasons, although the building is protected from overheating, as it is located on the south side of United Kingdom.

Figure 6.6322: EIIC, south side

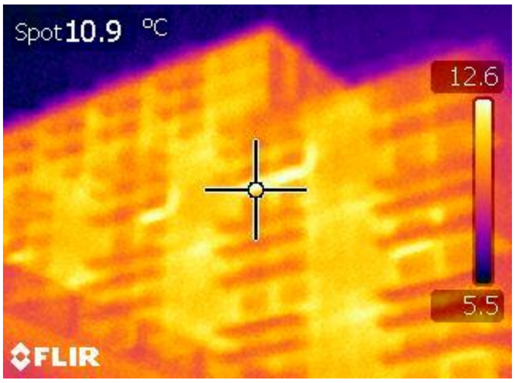


Figure 6.6423: Infrared image of the EIIC, south side

West side of Five Ways House and the EIIC

The infrared image in the west facing facade of the Five Ways House (figure 6.65, 6.66) points out anomalies due to the poor thermal mass of the building. The fact that the building has no insulation can be seen also.

Figure 6.6524: Five Ways House west side

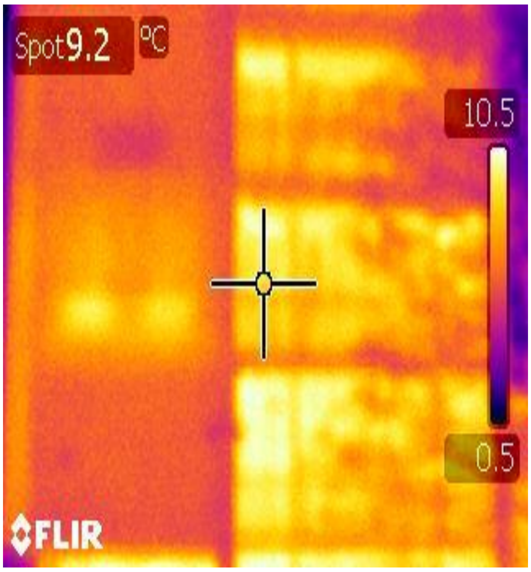


Figure 6.66: Infrared image of Five Ways House, west side

The front facade of the EIIC with the vertical exposed brick structures shows high heat retention and well sealed windows (figures 6.67, 6.68). Some heat losses can be seen from the window frames. Further to the previous notes, the infrared image from the west facing facade shows low heat losses from the windows and high thermal resistance from the brick exposed structure. On the top of the brick surrounded structure there are ducts which take the air inside the building and ventilate it through the floorplates, which also helps to cool the building. However this does not contribute to cooling down the surface temperature of the exposed brick structure. Therefore the heat retention of the brick warms up the indoor temperatures and the excess heat escapes from the windows while the ventilated air from the ducts entering the windrafts escapes in a cycle back up to the windrafts.

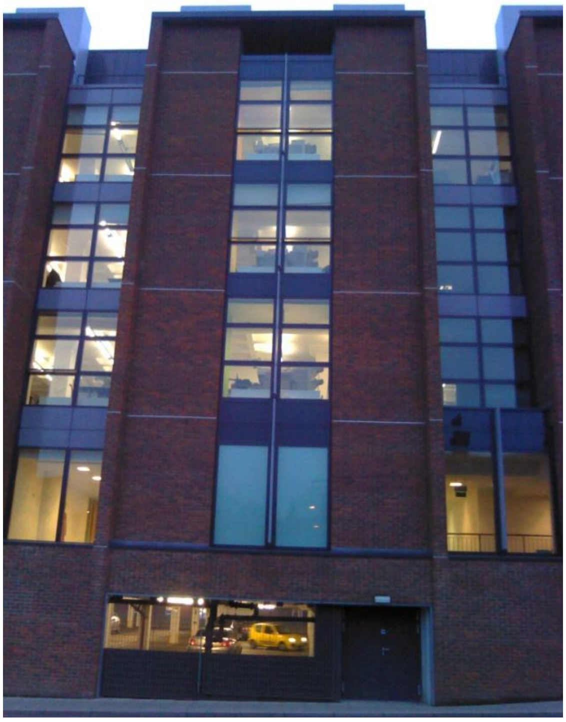


Figure 6.6725: EIIC, west side

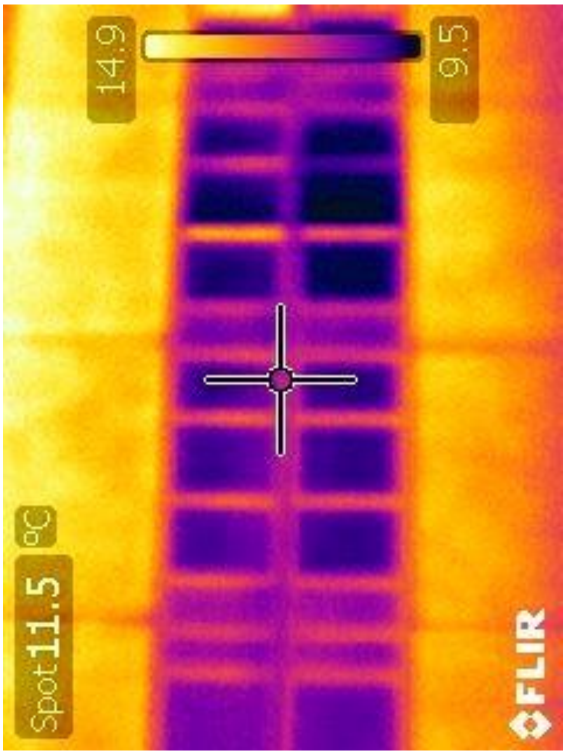


Figure 6.6826: Infrared image of the EIIC, west side

North side of Five Ways House and the EIIC

The infrared images of Five Ways House (figures 6.62, 6.66) show a north view of the buildings which has low thermal resistance due to the concrete structure and the fact that there is no insulation in the building. The infrared image of the east northern corner of the building shows also the thermal bridges, allowing the heat to be transferred.

Figure 6.6927: Five Ways House, north side

Figure 6.7028: Infrared image of the Five Ways House, north side

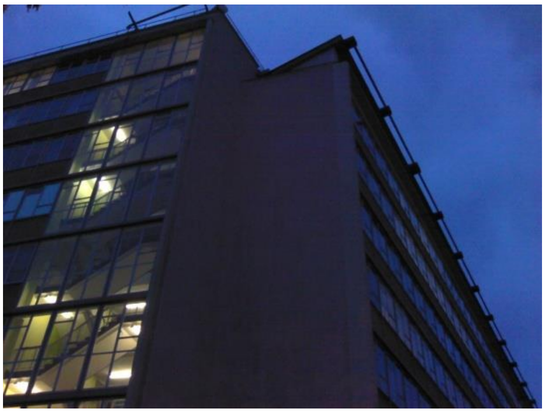


Figure 6.7129: Five Ways House, north side

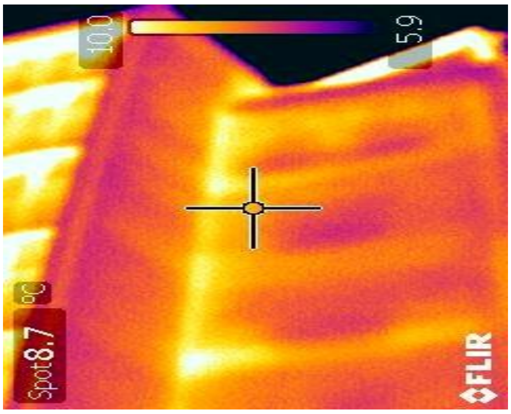


Figure 6.72: Infrared image of Five Ways House, north side

The north side of the EIIC has a metallic facade (figure 6.73). The infrared image, figure 6.74, shows few heat losses from the windows. Few windows were open at the time of the survey. The metallic structure appears to retain less heat compared to the exposed brick structure.

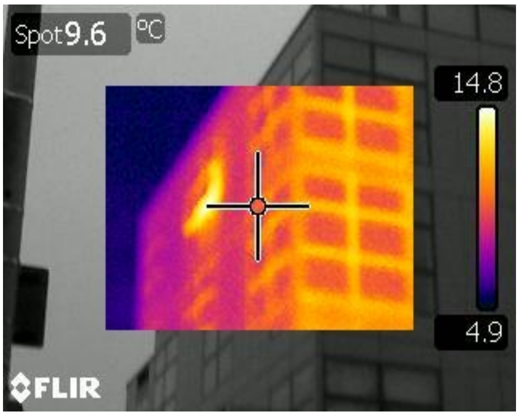


Figure 6.7330: Infrared image of the EIIC, north side

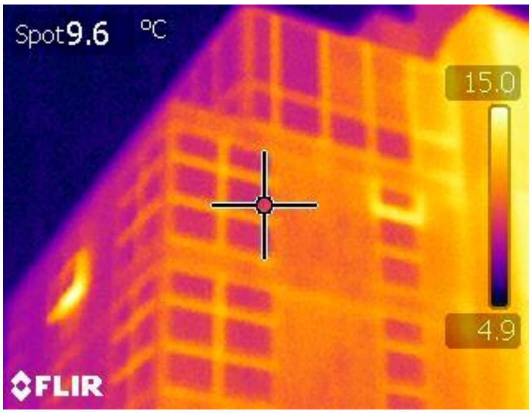


Figure 6.7431: Infrared image of the EIIC, north side

East side of Five Ways House and the EIIC

The east facing facade of Five Ways House shows high heat losses from the non insulated single glazed windows (figures 6.77, 6.78). The south-east part of the building with the balconies (figures 6.77) indicates some heat losses from the single glazed windows and no heat retention in the concrete structure.

Figure 6.75: Five Ways House, east side

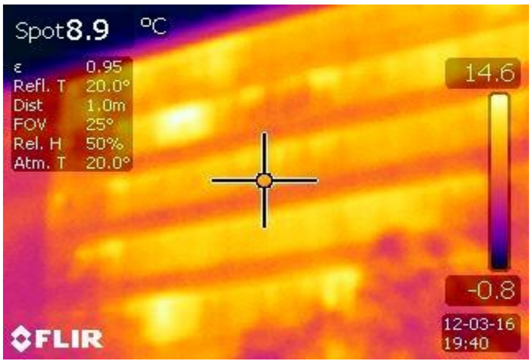


Figure 6.76: Infrared image of Five Ways House, east side

Figure 6.77: Five Ways House, east side

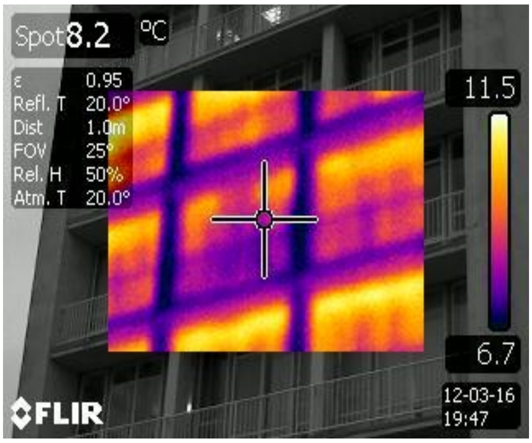


Figure 6.7832: Infrared image of the Five Ways House, east side

On the other hand, the east facade of the EIIC (figure 6.79, 6.80) shows low heat retention on the brick structure although several windows were open while heating was on and heat escaped through them.

Figure 6.7933: EIIC, east side

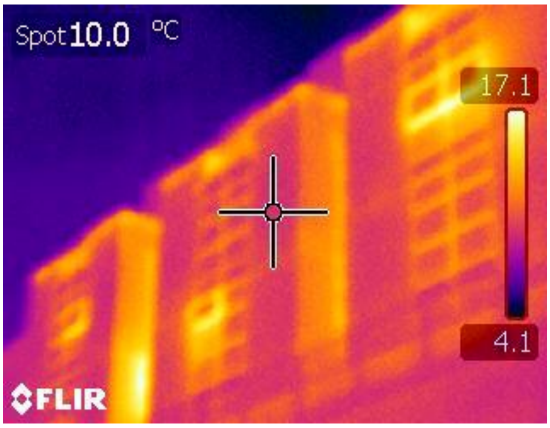


Figure 6.80: Infrared image of the EIIC, east side

6.5.3 Outcome

The infrared images of the conventional buildings reveal that they are cold in the winter and warm in the summer. The fact that the buildings are not insulated, with single glazed windows, increases the demand for heating-cooling in the interior spaces, increasing the hours of heating-cooling. As the exact U-values of the buildings are not known, the infrared analysis has helped to find that the structures have low thermal transmittance, therefore high U-values (about 0.94 W/m^{2}K, estimated using CBA U-Value Calculator). Brick is known for having higher heat resistance, in the EIIC (about 0.15 W/m^{2}K, estimated using CBA U-Value Calculator) compared to other structural materials (see also MATRIX table on U-values, appendix 8). The infrared images of the sustainable offices have detected heat losses from several windows which need further insulation.

6.6 Discussion

Interesting research findings demonstrate the performance gap that exists between building design, energy consumption and building performance. From section 5.3 (chapter 5) it can be seen that even though the sustainable office buildings were certified as ‘excellent’ (Potterow 71.99% and EIIC 72.89%), during operation, buildings do not perform as ‘excellent’. Both office buildings have a great amount of energy efficient technologies installed to enhance energy efficiency, although if these technologies are not used and managed properly, they will not perform efficiently. Apart from that, even if these buildings have been designed to perform as energy efficient with insulations, double-glazing, low U-values, with exposed thermal mass for night cooling, with wind through for natural ventilation, this does not mean that buildings have achieved the ‘excellent’ level of efficiency, since heat losses can be detected. From the existing and different POE survey to this study at EIIC office building, it was found that the occupants were not satisfied with indoor heating and cooling comfort and with the set temperatures. Consequently, further to the internal and external parameters explained in the discussion section in chapter 5, this chapter adds that building operation through effective management of the heating and cooling systems operation and control and proper installation of building equipment are another two highly important parameters that need to be considered.

For example, the HDD evaluation on the Potterrow office building showed negative correlations between heating and heating degree days. However this building has a different type of heating technology compared to other office buildings. The CHP, in order to be energy efficient, must have maximized usage, and so it performs differently and is operated at different times of the day and even during the night so that efficiency can be enhanced and heating recovered. It could also be the case that metering readings provided are not correct or that metering readings according to the DECC publication on HHD (mentioned in research design, chapter 4), were not taken correctly, on standard days of every month. This is a more technical aspect that can be better understood from the facility management. All the other office buildings - the EIIC and the other two conventional offices - had a positive correlation to the HDD. The conventional office building energy management, seems to consider more the outside degree temperatures, considering that in summer cooling is natural ventilated. An increased amount of heating is still consumed even if the correlation to the HDD seems positive, considering that these buildings have old heating and cooling systems or even upgraded yet not that advanced ones with poor thermal heating-cooling fabrics. The thermographic survey demonstrates the poor condition of the conventional office buildings according to the structural heat losses that were identified.

Another issue identified from the POE surveys, and as mentioned in the literature (chapter 2), is that current sustainable office building energy and CO_2performance is compared to the old benchmarks for best practice. Section 6.3 presents the benchmarking of the EIIC as given from the previous POE survey to the building architects, which clearly reflects this issue. Since this office building was built, there were not many BREEAM refurbished office buildings, and none of them yet had a BREEAM outstanding rating. However, since building regulations changed since the last benchmarking update in 2003, the benchmarking should have been updated and the existing EPCs and DECs could play a greater role in influencing a change in benchmarking of office buildings.

In terms of the heating and cooling system operation and its relation to occupancy behaviour, the occupants in all the office building had no interaction with these systems, apart from turning on/off the radiator valves in their office space. The whole system operation and the set temperatures are the responsibility of the facility management team and as revealed from interviews with the building managers (appendix 22), the facility management would change the set temperatures after a large number of complaints had been received. The 28 degree celcius set temperature in the EIIC is obviously a temperature needed for the indoor temperature to be comfortable for the occupants, as the building is single glazed with no insulation, with a north orientation (larger parts of the building can be too hot or too cold, depending on the season). Although the HDD parameter is 15.5 degree celcius for the building location, meaning that the 28 degrees must be reduced at least to 22 degrees, this is closer to the standard 21 degree temperature for office buildings. By doing that, energy consumption-costs will be reduced and these savings can be used to improve the building fabric. Through the existing UK funding schemes for energy efficient building refurbishments (section 2.5), the energy efficiency can be highly improved.

The key issue from the above-mentioned matters is the fact that the energy indicator assessed by BREEAM before the in-use phase has been fully explored and evaluated during operation of other previous BREEAM excellent certified office buildings. It seems that the energy indicator under BREEAM is too generic and predictions cannot predict a closer picture to the actual energy performance during use. Existing POE methods, such as Soft Landings, is still new and as POE methods are not standard and can be used individually to investigate different issues, a holistic overview of what is causing the unexpected building energy performance is not there yet. Therefore this study has tried to develop a new sustainability indicator where t energy indicators are further explored and investigated in parallel to another indicator: raw-materials. The connection between the two from this chapter is that, in order for energy efficiency to be enhanced, an increased amount of claimed high energy efficient technologies have been used in sustainable office buildings, although they do not operate as expected and beyond that, the embodied raw-material emissions have increased in order for such technologies to be produced. So by looking at the overall performance gap, there is a bigger issue, which is the overall environmental performance gap and the need to sustain energy efficiency with raw-material efficiency.

By looking at the emission reduction diagram of the Potterrow building (chapter 5), initially another sustainability indicator must be added - raw materials - and then it must be shown that energy and raw-material indicators must be studied in parallel. This could lead to building innovative design and to thinking for alternative technologies. The energy performance POE evaluation needs a thorough set of standard methods and approaches and suggestions for additional optional tools. This chapter shows mixed methods that could be used as standard approaches in POEs, although this list needs a combination of more methods.

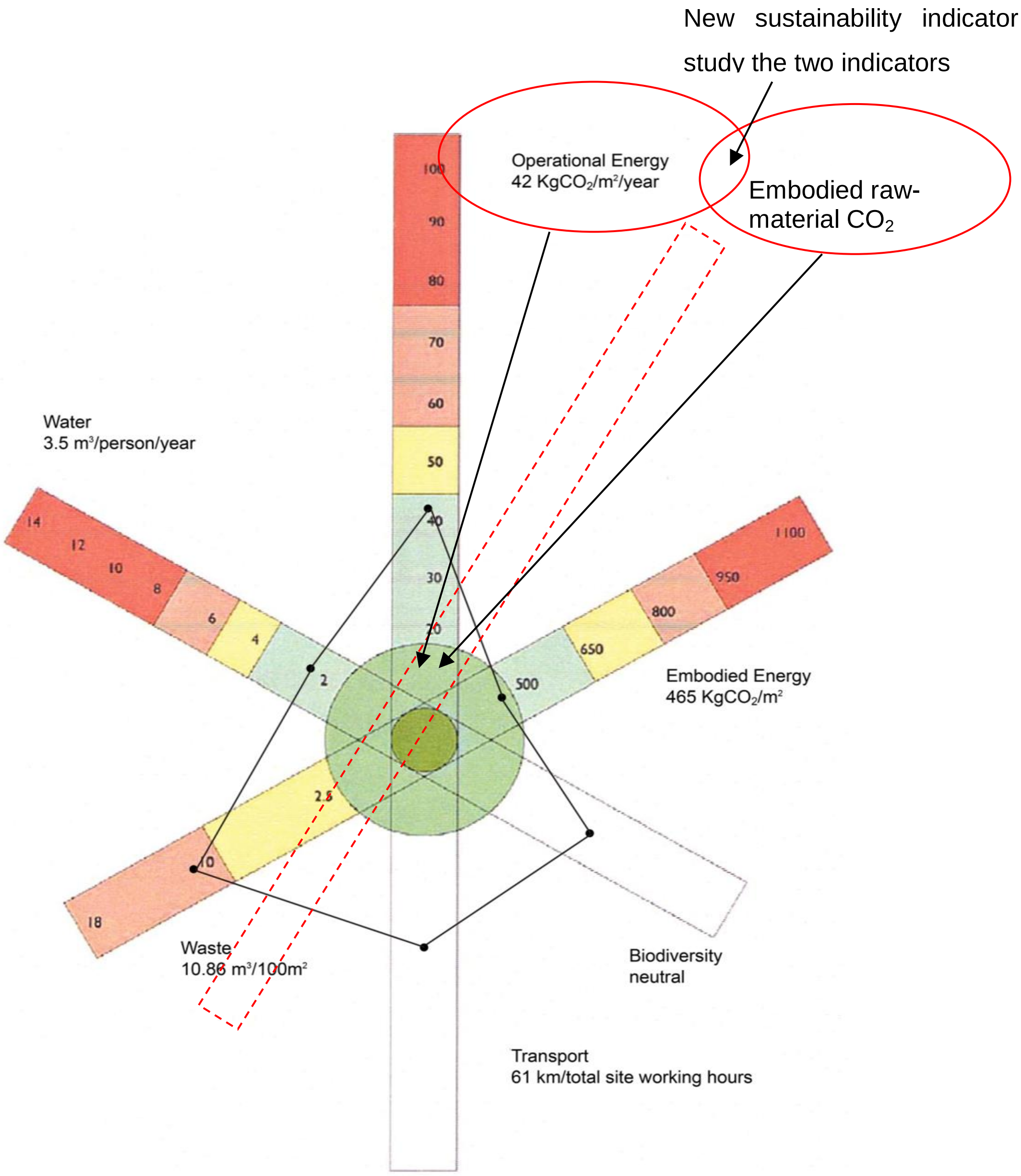


Figure 6.81: new performance inidcator has been added to the 6 key Environmental Performance Indicators promoted by the Movement for Innovation (M4i), a model that was used for the Potterrow building and can be used to show the neew for the new sustainability indicator.

6.7 Summary

This chapter has discussed the analysis of three POE methods on the energy and building fabric thermal performance; energy consumption for heating and cooling, correlation heating consumption with the heating degree data through regression analysis and thermographic survey. Interesting research findings show performance gaps between building design, energy management by facility teams and building installation (from planning and building design) on proper sealing and insulation of the office buildings. This issue leads to a wider issue, which is the environmental performance gap. Chapter 7 evaluates the environmental consequences as a result of energy consumption, heat losses and energy management.

CHAPTER 7: LCA HEATING AND COOLING MECHANISMS BETWEEN SUSTAINABLE AND CONVENTIONAL OFFICE BUILDINGS

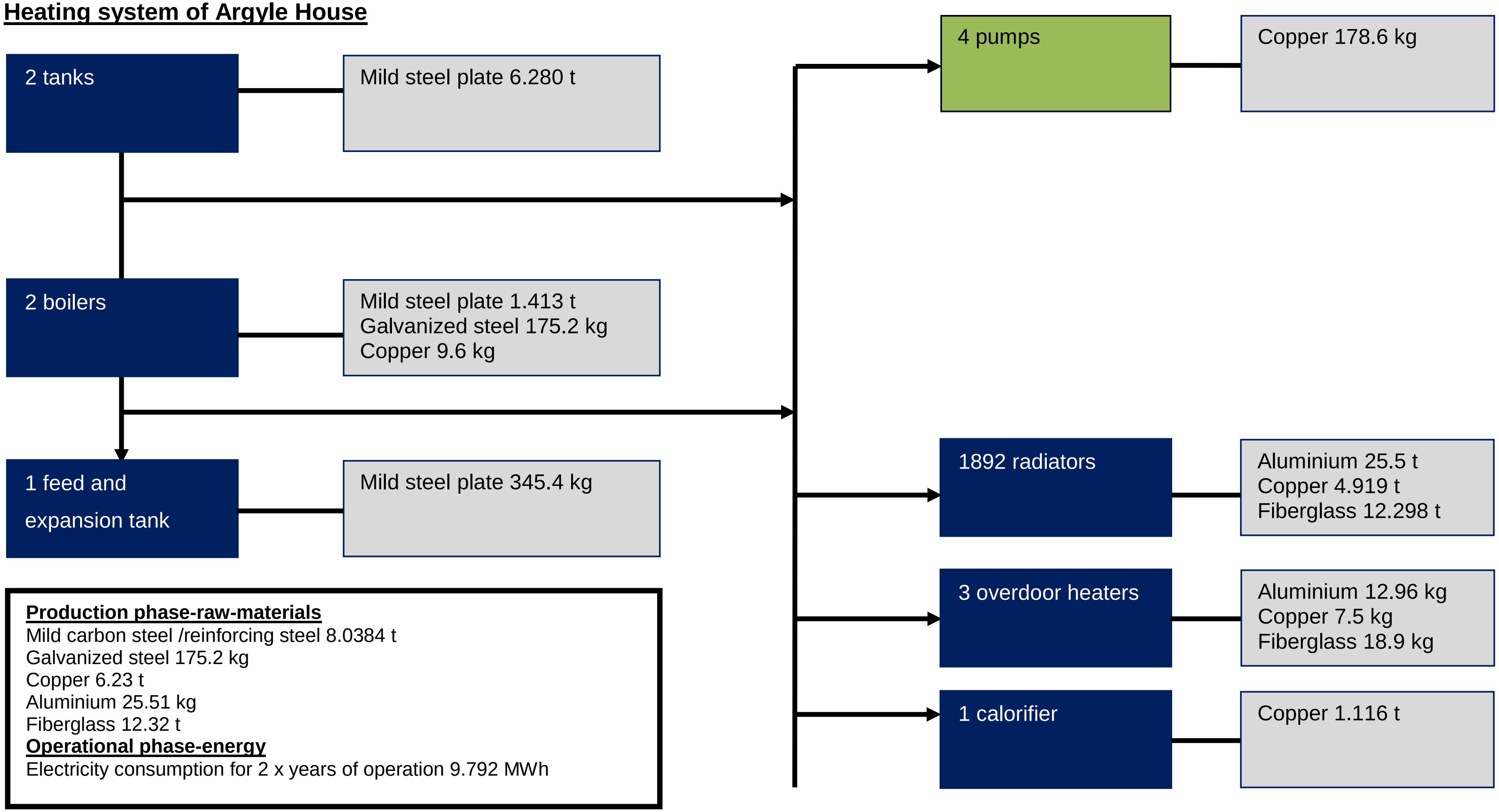
This chapter focused on evaluating the environmental performance gap by assessing the two indicators mentioned: energy and raw-materials. LCA analysis is provided individually for each office building and also for the case study comparison evaluation, both for the heating and the cooling systems. Further to this chapter, hypothetical long run scenarios have been developed to consider potential increase or decrease of energy efficiency and raw-material efficiency of the heating and cooling systems. In addition, sensitivity LCA analysis is provided to assess the environmental impacts of the existing systems compared to alternative low and zero carbon technologies, in order to support further the hypothetical scenarios. LCA uncertainty evaluation has been conducted to assess the data quality of the results. Finally this chapter explains how the LCA becomes a fundamental part of the development of the new sustainability indicator (see more details in chapter 8).

7.1 LCA in conventional office buildings

7.1.1 LCA inventory data

This section presents the inventory data that has been used for the LCA evaluation (figures 7.1-7.4). It shows the heating/cooling process, the system type and which components are used. Additionally it shows which raw-materials have been used in the system and in what amounts. It also includes the heating and cooling consumption data.

Heating system of Argyle House



Production phase-raw-materials

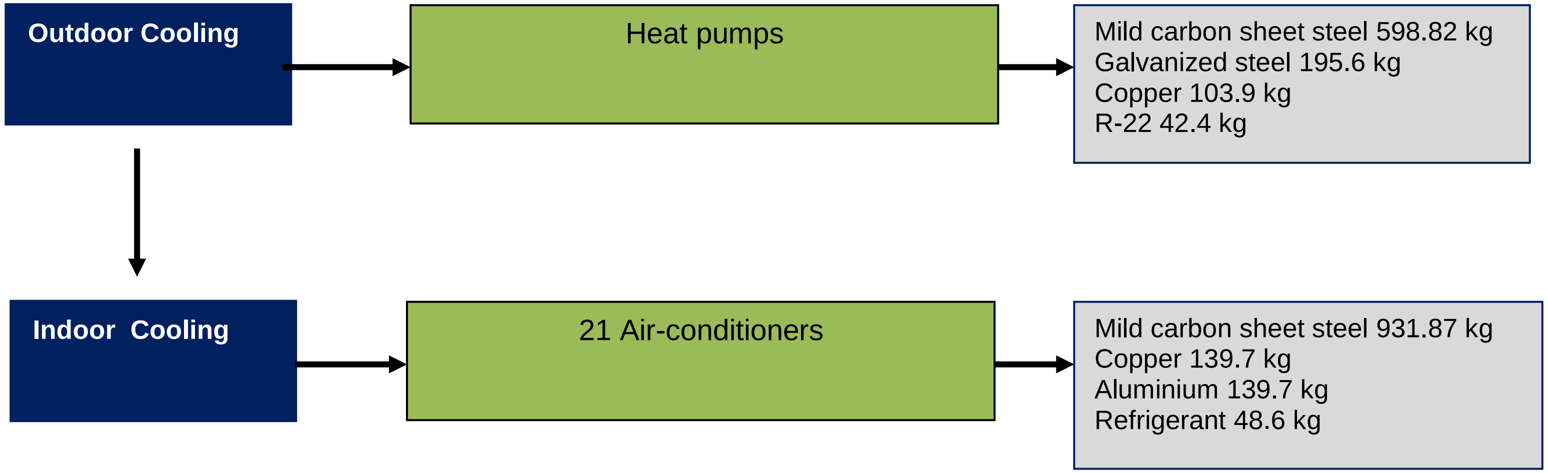
Mild carbon steel /reinforcing steel 8.0384 t
Galvanized steel 175.2 kg
Copper 6.23 t
Aluminium 25.51 kg
Fiberglass 12.32 t

Operational phase-energy

Electricity consumption for 2 x years of operation 9.792 MWh

Figure 7.1: Inventory table of the heating system in Argyle House

Cooling system of Argyle House



Production phase-raw materials
Mild carbon steel /reinforcing steel 1.53 t
Galvanized steel 195.6 kg
Copper 243.6 kg
Aluminium 139.7 kg
Operational phase-energy and gas
Cooling consumption for 2x years of operation 226.41 KWh
Refrigerant 91 kg
Electricity consumption for 2x years of operation

9.792 MWh

Figure 7.2: Inventory table of the cooling system in Argyle House

Heating system of Five Ways House

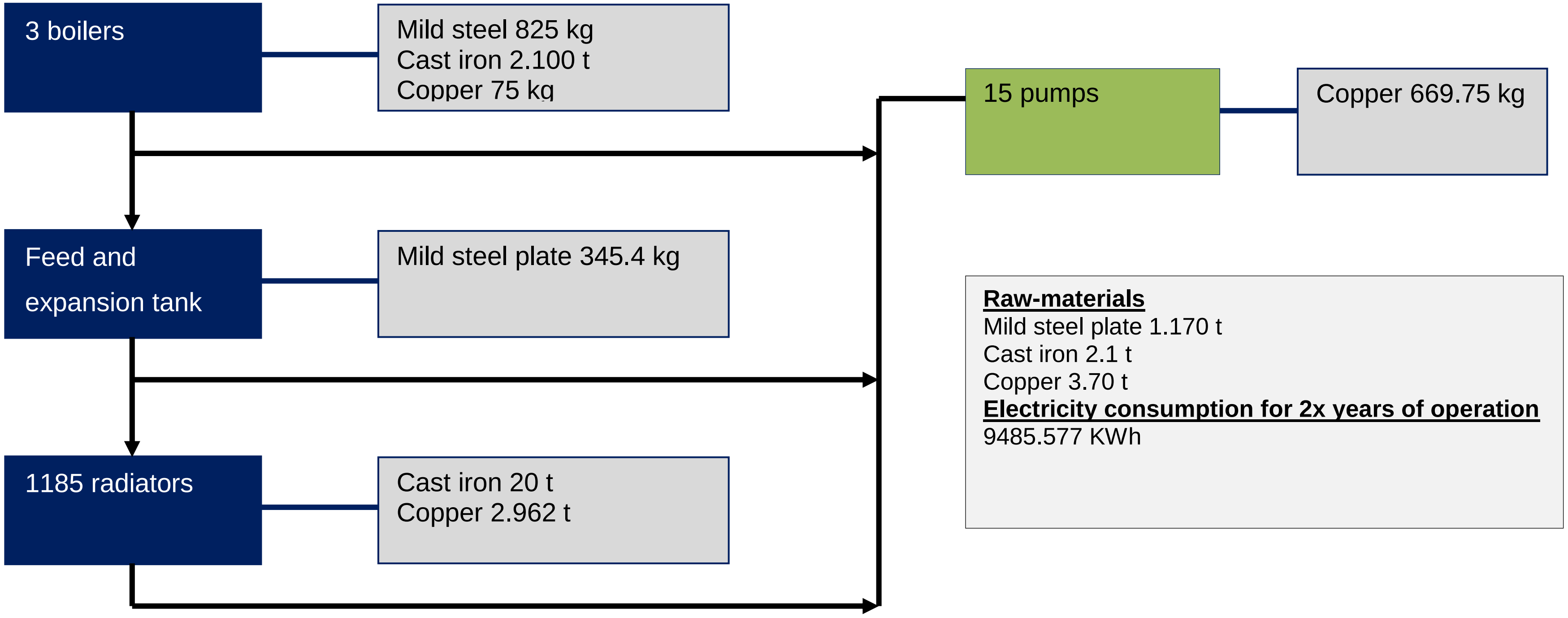
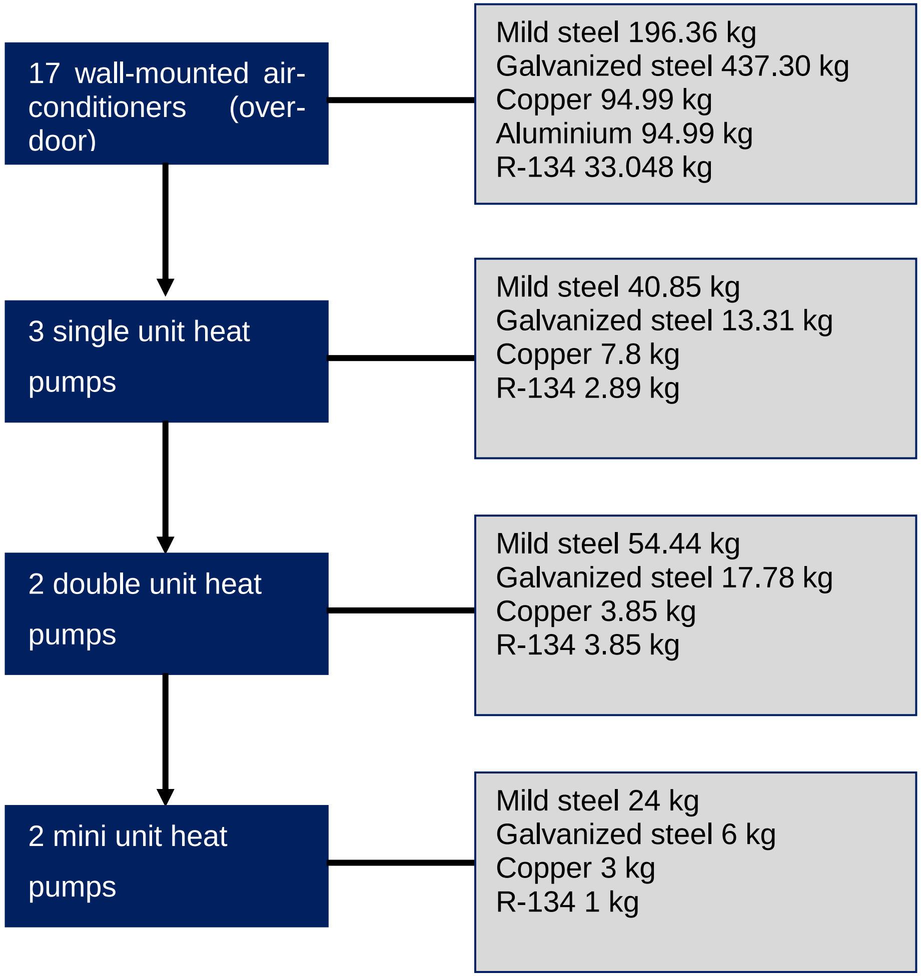


Figure 7.3: Inventory data, heating system, Five Ways House

Cooling system of Five Ways House



Raw-materials
Mild steel 556.56 kg
Galvanized steel 233.46 kg
Copper 114.51 kg
Aluminium 94.99 kg
R-134 kg 40.7 kg
Electricity consumption for 2 x years of operation
n/a

Figure 7.4: Inventory data, cooling system, Five Ways House

7.1.2 LCA network evaluation of raw-materials of the heating system

The conventional building design of the 53-year-old Argyle House required two oil-fired boilers to provide heat to the building via the 1892 radiators, through its central heating type. The consequence of its technology requirements since 1960 is a high amount of copper, which contributes (G-CuZn40 I) 56.2% to the overall environmental burden, followed by glass fibre 39.6% and by reinforcing steel 4.08% (figures 7.5, 7.6).

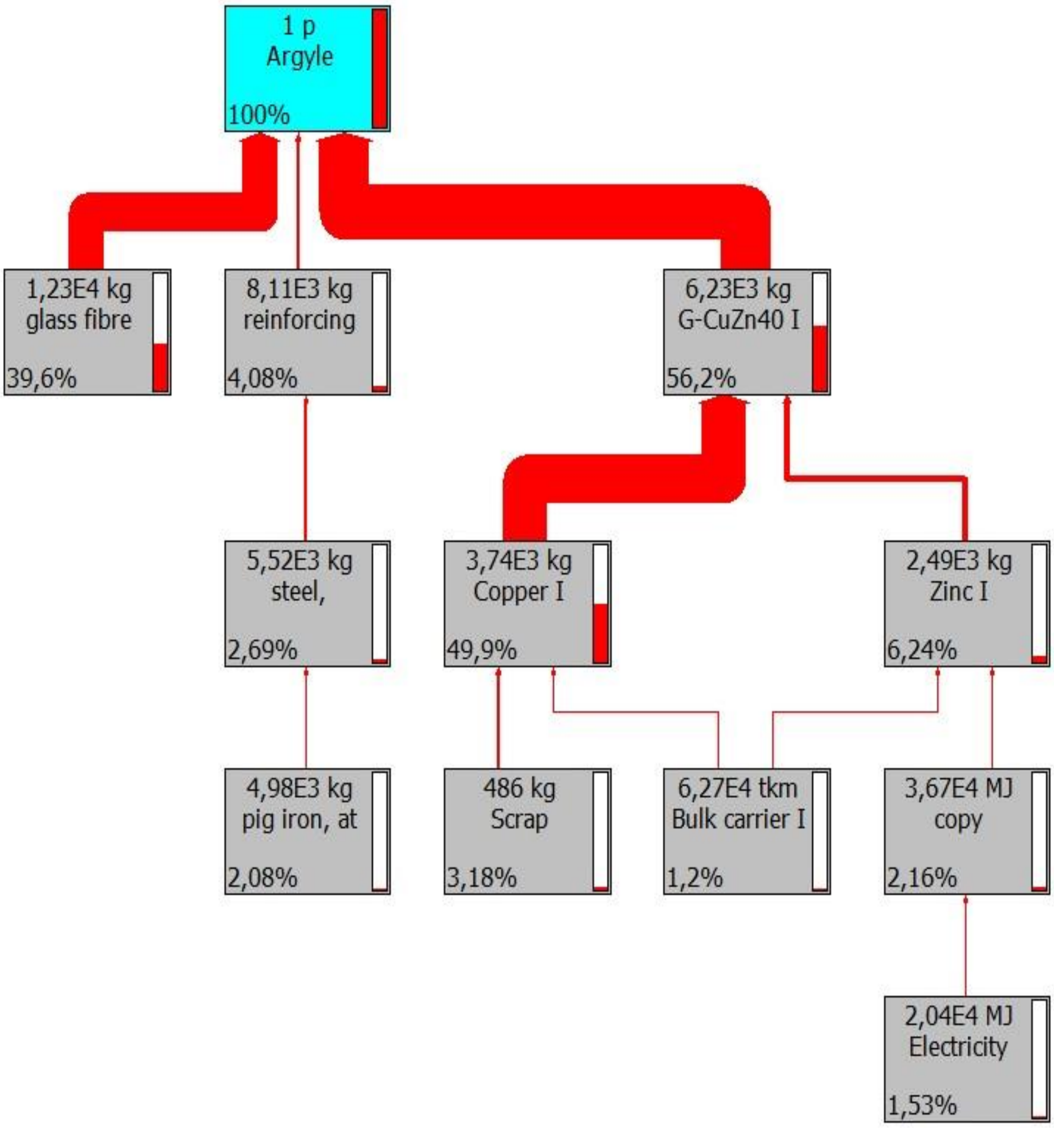


Figure 7.5: Network evaluation of the dominant raw-materials, heating system, Argyle House

Similarly the conventional building design of Five Ways House that had an upgrade in its heating system in 2001 required the installation of three natural gas boilers to provide heating through 1185 radiators (see inventory data, figure 7.3). The consequences of that is, high amounts of copper that contributes to the overall environmental burden 96.3% followed by cast iron 2.42% and by mild steel/reinforcing steel 1.32% (figure 7.6).

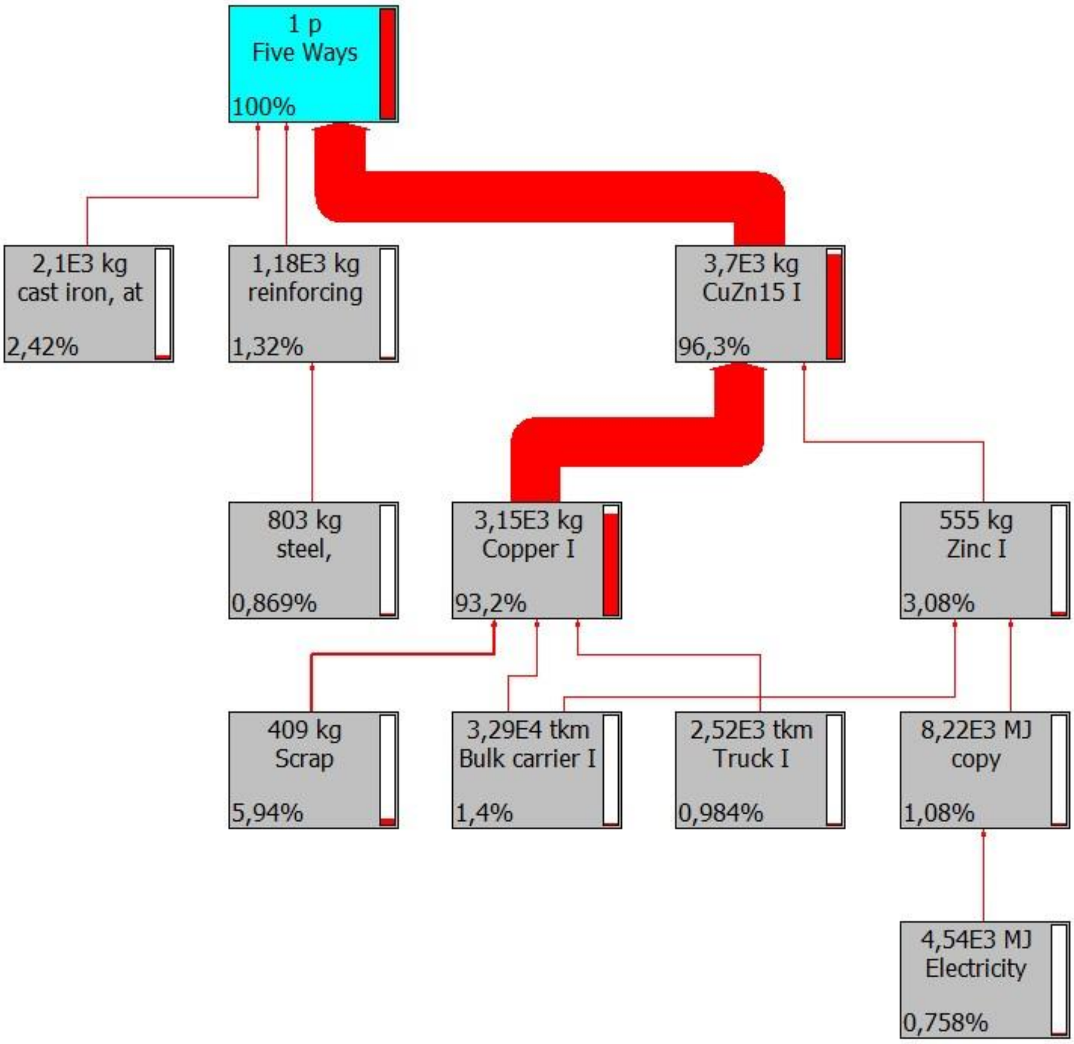


Figure 7.6: Network evaluation of the raw-materials on the heating system of Five Ways House

7.1.3 LCA single score evaluation of raw-materials of the heating system

The single score evaluation of Argyle House (figure 7.7) shows that copper is the dominant raw-material used with the higher environmental impact load and impacts in minerals 5.38kPt, in respiratory inorganics 3.06kPt, in fossil fuels 2.01kPt, in land use 0.309kPt, in acidification/eutrophication 0.274kPt and in climate change 0.163kPt. High single scores are also shown from the glass fibre raw-material in fossil fuels 6.39kPt, in respiratory inorganics 0.919kPt, in climate change 0.436kPt with fewer impacts in acidification/eutrophication 0.0989kPt. From the dominant raw-material, fewer impacts are shown from the mild steel/reinforced steel with impacts in fossil fuels 0.288kPt and in respiratory inorganics 0.307kPt.

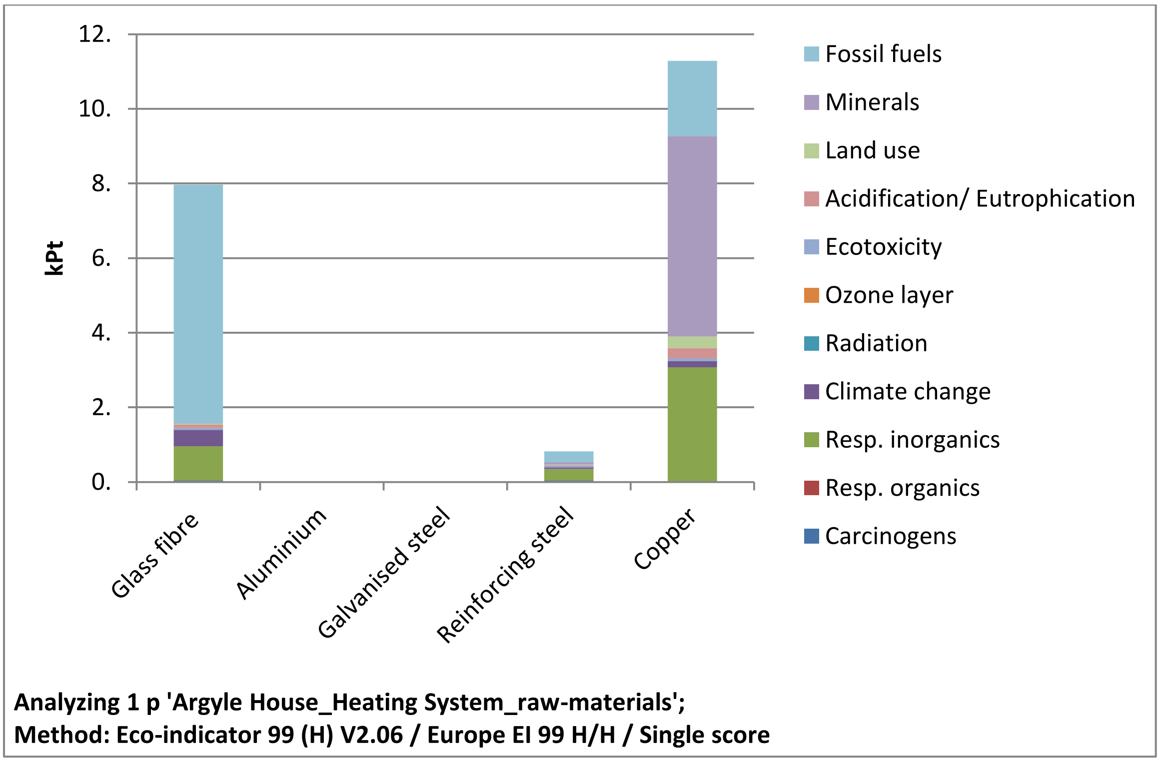


Figure 7.7: Single score evaluation, raw-materials, heating system, Argyle House

The single score evaluation of Five Ways House (figure 7.8) shows that copper is the dominant raw-material of the heating system with significant impacts in mineral 4.29kPt, inrespiratory inorganics 2.44kPt, in fossil fuels 1.41kPt, in land use 0.24kPt, in acidification/eutrophication 0.213kPt and in climate change 0.108kPt.

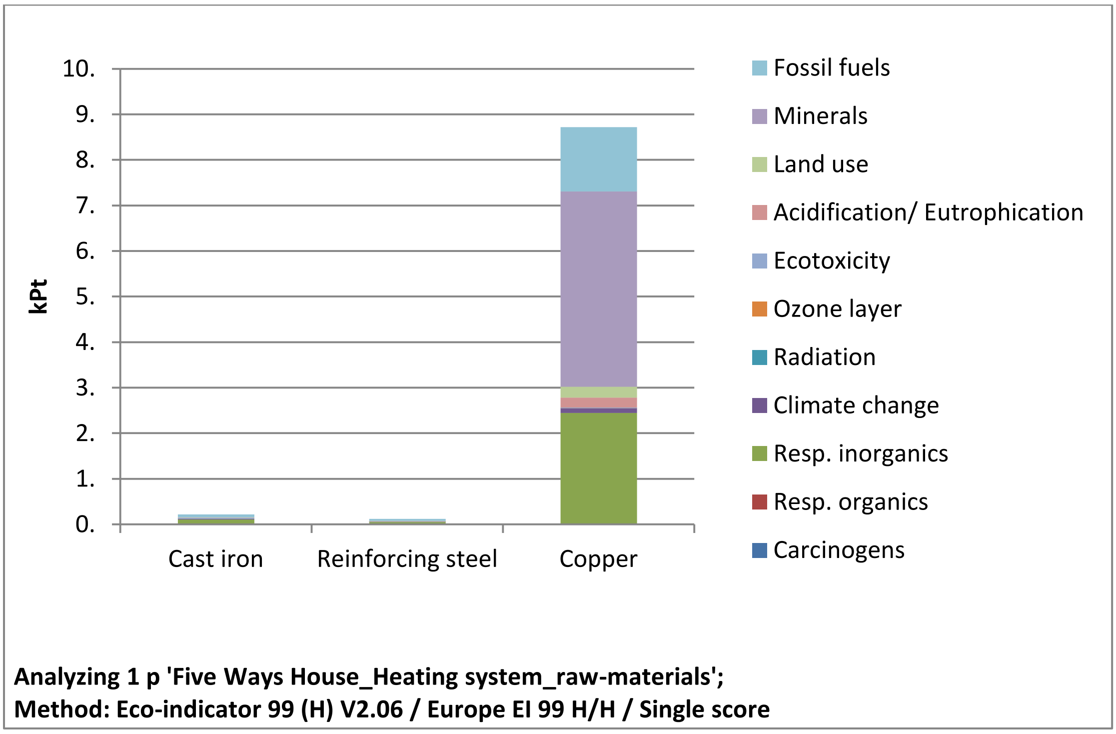


Figure 7.8: Single score of the raw-material of the heating system on Five Ways House

7.1.4 LCA single score evaluation of the heating consumption

The single indicator score of heating consumption of Argyle House (figure 7.9) shows the consequences of the oil-fired heating technology and of the poor building fabric, as discussed in section 8.6. The heating consumption contributes to fossil fuels by 62.2 kPt, to climate change 3.56 kPt, to respiratory inorganics 11 kPt and to acidification/eutrophication 2.09 kPt. The single indicator evaluation score of Five Ways House (figure 244) demonstrates that the most significant impacts of the heating consumption burning natural gas in condensing modulating boilers for two years of operation are in fossil fuels 108 kPt, in climate change 5.26 kPt and in respiratory inorganics by 2.08 kPt.

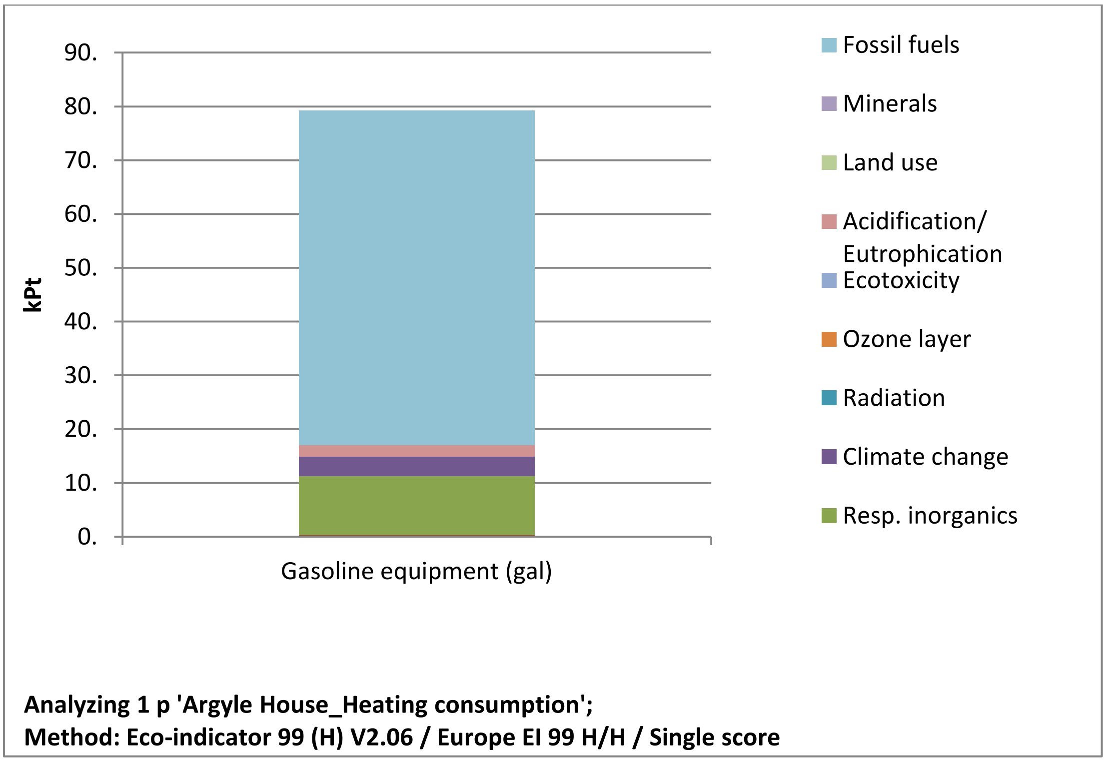


Figure 7.9: Single score evaluation, heating consumption

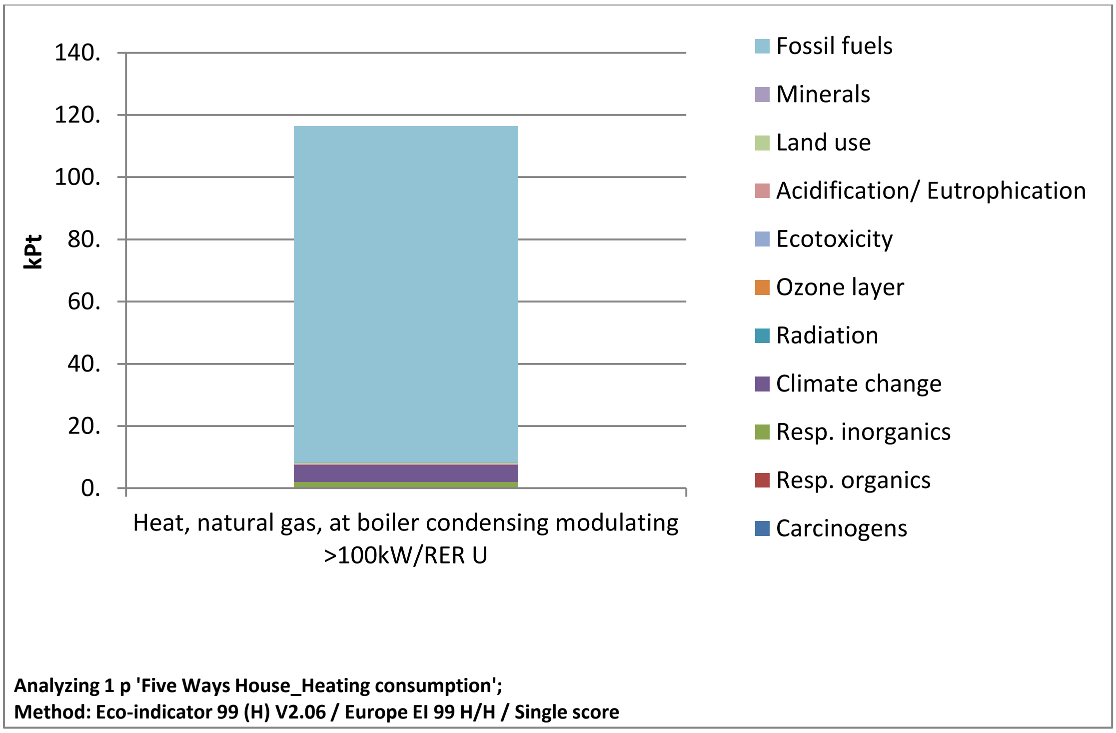


Figure 7.10: Single indicator score, heating consumption, Five Ways House

7.1.5 LCA network evaluation of the raw-materials of the cooling system

The LCA network application of the local split system air-conditioning type of Argyle House shows that the dominant material is copper (CuSn8 I) with 85% overall contribution, followed by reinforcing steel (6.6%), aluminium (6.41%) and stainless steel (x35CrMo17 I, 6.33%) (figure 7.11).

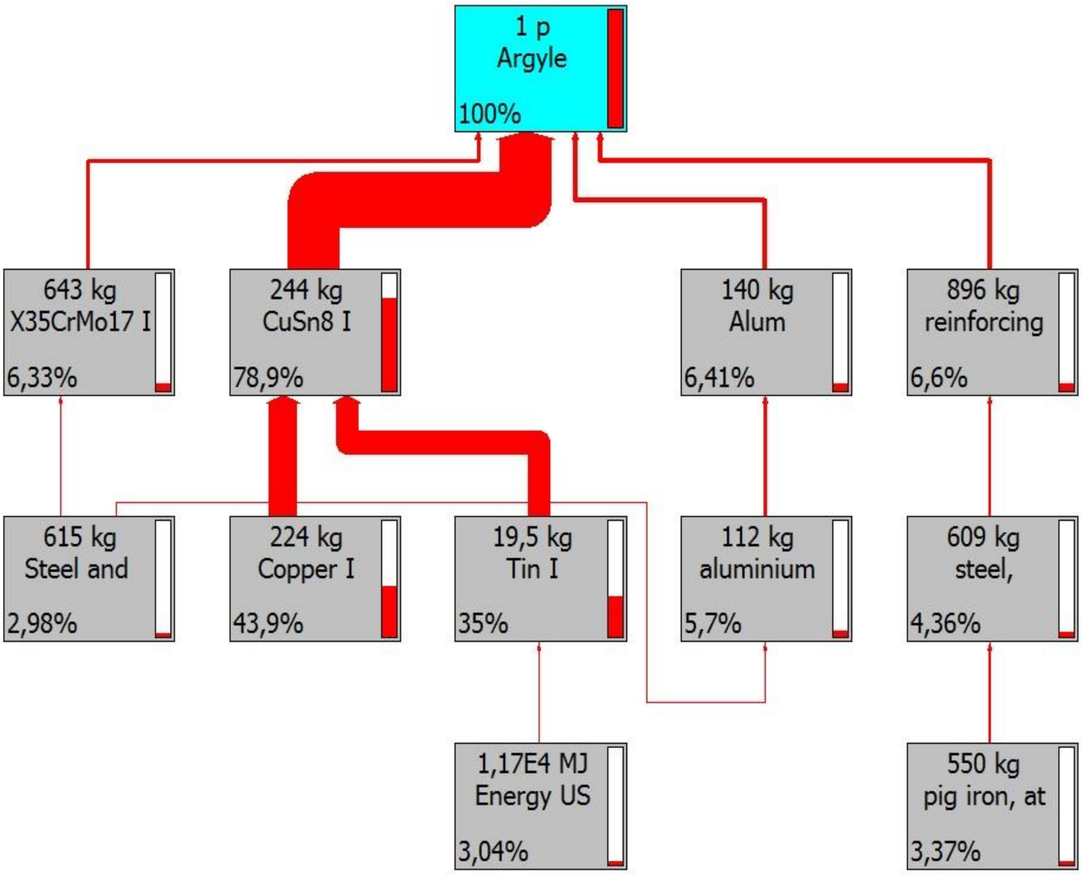


Figure 7.11: Network evaluation of the dominant raw-materials, cooling system, Argyle House

The network evaluation of the split system air-conditioning of Five Ways House (figure 7.12) shows that galvanized steel is the dominant raw-material used 43.7%, followed by reinforcing steel 23.7%, aluminium 16.9% and copper 15.7%.

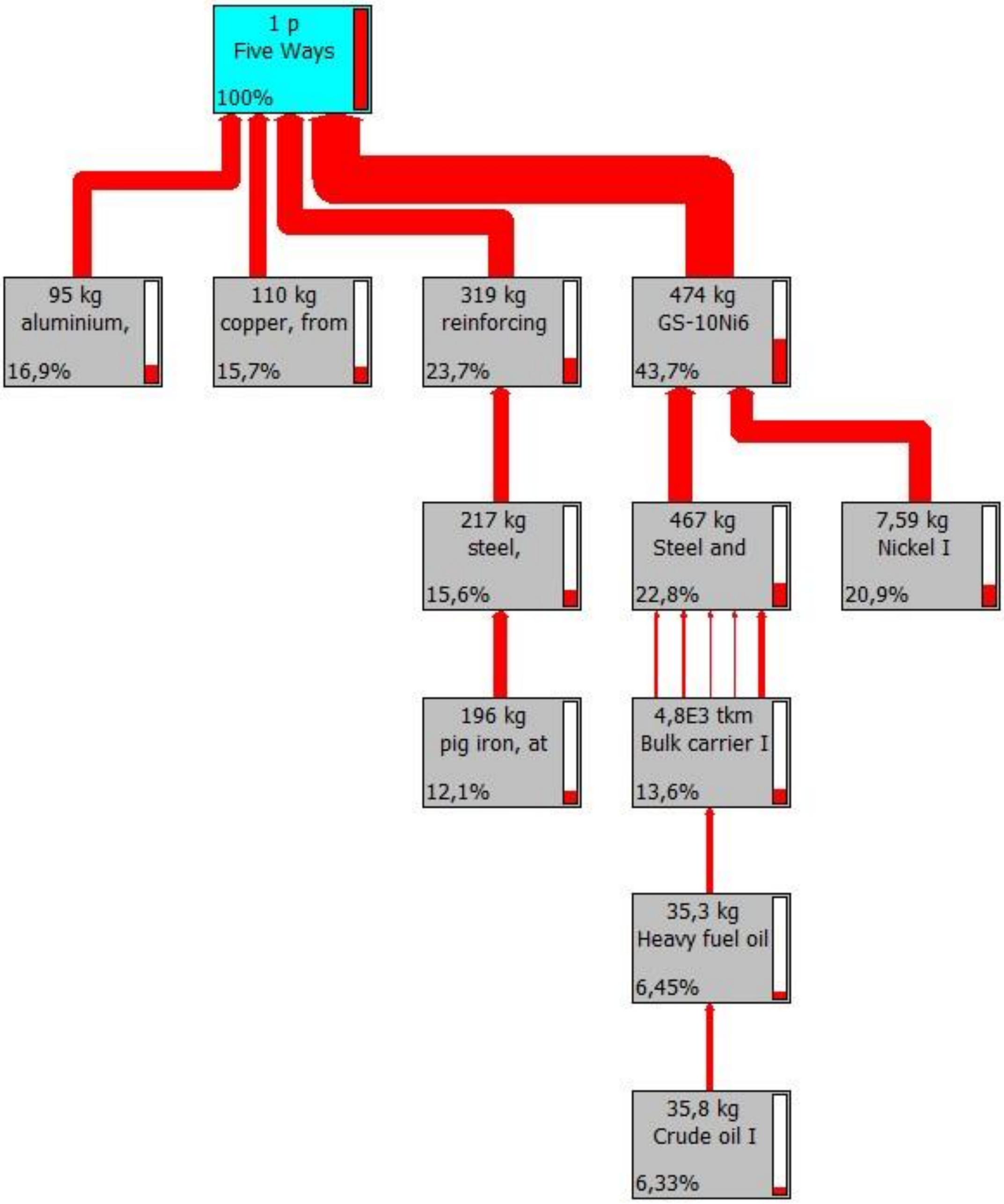


Figure 7.12: Network evaluation of the raw-materials of the cooling system, Five Ways House

7.1.6 LCA single score evaluation of the raw-materials of the cooling system

The single indicator score of Argyle House (figure 7.13) shows that copper is the dominant raw-material with higher impacts in minerals 763 Pt, in respiratory inorganics 173 Pt and in fossil fuels 105 Pt. Fewer impacts are shown in land use 16.7 Pt and in acidification/eutrophication 15.1Pt. Other raw-materials with fewer indicator scores are aluminium, reinforcing steel and stainless steel.

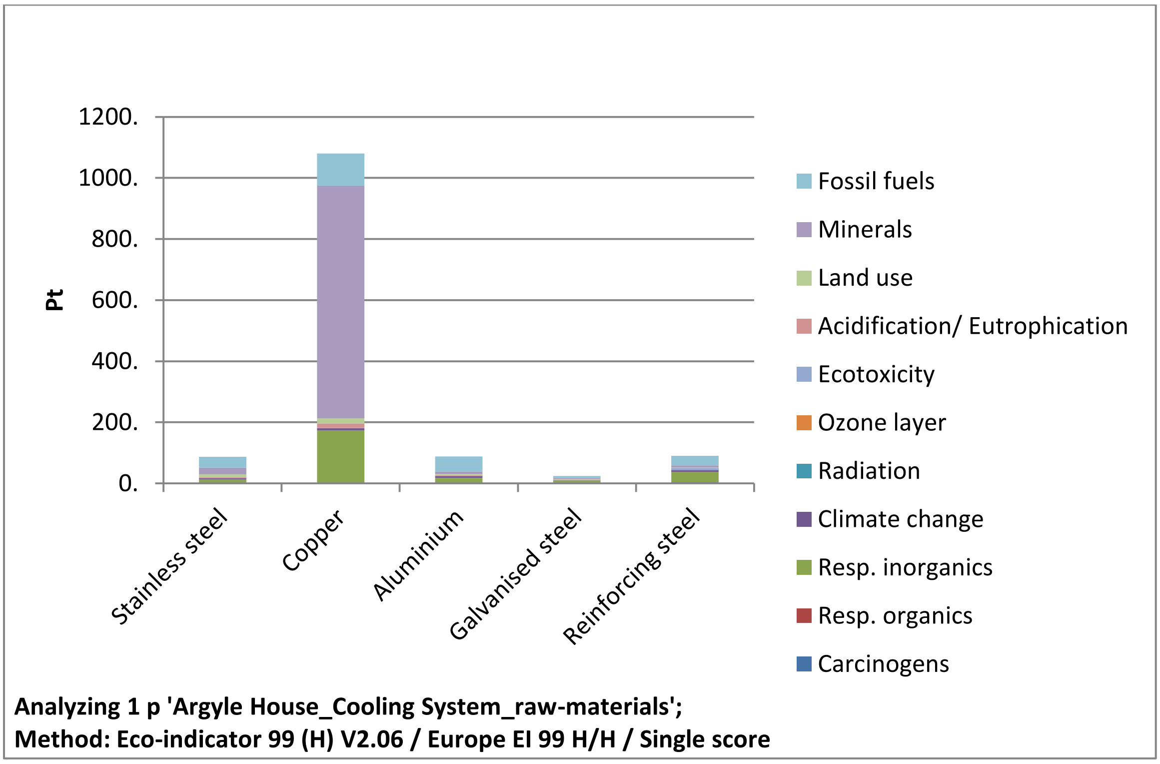
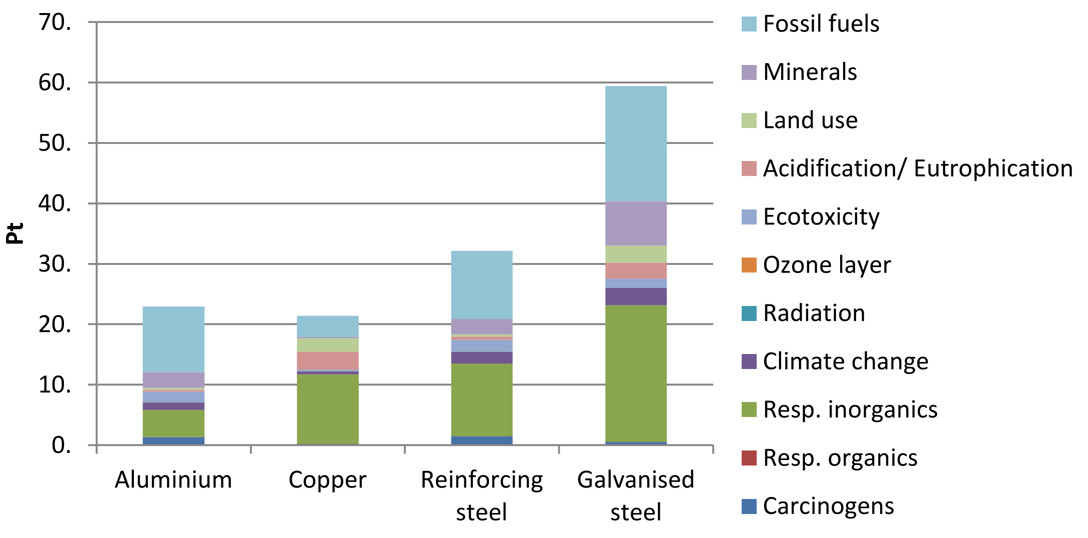


Figure 7.13: Single score evaluation, raw-materials, cooling system, Argyle House

The single score of Five Ways House (figure 7.14) shows that galvanized steel is the dominant raw-material used, with impacts in respiratory inorganics 22.6 Pt, in fossil fuels 19.1 Pt, in minerals 7.35 Pt., in land use 2.8 Pt, in acidification/eutrophication 2.66 Pt, in climate change 2.88 Pt and in ecotoxicity 1.51 Pt.

The single score of Five Ways House (figure 7.14) on reinforcing steel has impacts in respiratory inorganics 12.1 Pt, in fossil fuels 11.3 Pt, in minerals 2.51 Pt, in ecotoxicity 1.97 Pt in climate change 1.91 Pt and in carcinogens 1.49 Pt. Copper contributes in respiratory inorganics by 11.5 Pt, in fossil fuels by 3.49 Pt, in acidification/eutrophication 2.97 Pt and in land use 2.23 Pt. Finally, aluminium contributes in fossil fuels by 10.9 Pt, in respiratory inorganics by 4.5Pt, in minerals 2.61 Pt, in ecotoxicity 1.78 Pt, in climate change 1.19Pt and in carcinogens 1.36 Pt.



Analyzing 1 p 'Five Ways House-raw-material-cooling system';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Single score

Figure 7.14: Single score of the raw-materials of the cooling system, Five Ways House

7.1.7 LCA network evaluation of the cooling consumption

The operational life cycle phase examines the energy indicator which includes the electricity used for cooling as well as refrigerant use. It is assumed that in the 1960s a less environmentally friendly refrigerant was used in the cooling systems; however, SimaPro libraries contain only the R134a which is currently widely used. According to the LCA network of Argyle House (figure 7.15), the environmental impact contributions of the R134a are higher by 90.3% compared to the electricity consumption for cooling for two years of 9.69%. The network evaluation presents also some processes of the refrigerant.

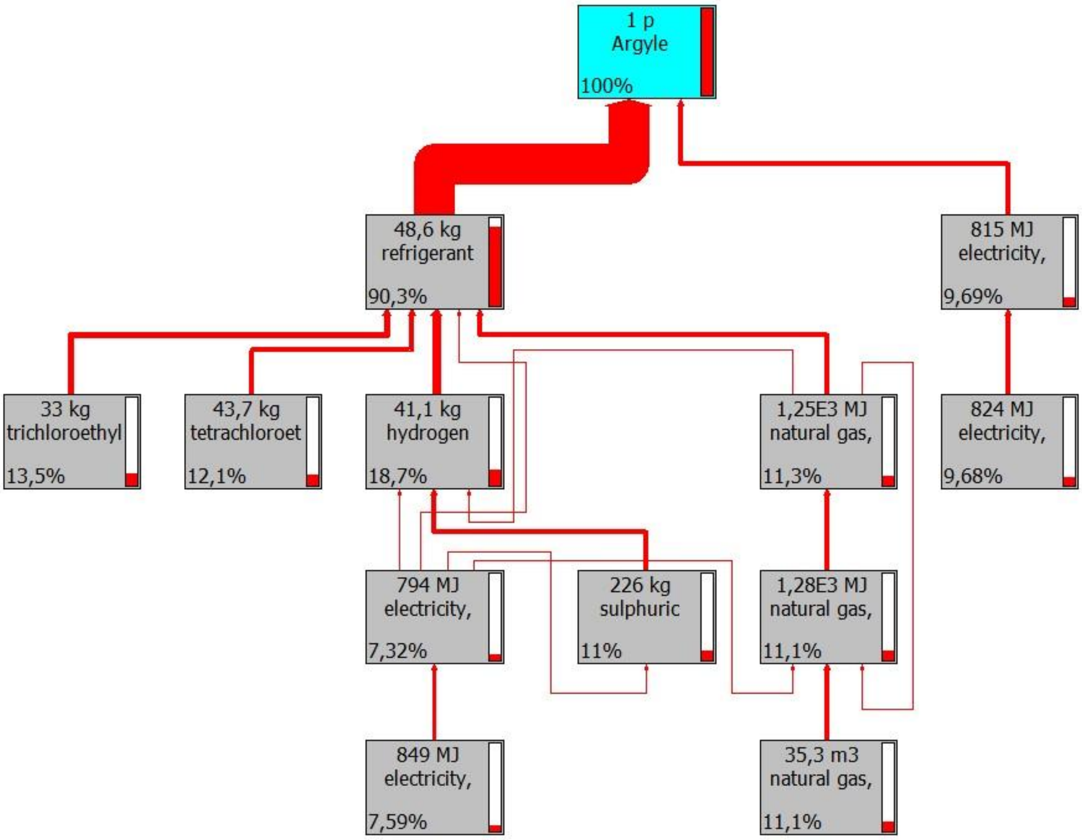


Figure 7.15: Cooling consumption network evaluation

Five Ways House is naturally ventilated with mechanical cooling only in the comms rooms and in the IT server rooms (24/h/day). The electricity consumption for cooling has been assumed to be about 10% (maximum) from the overall electricity consumption of the building. In the network evaluation the LCA system for the operational phase, includes the use of the refrigerant and of the electricity. Overall the refrigerant has more impact (81.2%) than the cooling consumption (18.8%) (Figure 7.16).

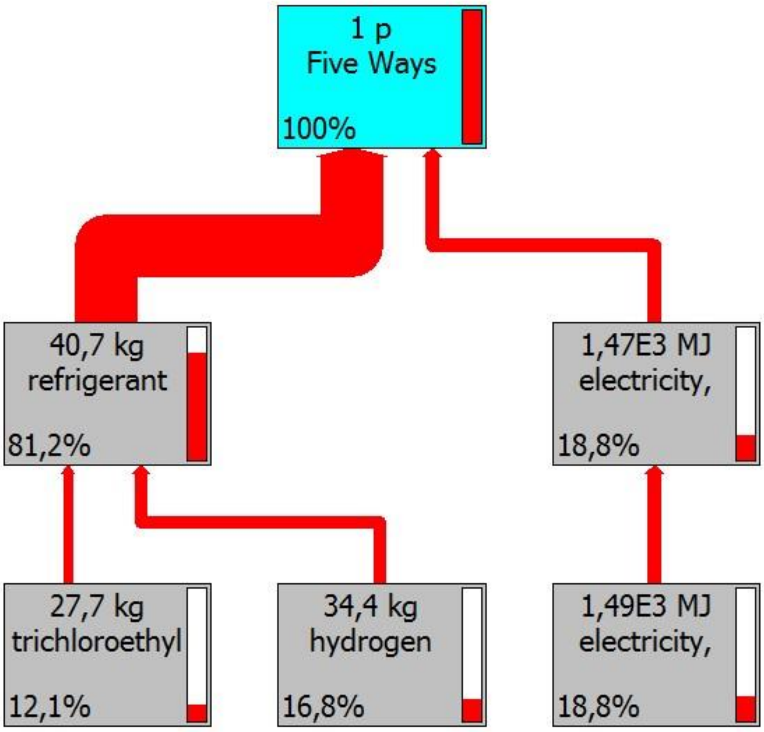


Figure 7.16: Cooling consumption network Five Ways House

The R134a includes 18.7% hydrogen, 12.1% tetrachloroet and 13.5% trichloroethylene. The use of chlorofluorocarbons (CFCs)[10] has increased rapidly since the 1930s because of their properties, such as non-flammable, non-toxic, thermal and chemically stable, and because of appropriate thermodynamic characteristics. They have been especially used in the refrigeration and freezer industry. Nowadays, it is well known that chlorine atoms liberated from CFCs act as catalysts in ozone depleting reactions and contribute to the greenhouse effect. Therefore many actions have been taken to cut CFCs since 1987, where the Montreal Protocol (an international environmental agreement) forced their cut, gradually. Since then, working fluids with no or negligible ozone depletion potential (ODP) and global warming potential (GWP) that can improve energy efficiency have been introduced. Several mixtures of different refrigerants have been suggested to replace R22 and CFCs such as Hydrochlorofluorocarbons (HCFCs)[11], hydrofluorocarbons (HFCs), natural refrigerants (NRs) and mixtures of (environmentally friendly) refrigerants (Karagoz et al. 2004 p.182). The refrigerant use plays a significant role for the COP (coefficient of performance is the ratio of the change in heat at the "output" to the supplied work) of the air-conditioner or heat pump. A study by Karagoz et al. (2004), shows that a mixture of R134a and R22 has a better

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[10] CFCs The first F-gas, ozone depleting and GHG, since 2010 its production is banned, regulated by the Montreal protocol.

[11] The second generation of F-gases, less ozone depleting, contributes less to global warming. Developed countries will be using them until 2020 and developing countries until 2030, regulated by the Montreal Protocol.

COP than the R134a alone (Karagoz, Yilmaz, Comakli, & Ozyurt 2004 p.194). R22 has been employed extensively as the refrigerant for residential heat pump and air-conditioning systems for more than four decades due to its excellent safety, energy efficiency and operating characteristics. It is a partly halogenated refrigerant (HCFC) with a lifetime of approximately 20 years and ODP (ozone depletion potential) of 0.055(Karagoz, Yilmaz, Comakli, & Ozyurt 2004 p.183). R134a is a colourless, non-flammable and non-corrosive gas, with an ODP equal to zero and a GWP (global warming potential) lower than that of R22 (GWPR22 ¼1700; GWPR134a ¼1300) (Karagoz, Yilmaz, Comakli, & Ozyurt 2004 p.184). Emissions from the F-gases occur through leaks, during maintenance, or when an appliance is scrapped at the end of its life. This means that if the appliances fed by refrigerants were properly sealed, serviced, better built and responsibly disposed of the release into the atmosphere of F-gas could be avoided. However, it is has been found that about 61% of HFC134[12] is already in the atmosphere. Greenpeace has called for a global network for the recapture, recycling and destruction of the F-gases. It has been assumed that 1 kilo of F-gas produced will eventually be emitted in the atmosphere (Greenpeace 2009). This is important information to consider when a large quantity of air-conditioners and chillers are used in office buildings to serve with cooling comms rooms and server IT rooms. From the recording survey of the available cooling systems in Argyle House several appliances are no longer in operation, not only because less staff occupies the building but also due to mechanical faults. Therefore it can be imagined that if 46.5 kg of R134a is used in total, the release of gases will be due to the issues mentioned above.

7.1.8 LCA single score of the cooling consumption

The single score of the cooling consumption of Argyle House shows the impacts of the refrigerant and of the energy consumption for cooling (figure 7.17).

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[12] The third generation of F-gases is the HFCs[12] (hydrofluorocarbons) included in the UNFCCC basket of controlled greenhouse emissions.

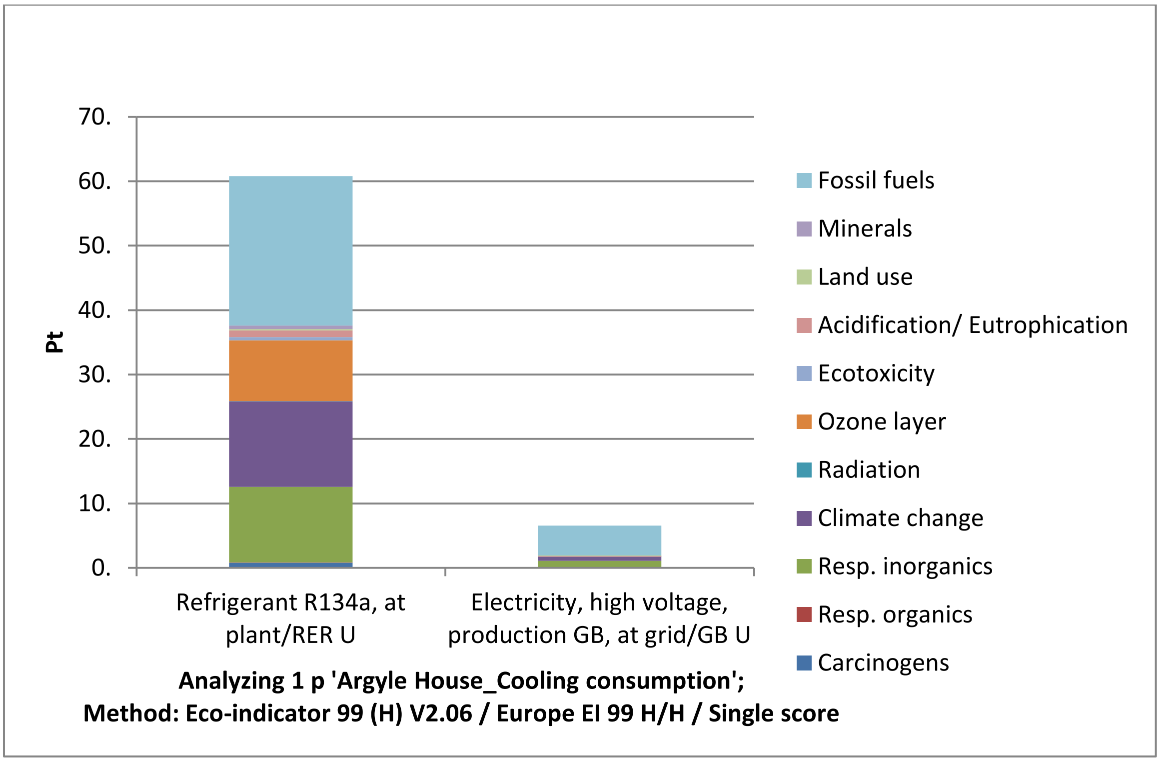


Figure 7.17: Single-indicator score, cooling consumption, Argyle House

The single indicator score of Five Ways House concerning the electricity consumption (figure 7.18) shows impacts in fossil fuels 8.32Pt, respiratory inorganics 1.9Pt and climate change 1.01Pt. The single indicator scores of the refrigerant are in fossil fuels 19.4Pt, climate change 11.1Pt, respiratory inoragnics 9.83Pt, acidification/eutrophication 0.871Pt and carcinogens 0.678Pt.

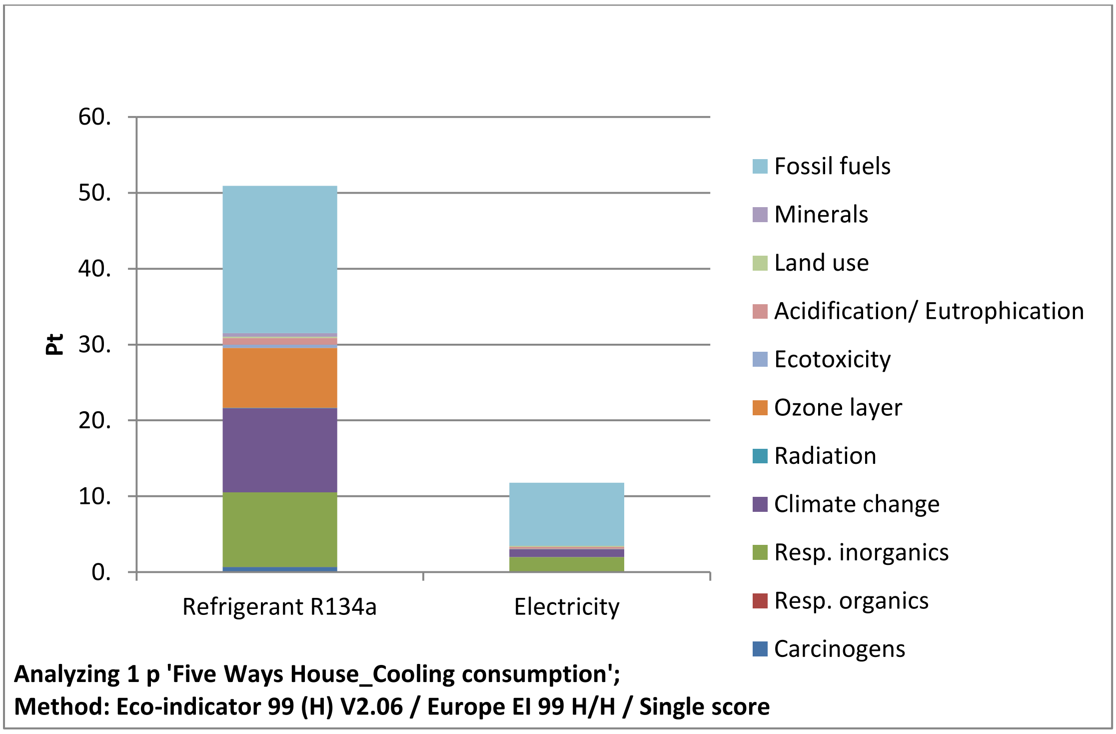


Figure 7.18: Single score, cooling consumption, Five Ways House

7.2 LCA IN SUSTAINABLE BREEAM OFFICE BUILDINGS

7.2.1 Inventory data

The results from Argyle house have shown that it is the amount of the same type of equipment used in a system, the size and the volume, that impact the LCA outcome. The heating system in the Potterrow building has 522 radiators installed, more than half the amount installed in Argyle house. However the Potterrow building included additional heaters, like trench systems, underfloor heating and overdoor heaters. To provide LTHW to these different circuits, a large amount of piping system has been used, internally and externally coming from the CHP unit. Further, the CHP located outside the building includes three boilers and three turbines in the CHP to provide district heating. The system boundary on the heating system of the building to provides heating in the office building spaces and therefore the material content of the CHP is included, although it has to be considered that the CHP technology serves a network of other buildings that belong to the University of Edinburgh. Consequently the environmental impacts related to the CHP are shared by all the buildings in the network or the impacts are taken as an overall CHP value which adds up to the embodied emissions of every building that is connected to it. In this case it is considered that the CHP has its own environmental impacts that are added to the embodied emissions of the building for heating. The inventory data is presented in figures 7.19-7.22.

Heating system of Potterrow Building

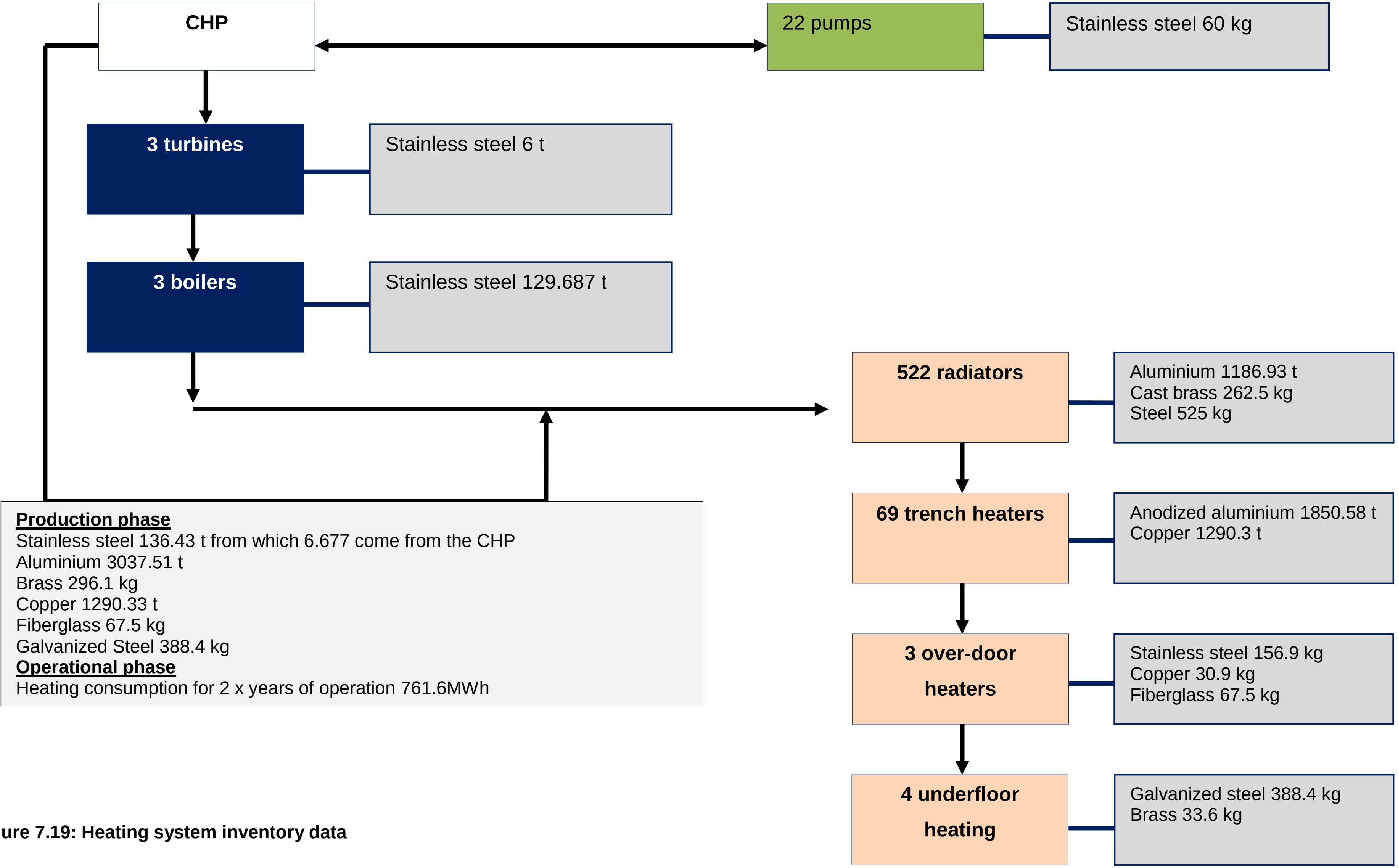
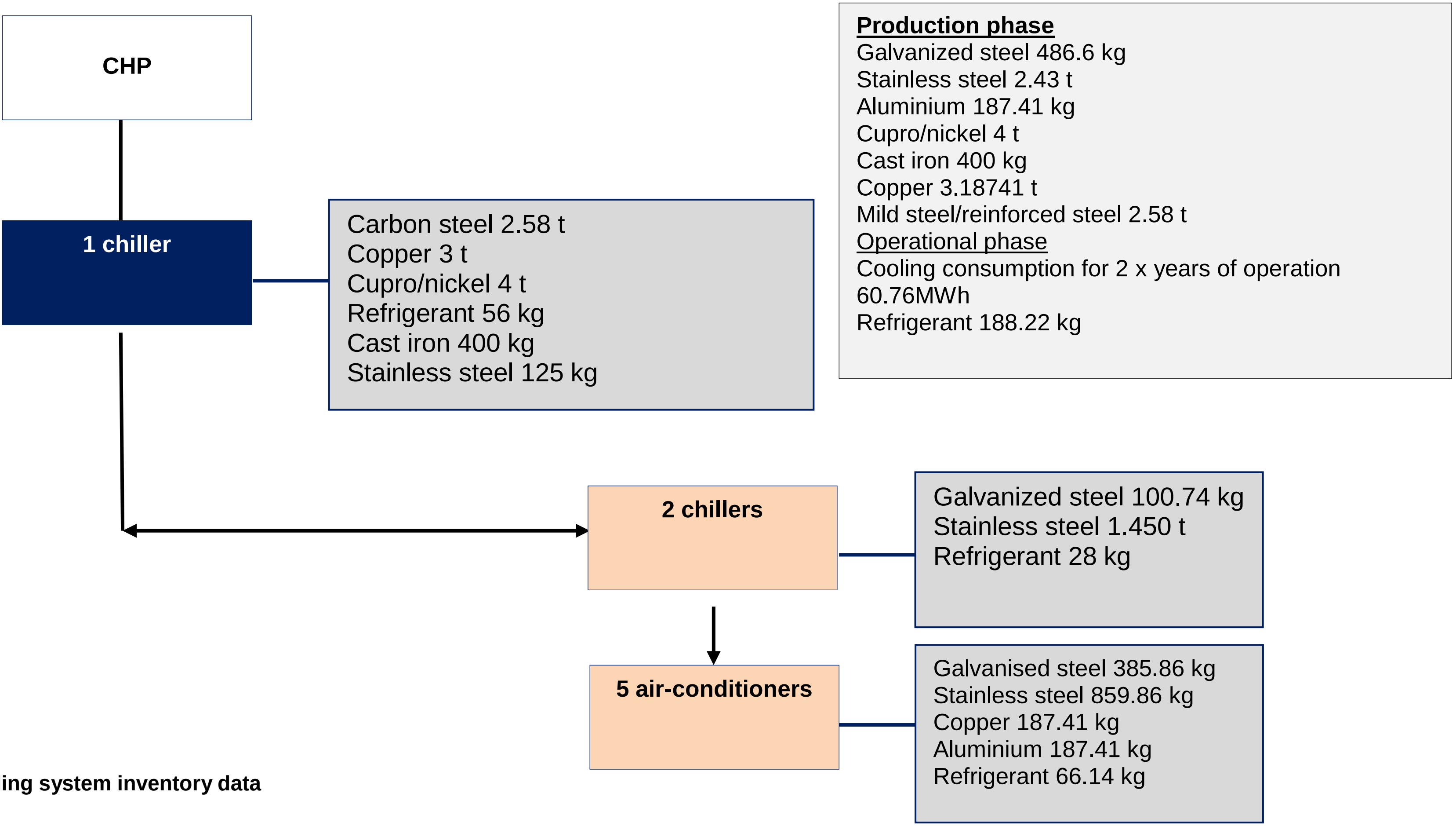


Figure 7.19: Heating system inventory data

Cooling system of Potterrow Building



Production phase
Galvanized steel 486.6 kg
Stainless steel 2.43 t
Aluminium 187.41 kg
Cupro/nickel 4 t
Cast iron 400 kg
Copper 3.18741 t
Mild steel/reinforced steel 2.58 t
Operational phase
Cooling consumption for 2 x years of operation 60.76MWh
Refrigerant 188.22 kg

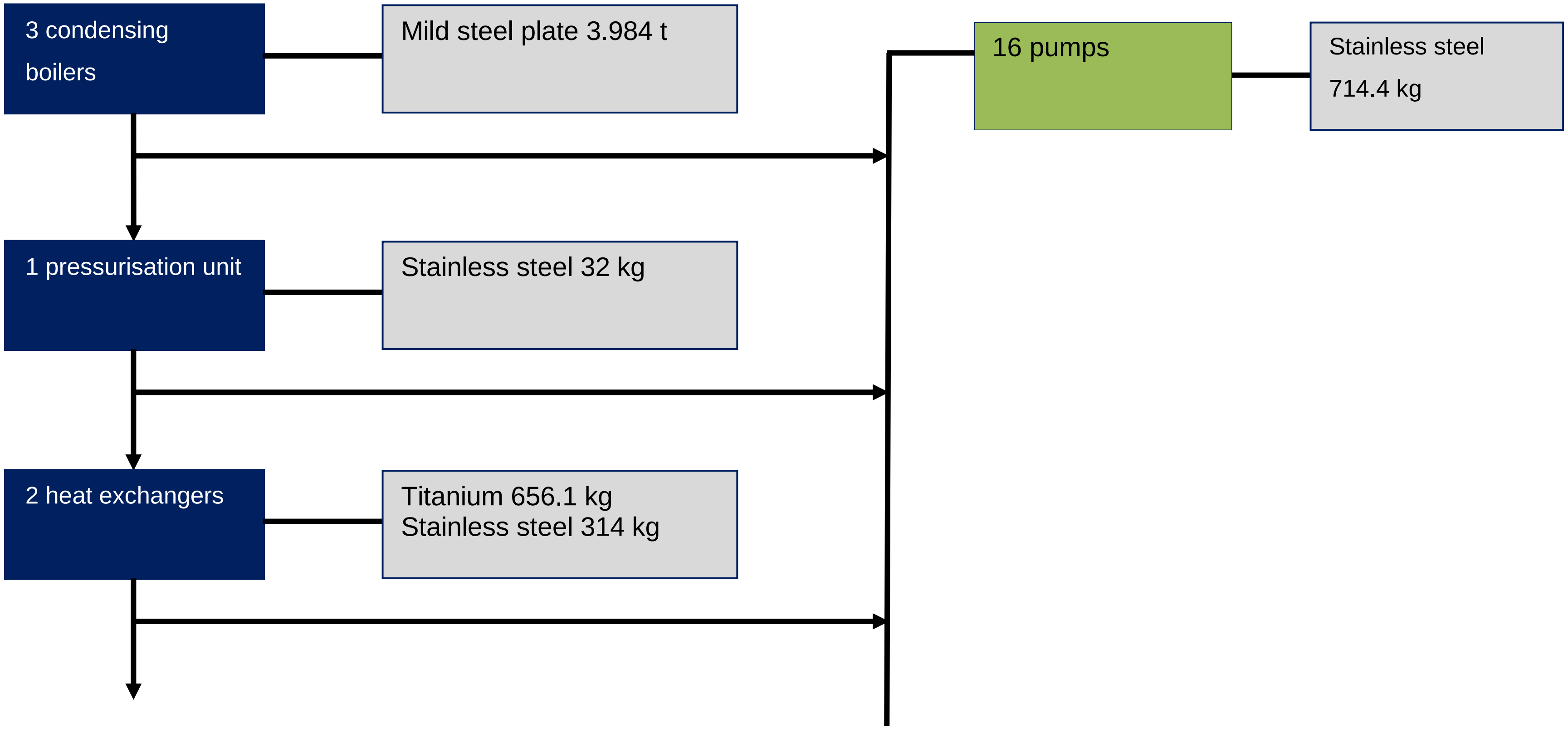
Carbon steel 2.58 t
Copper 3 t
Cupro/nickel 4 t
Refrigerant 56 kg
Cast iron 400 kg
Stainless steel 125 kg

Galvanized steel 100.74 kg
Stainless steel 1.450 t
Refrigerant 28 kg

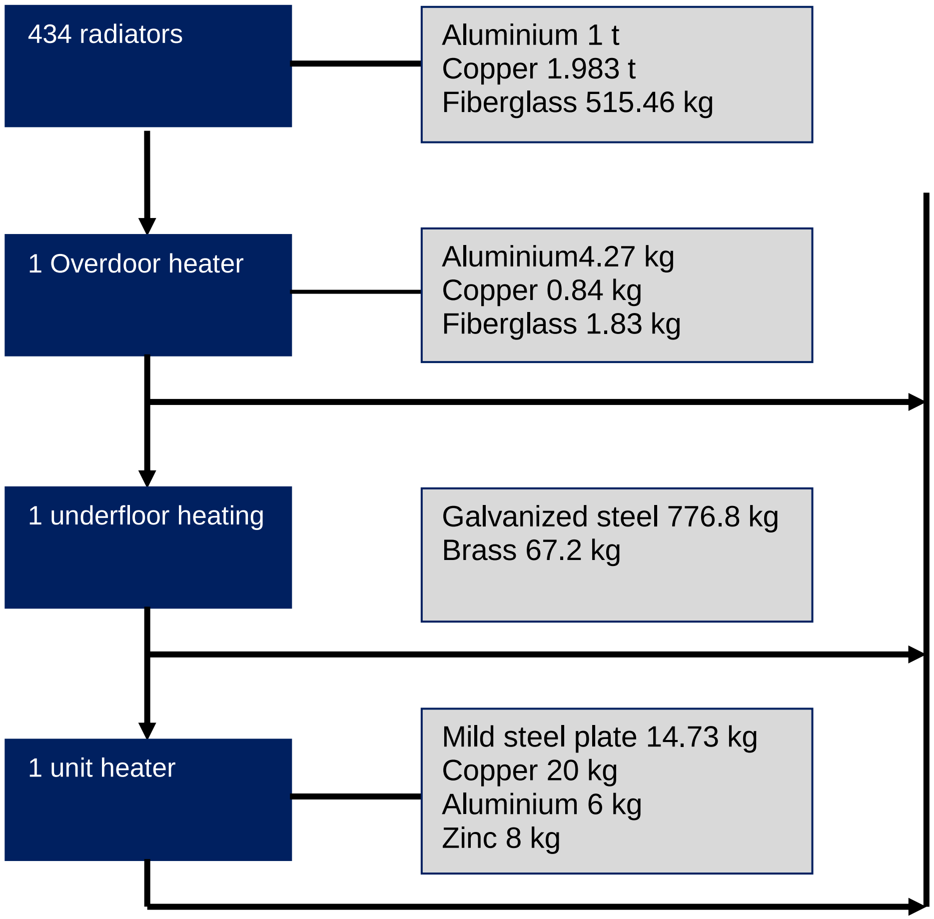
Galvanised steel 385.86 kg
Stainless steel 859.86 kg
Copper 187.41 kg
Aluminium 187.41 kg
Refrigerant 66.14 kg

Figure 7.20: Cooling system inventory data

Heating system of the Elizabeth II Courts



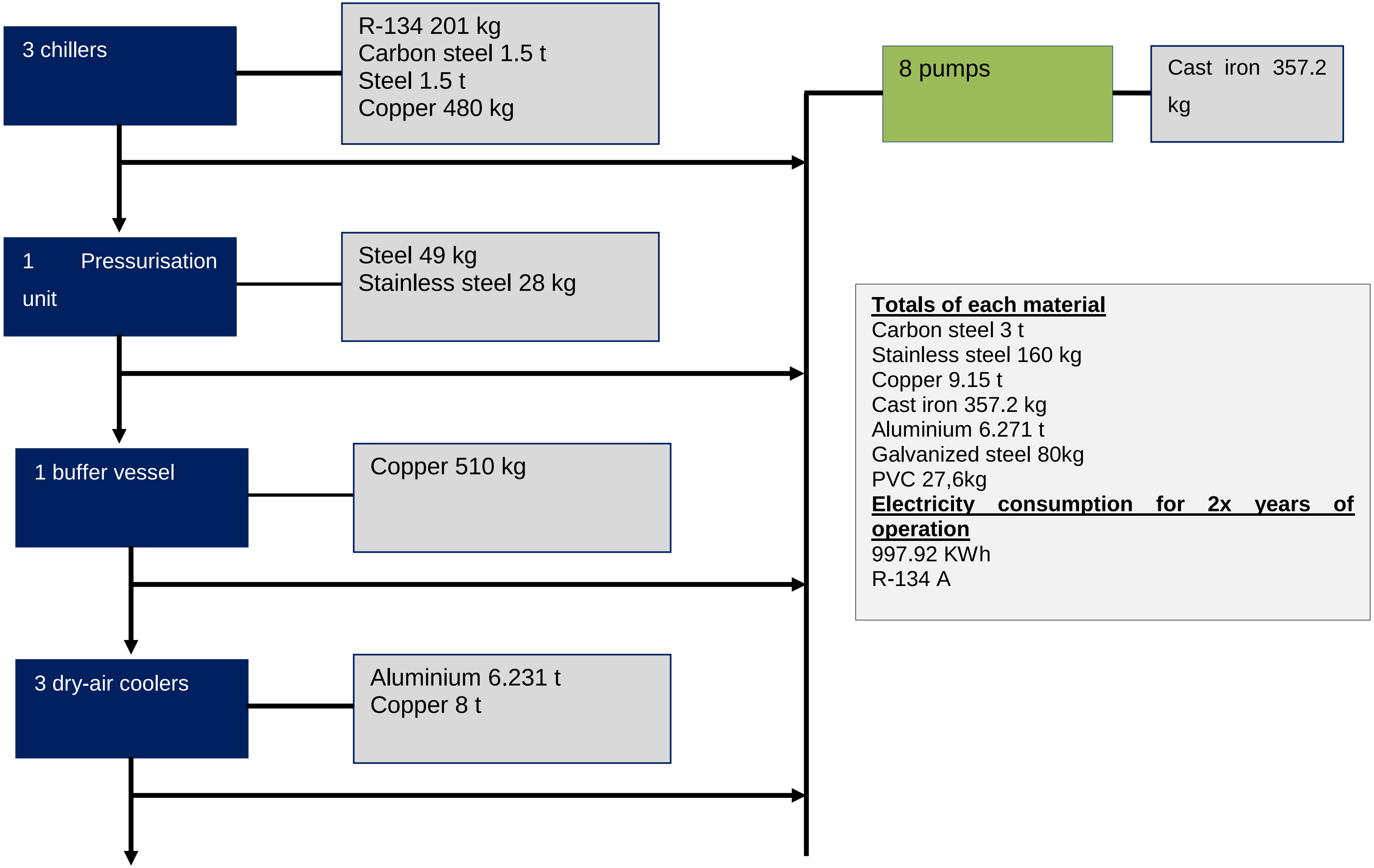
Heating system of the Elizabeth II Courts



Totals of each material
Mild steel/reinforcing steel 4t
Stainless steel 1 t
Titanium 656.1 kg
Aluminium 1 t
Copper 2 t
Fiberglass 515.46 kg
Galvanized steel 776.8 kg
Zinc 8 kg
Electricity consumption for 2x years of operation
1612.8 KWh

Figure 7.21: Heating system inventory data

Cooling system of the Elizabeth II Courts



3 chillers

R-134 201 kg
Carbon steel 1.5 t
Steel 1.5 t
Copper 480 kg

1 Pressurisation unit

Steel 49 kg
Stainless steel 28 kg

1 buffer vessel

Copper 510 kg

3 dry-air coolers

Aluminium 6.231 t
Copper 8 t

8 pumps

Cast iron 357.2 kg

Totals of each material
Carbon steel 3 t
Stainless steel 160 kg
Copper 9.15 t
Cast iron 357.2 kg
Aluminium 6.271 t
Galvanized steel 80kg
PVC 27,6kg
Electricity consumption for 2x years of operation
997.92 KWh
R-134 A

Cooling system of the Elizabeth II Courts

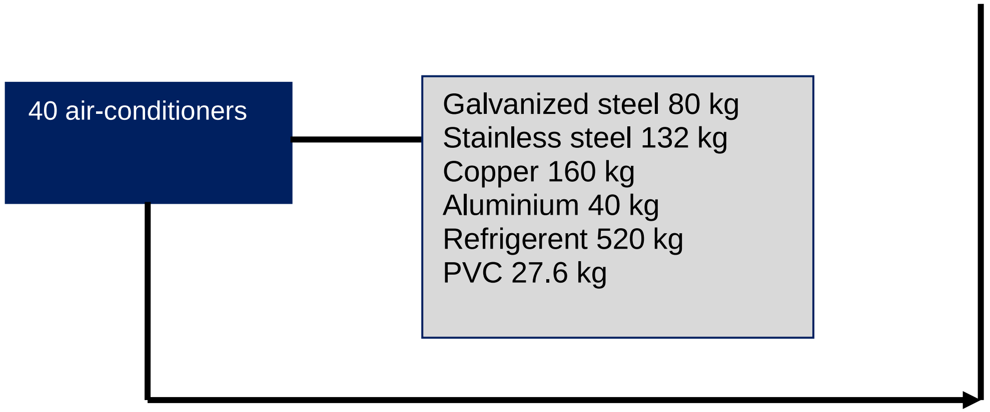


Figure 7.22: Inventory data, cooling system, Elizabeth II Courts

7.2.2 LCA network evaluation of the raw-materials of the heating system

The LCA network evaluation of the Potterrow's district CHP heating system type (figure 7.23) shows that the use of copper (G-CuZn40 I) in the heating system, contributes significantly to the environment by 71.5% and the aluminium by 27.9%.

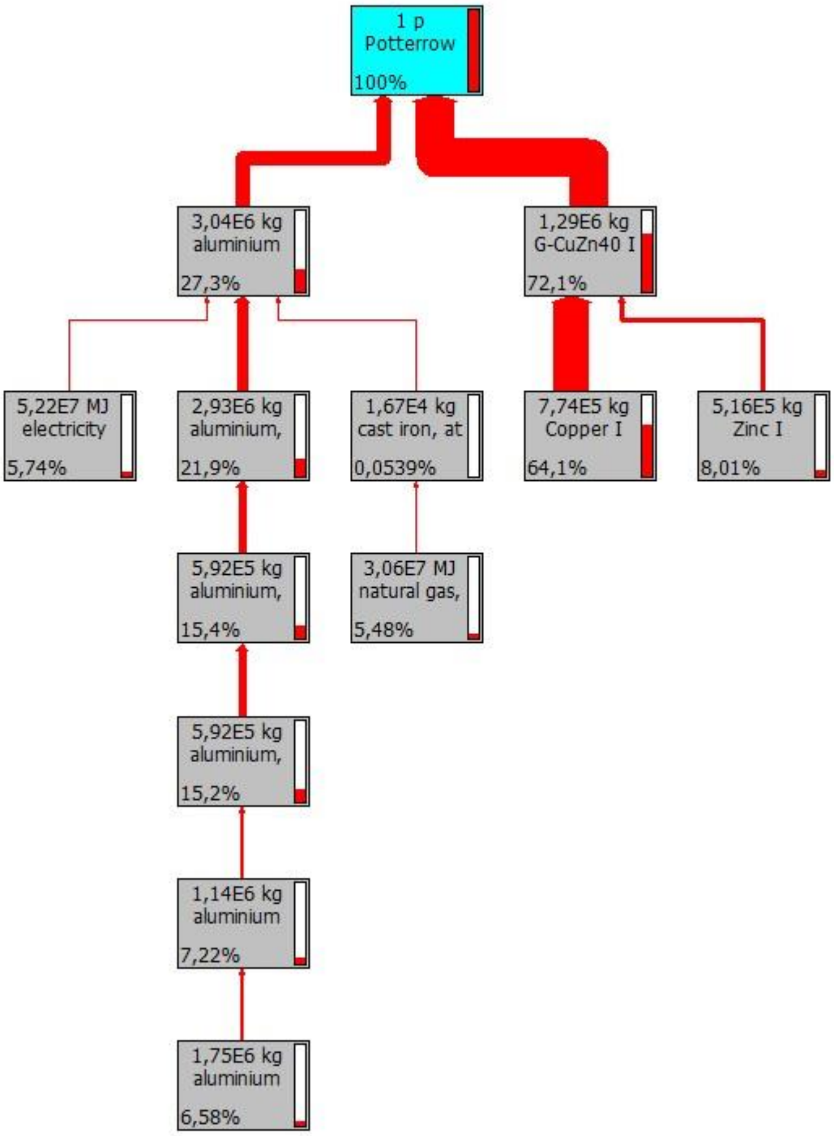


Figure 7.2334: Network of the dominant raw-materials, heating system, Potterrow building

The LCA network evaluation of the condensing natural gas central heating system of the EIIC (figure 7.24) shows that copper is the dominant raw-material used in the heating system of the sustainable refurbished office building at 67.2%, followed by stainless steel (x10CrNiMoNb) 11.5%, reinforcing steel 7.43%, aluminium 5.3% and titanium 4.53%.

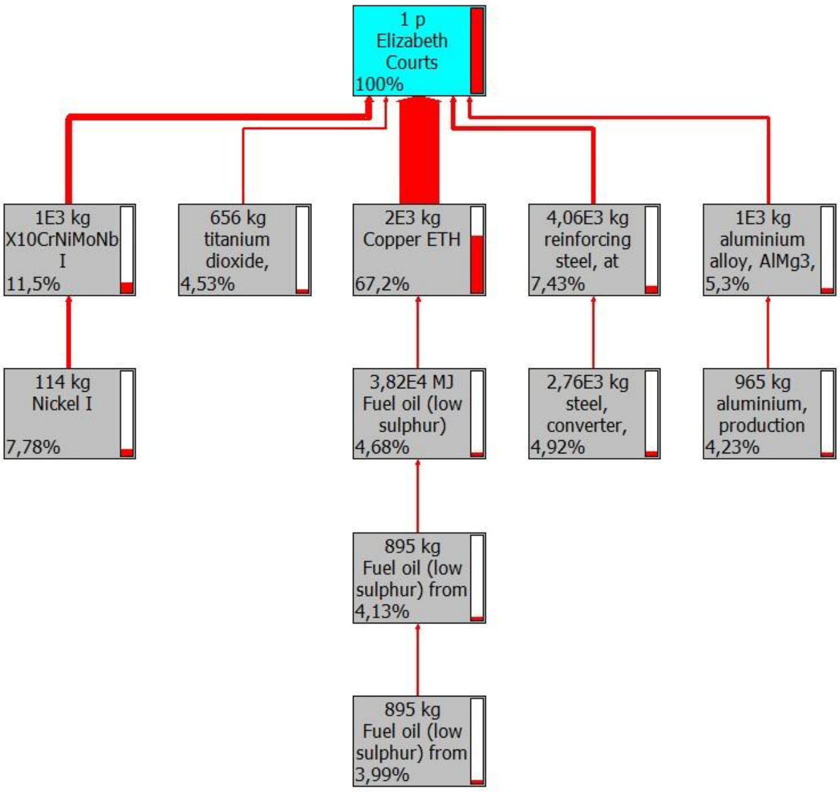
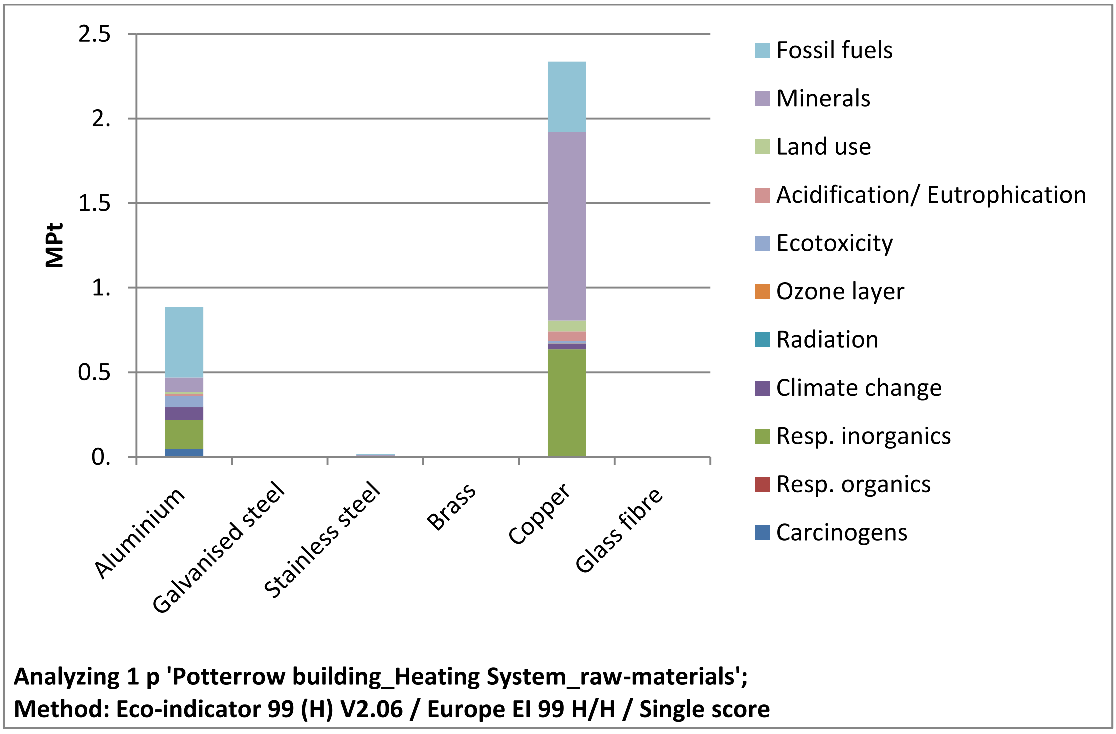


Figure 7.24: Network evaluation of the dominant raw-materials on the heating system in the Elizabeth Courts II

7.2.3 LCA single score evaluation of the raw-materials of the heating system

The single indicator score of the Potterrow building (figure 7.25) shows that copper has the highest impact of the overall environmental burden of the raw-materials used in the heating system in the sustainable new office building. The highest impact is in minerals 1.11 MPt, in respiratory inorganics 0.633 MPt, in fossil fuels 0.417 MPt, with lower impact in land use 0.0639 MPt and acidification/eutrophication 0.0568 MPt. Aluminium is the next raw-material used with high impacts to fossil fuels 0.416 MPt, to respiratory inorganics 0.172 MPt, to minerals 0.0855 MPt, to climate change 0.0759 MPt to ecotoxicity 0.0642 MPt and to carcinogens 0.0455 MPt.



Analyzing 1 p 'Potterrow building_Heating System_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Single score

Figure 7.2535: Single indicator score, raw-materials, heating system, Potterrow building

The single indicator score of the EIIC (figure 7.26) shows that copper is the dominant raw-material used in the heating system of the sustainable refurbished office building. Copper has higher impacts in minerals 2.62 kPt and fewer impacts in fossil fuels 0.516 kPt, in respiratory inorganics 0.329 kPt, in ecotoxicity 0.0875 kPt, in climate change 0.0449 kPt and in carcinogens 0.0497 kPt. Stainless steel follows with less environmental load from copper in respiratory inorganics 0.216 kPt, in fossil fuels 0.202 kPt and in minerals 0.14 kPt. Reinforcing steel contributes to fossil fuels by 0.143 kPt and to respiratory inorganics by 0.153 kPt. The impacts of titanium in fossil fuels are 0.192 kPt, of aluminium 0.137 kPt and of glass fibre 0.0724 kPt.

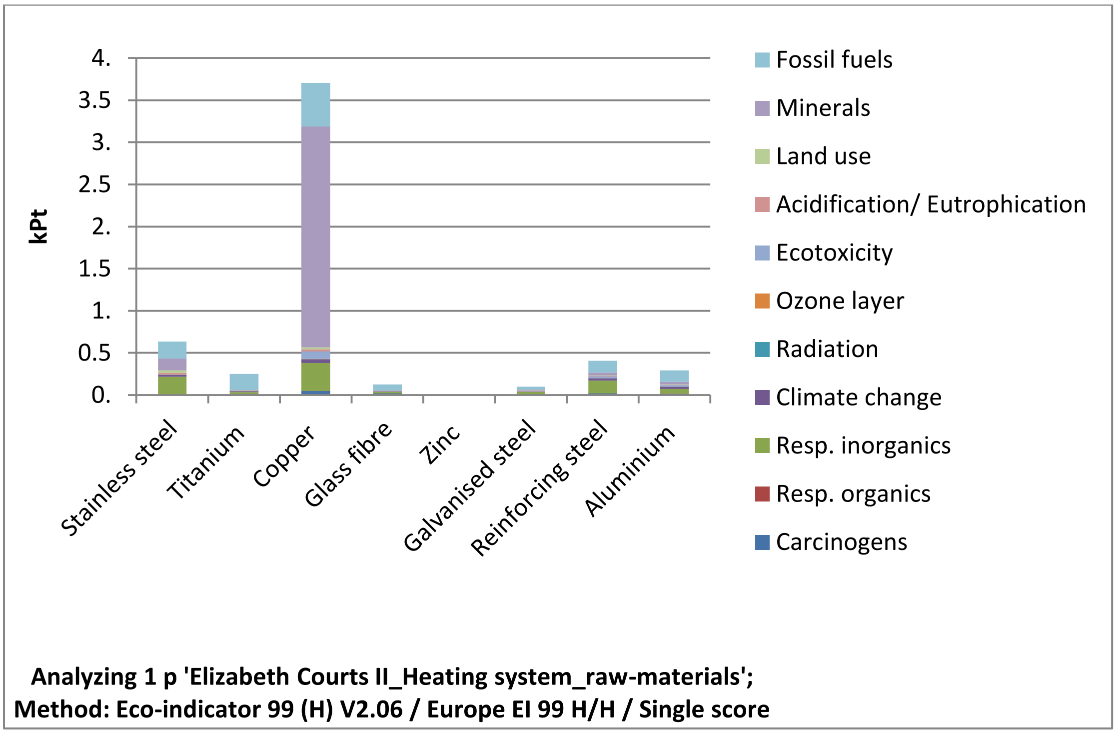


Figure 7.2636: Single score of the raw-materials on the heating system of the Elizabeth Courts II

7.2.4 LCA single score evaluation of the heating consumption

The single weighted indicator evaluation of the Potterrow building (figure 7.27) shows that the use of natural gas burned in the CHP technology to provide heating to the Potterrow Building, has lower contributions than Argyle House (see comparison, section 9.2.6) with impacts to fossil fuels 16.6 kPt, to climate change 0.802 kPt and to respiratory inorganics 0.323 kPt. The single indicator evaluation of the EIIC (figure 7.28) shows that heating contributes to fossil fuels by 108 kPt, to climate change by 0.404 kPt and to respiratory inorganics by 0.208 kPt.

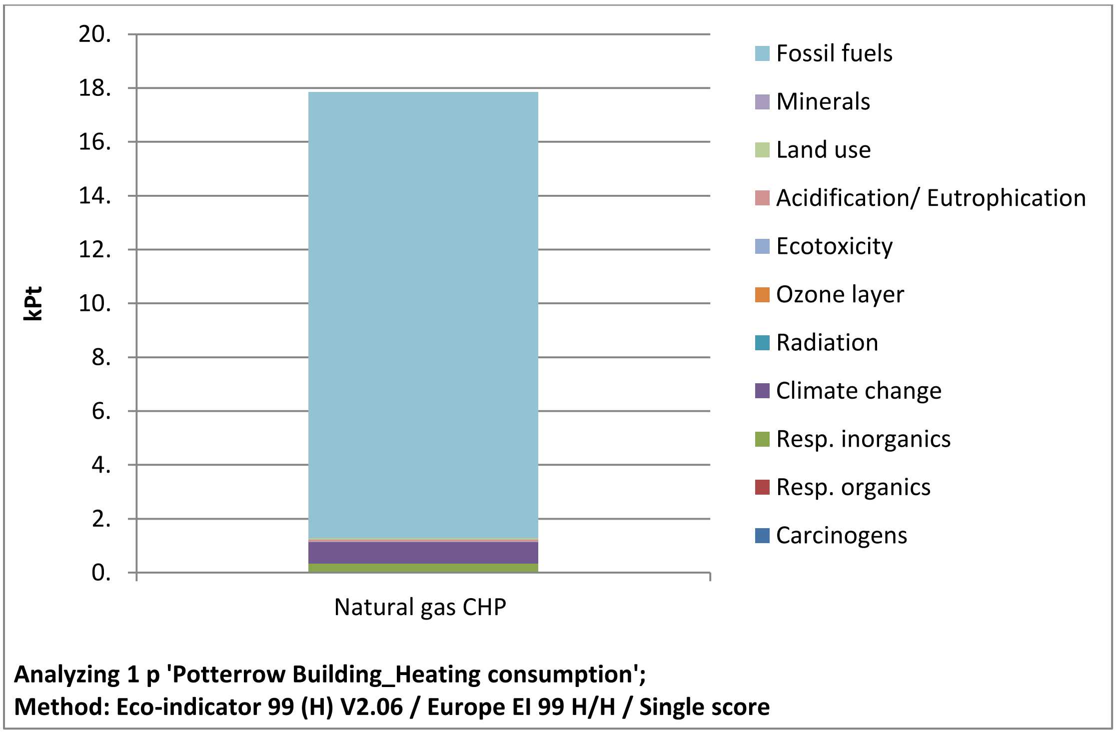


Figure 7.27: Single indicator cooling consumption

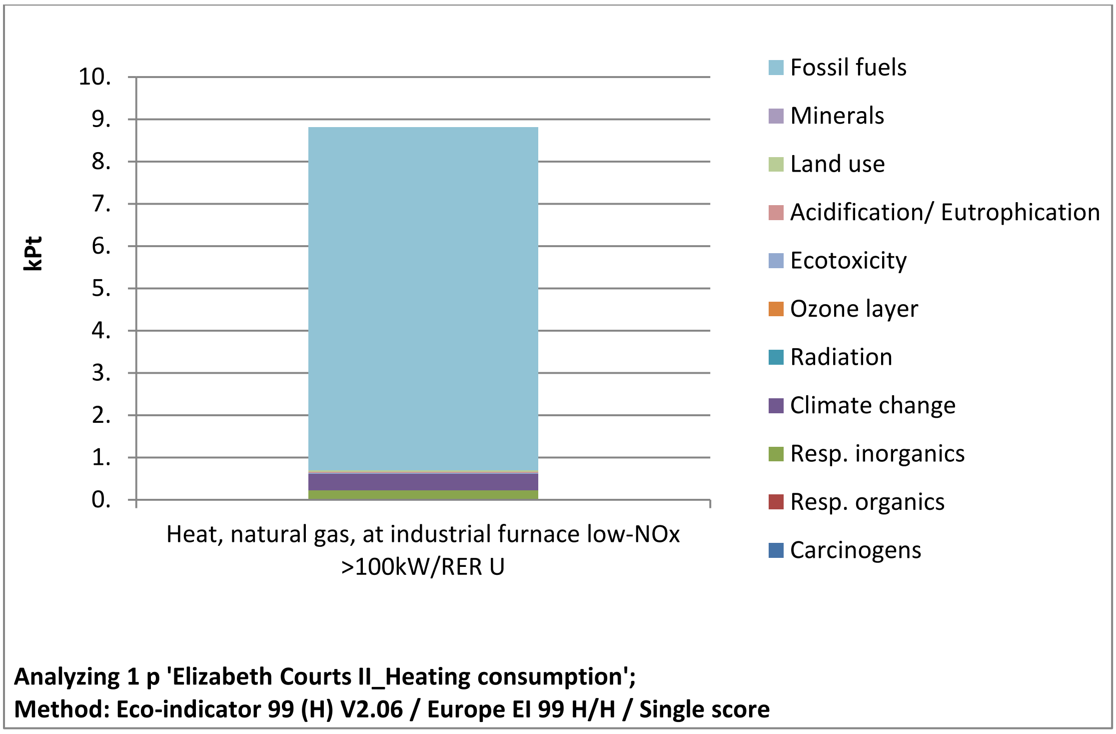


Figure 7.28: Single indicator score, heating consumption, Elizabeth II Courts

7.2.5 LCA network evaluation of the raw-materials of the cooling system

The raw-material network evaluation of the Potterrow building's centralised air system (figure 7.29) shows that the principal raw-material used in the cooling system is ferronickel 59.6%, followed by Copper (G-CuZn40 I) 36%, stainless steel (x35CrMo17 I) 2.04% and reinforcing steel 1.59%.

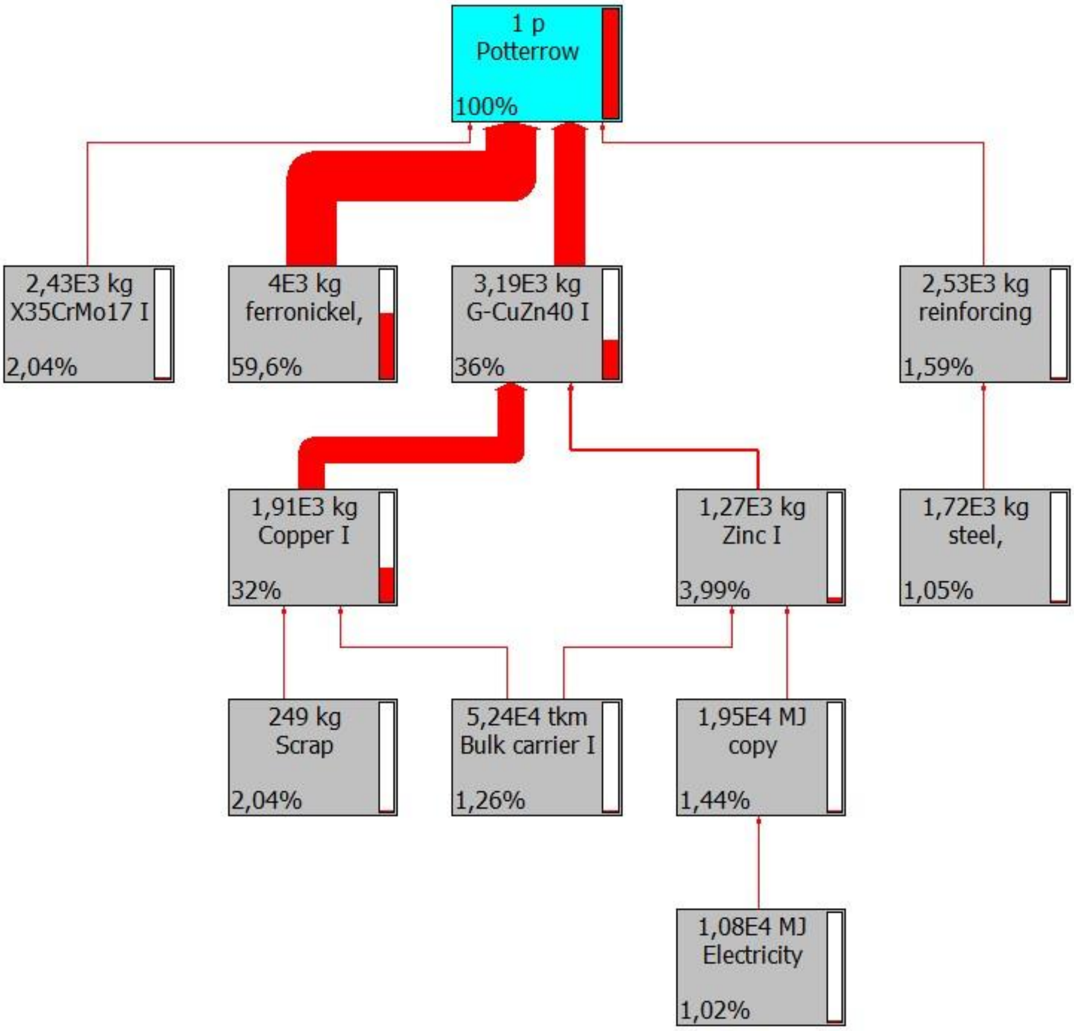


Figure 7.29: Network evaluation of the dominant raw-materials, cooling system, Potterrow building

The network evaluation of the raw-materials of the cooling system on the EIIC's VRV air conditioning technology (figure 7.30) shows copper is the dominant raw-material used 94%, followed by aluminium 4.16% and carbon steel/reinforcing steel 1.33%.

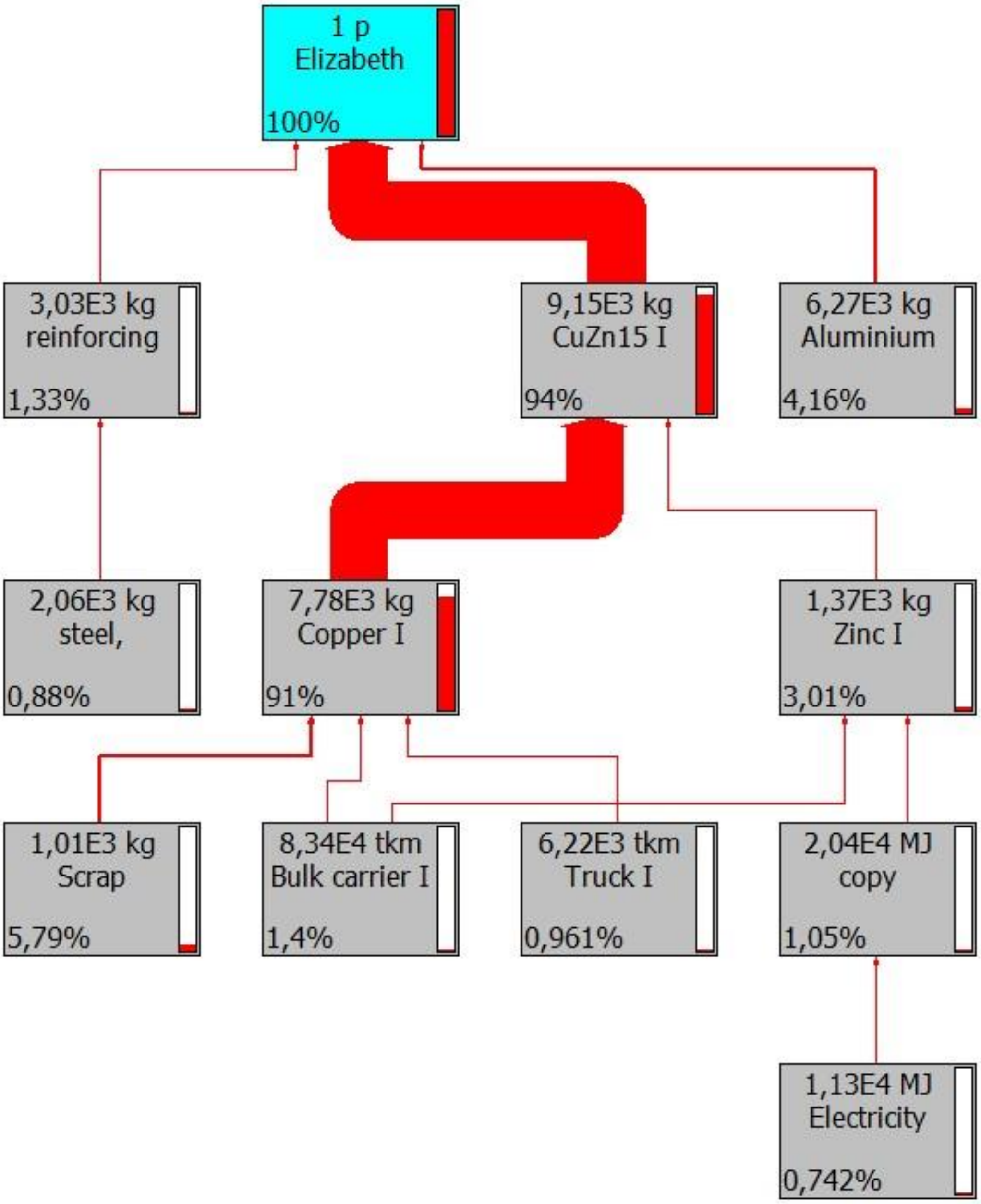


Figure 7.30: Network evaluation of the dominant raw-materials of the cooling system on the Elizabeth Courts II

7.2.6 LCA single score evaluation of the raw-materials of the cooling system

The single score of the Potterrow building (figure 7.31) shows that ferronickel, which is the dominant raw-material used in the cooling system, has impacts in minerals 5.94 kPt, fossil fuels 1.43 kPt, respiratory inogranics 0.95 kPt, ecotoxicity 0.856 kPt and in change 0.188 kPt. The single score for copper is 2.75 kPt in minerals, 1.56 kPt in respiratory inorganics 1.03 kPt in fossil fuels, 0.158 kPt in land use and 0.14 kPt in acidification/eutrophication.

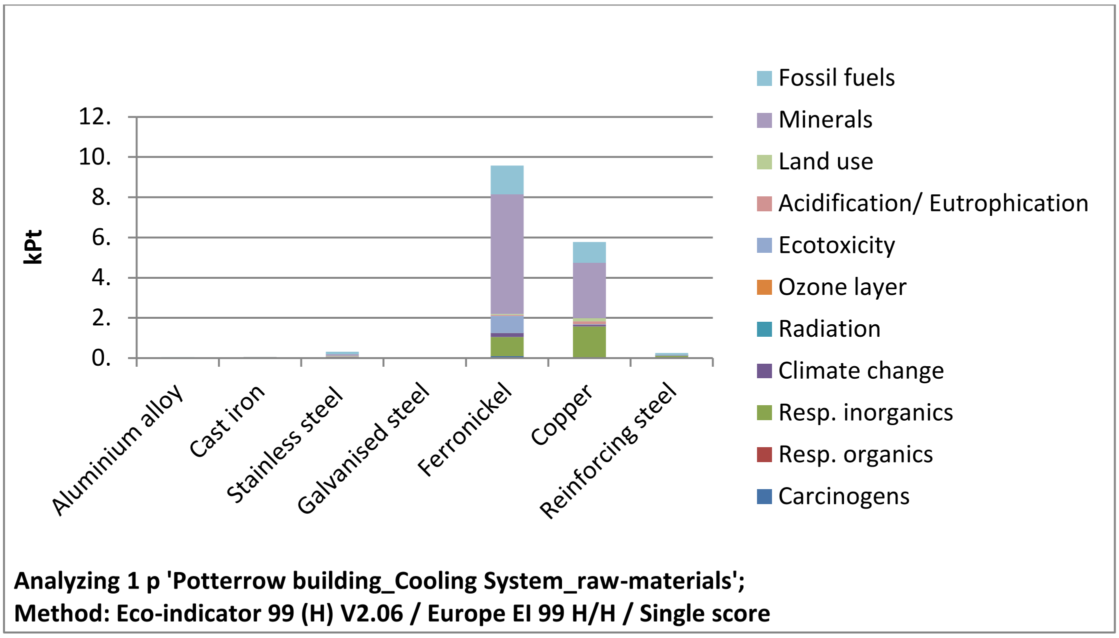


Figure 7.3137: Single score evaluation, raw-materials, cooling system, Potterrow building

The single score evaluation (figure 7.32) shows that copper is the dominant raw-material used in the cooling system with dominant impacts in minerals 10.6 kPt, in respiratory inorganics 6.03 kPt, in fossil fuels 3.49 kPt, in land use 0.593 kPt, in acidification/eutrophication 0.526 kPt and in climate change 0.266 KPt. Aluminium has fewer impacts in fossil fuels at 0.576 kPt and in respiratory inorganics 0.183 kPt.

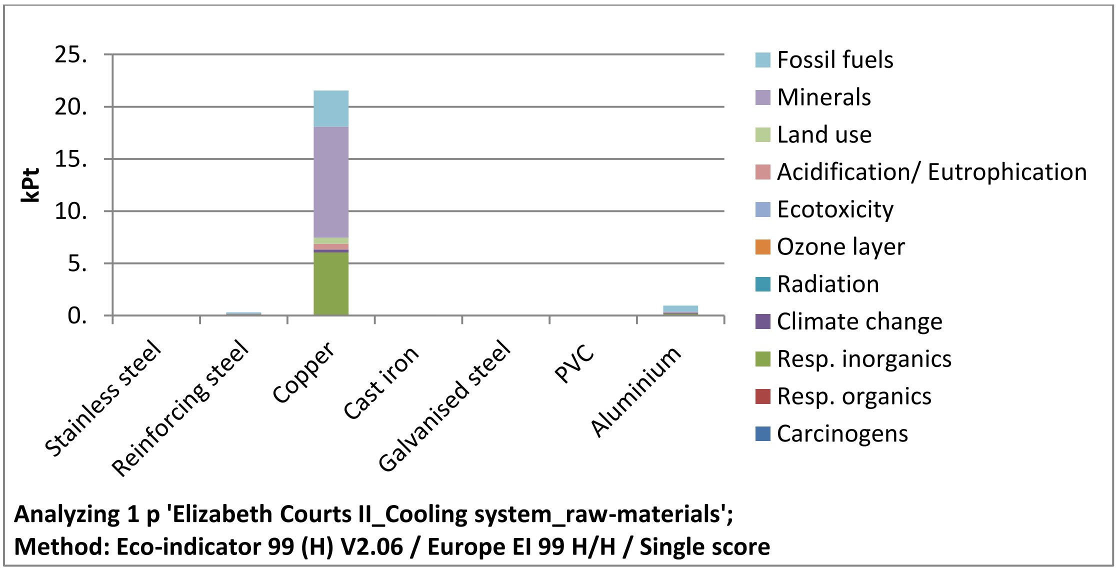


Figure 7.32: Single score of the raw-materials of the cooling system in the Elizabeth Courts II

7.2.7 LCA network evaluation of the cooling consumption

The cooling consumption network of the Potterrow building (figure 7.33) shows that the burning of natural gas in the CHP has higher contributions in two years of operation from the use of the refrigerant R-134a in the operational life cycle phase, with cooling contributing at 98.7% and the refrigerant at 1.33%.

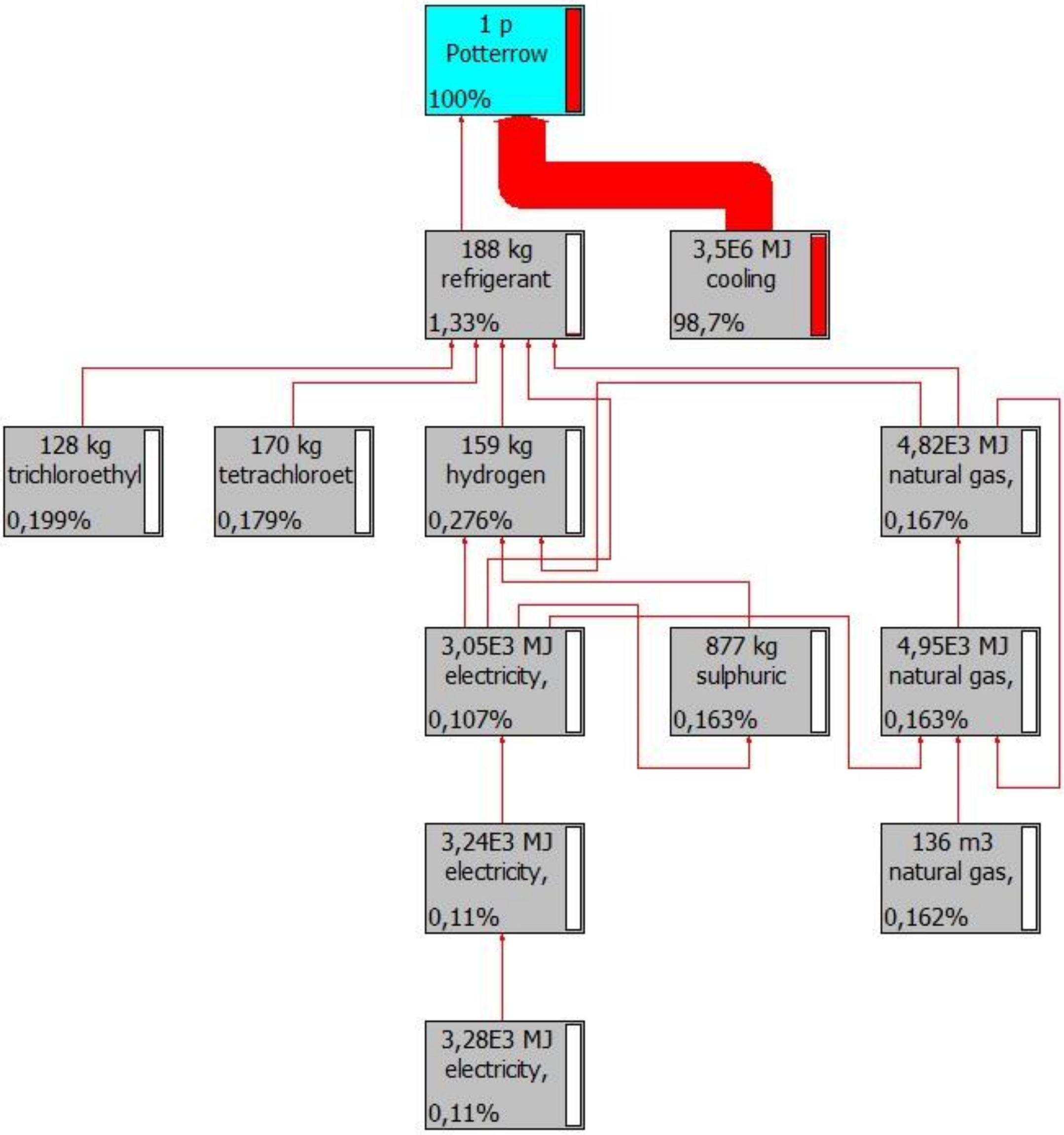


Figure 7.33: cooling consumption network, Potterrow building

In the operational phase of the life cycle of cooling two indicators have been evaluated, the energy for cooling and the use of the refrigerant. It could be argued that the refrigerant is used in the installation process, however in the LCA studies in this thesis it is used in the operational phase as no other indicators are examined from the installation phase and the use of the refrigerant, as explained previously, still has significant impacts in the environment. Overall, in a more direct way, the impact contribution of the refrigerant is 86.3% and from the energy for cooling 13.7% (figure 7.34).

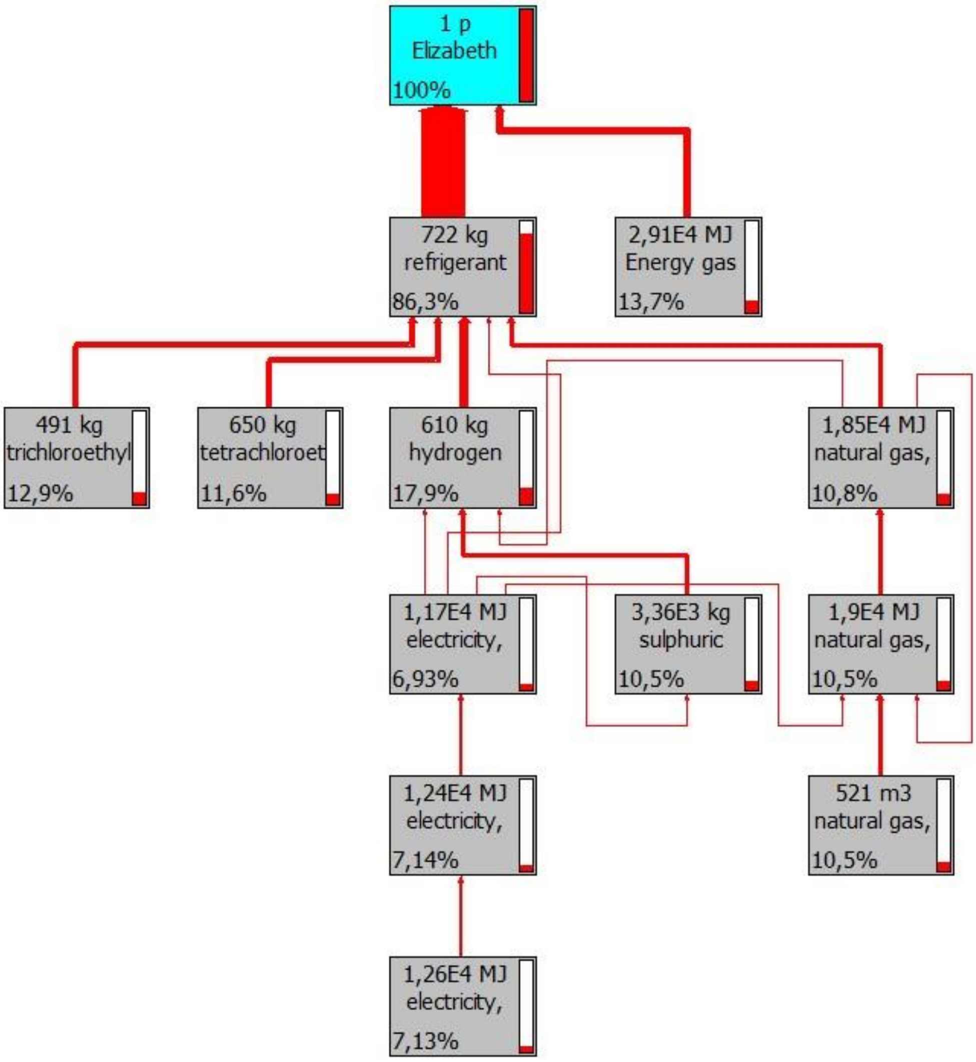


Figure 7.34: cooling consumption network evaluation

7.2.8 LCA single score of the cooling consumption

The single scores from the cooling consumption of the Potterrow building are 14.8 kPt for fossil fuels, 0.806 kPt for climate change, 0.719 kPt for respiratory inorganics, 0.47 kPt for minerals and 0.33 kPt for ecotoxicity (figure 7.35). The single indicator evaluation for the EIIC (figure 7.36) presents the weighted results of the inventory data, showing that the higher impacts of the refrigerant are in fossil fuels 345 Pt, in respiratory inorganics 174 Pt, in climate change 197 Pt, in ozone layer 140 Pt, in acidification/eutrophication 15.5 Pt and in carcinogens 12 Pt. The most significant impacts of the energy for cooling are in fossil fuels 124 Pt.

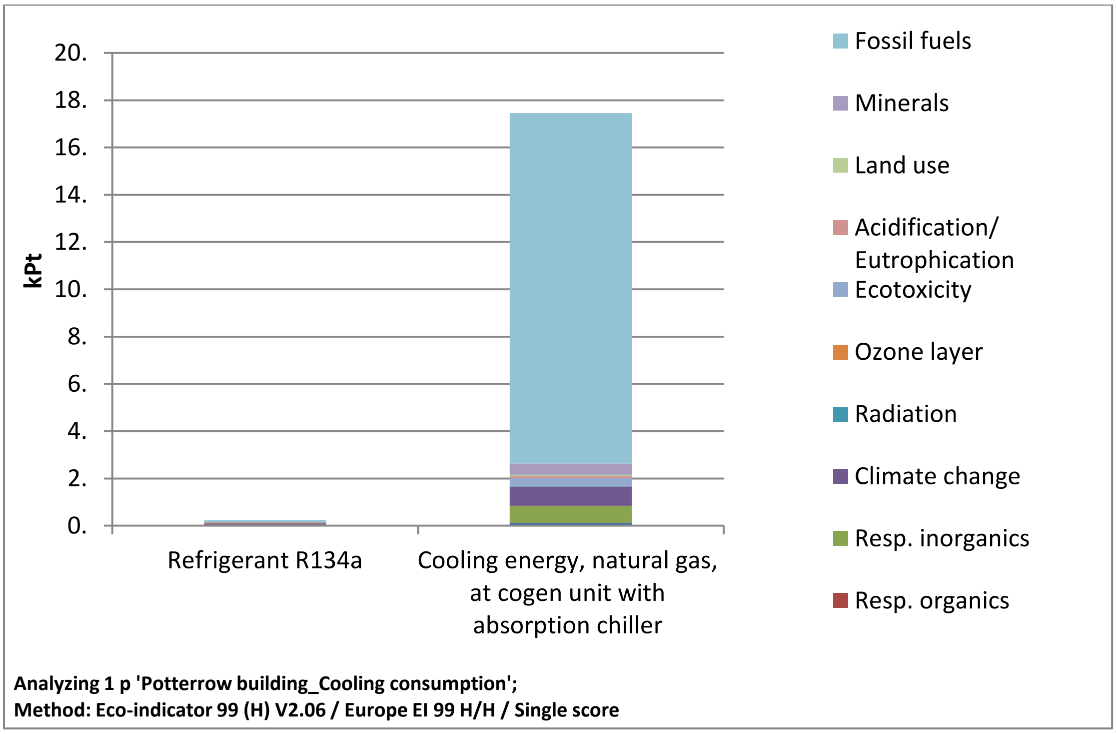


Figure 7.35: single indicator, cooling consumption, Potterrow building

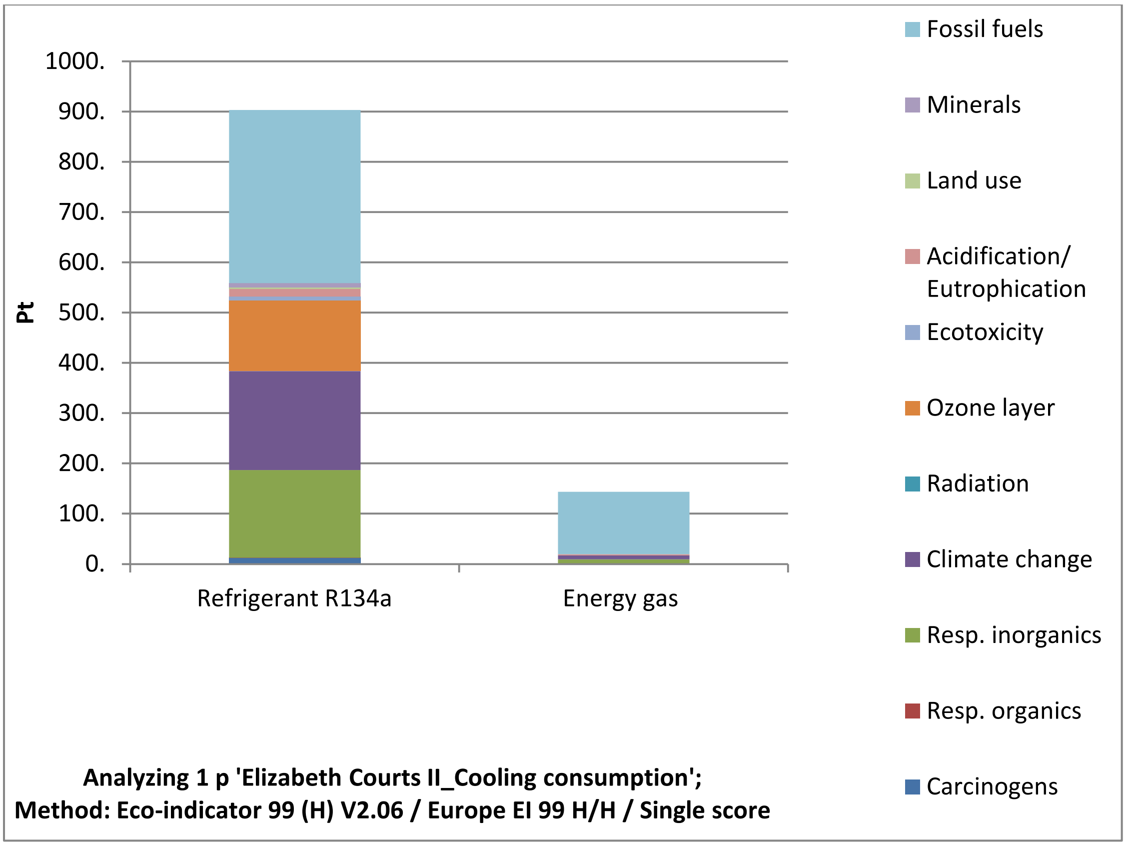


Figure 7.36: Single indicator score, cooling consumption

7.3 LCA comparison evaluation between sustainable and conventional office buildings: case study 1

This section presents the results of the comparison analysis on the environmental impacts of the heating and cooling systems on the conventional and on the sustainable office building. The argument discussed in this thesis is to what extend sustainable claimed office buildings are better than conventional office buildings, examining two indicators, the energy and the raw-materials, in the long run.

7.3.1 LCA single score comparison evaluation of the raw-materials on the heating system

The single score comparison evaluation (figure 7.37) shows that that the heating system of the sustainable new office building in Edinburgh has higher impacts than the conventional office building in Edinburgh. The conventional office building has more than a thousand radiators, around 50% more than those in the sustainable building. This can be explained due to the amount of heating equipment used in the building with different distribution types (chapter 7) to serve different areas in the building. This equipment has also been used in order to enhance the energy efficiency of the CHP.

The dominant environmental impacts of the cooling system on the Potterrow building are in minerals 1.2MPt, in respiratory inorganics 0.807MPt and in fossil fuels 0.84MPt. Fewer impacts are shown in climate change 0.11MPt, in ecotoxicity 0.0807MPt, in acidification/eutrophication 0.0698MPt, 0.0785MPt in land use and 0.0487MPt in carcinogens.

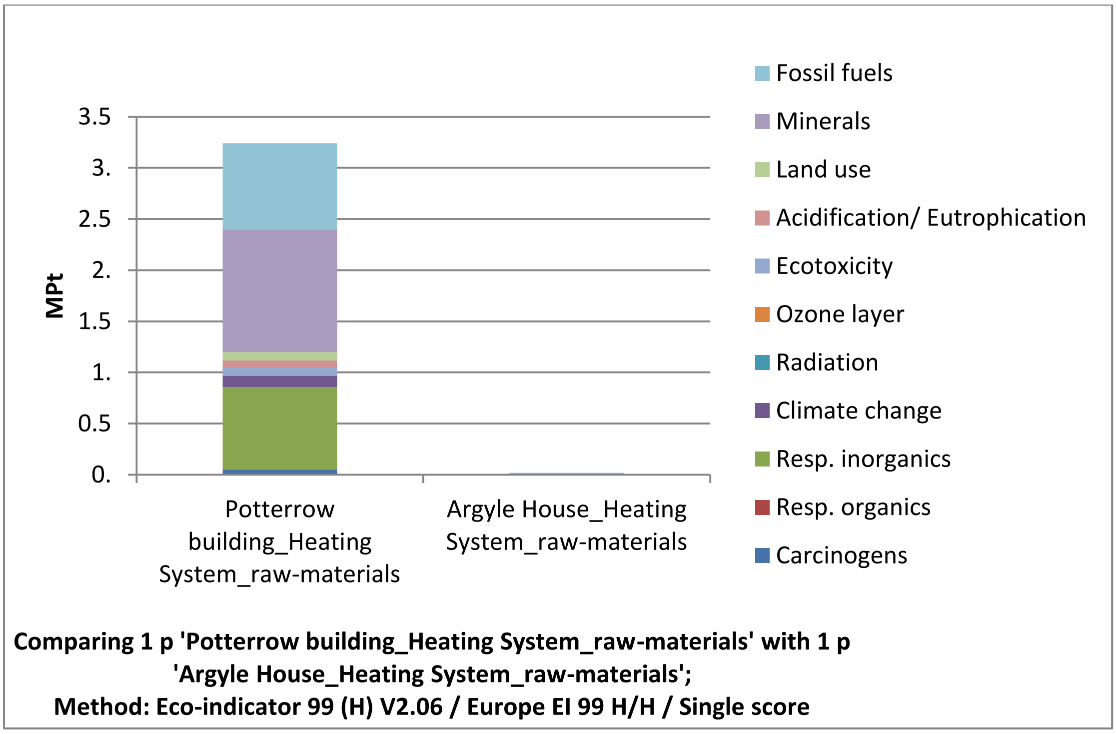


Figure 7.37: Single indicator score, comparison evaluation, raw-materials on heating system

7.3.2 LCA single score comparison evaluation of the heating consumption

The weighted characterisation data to a single indicator score (figure 7.38) shows that the conventional office building heating consumption has more than double the environmental impact contributions compared to the sustainable buildings that has less than half the contributions compared to the conventional office building. This result was expected considering the low-energy systems used in the conventional office building (Argyle House) and the burning of oil fuel. As now evaluated with LCA, the environmental impact contributions of the conventional office building are: 62.2kPt fossil fuels, 1kPt respiratory inorganics, 3.56kPt climate change, 20.9kPt acidification/eutrophication. The environmental impact contributions of the sustainable office building are: 16.6kPt on fossil fuels, 0.802kPt.

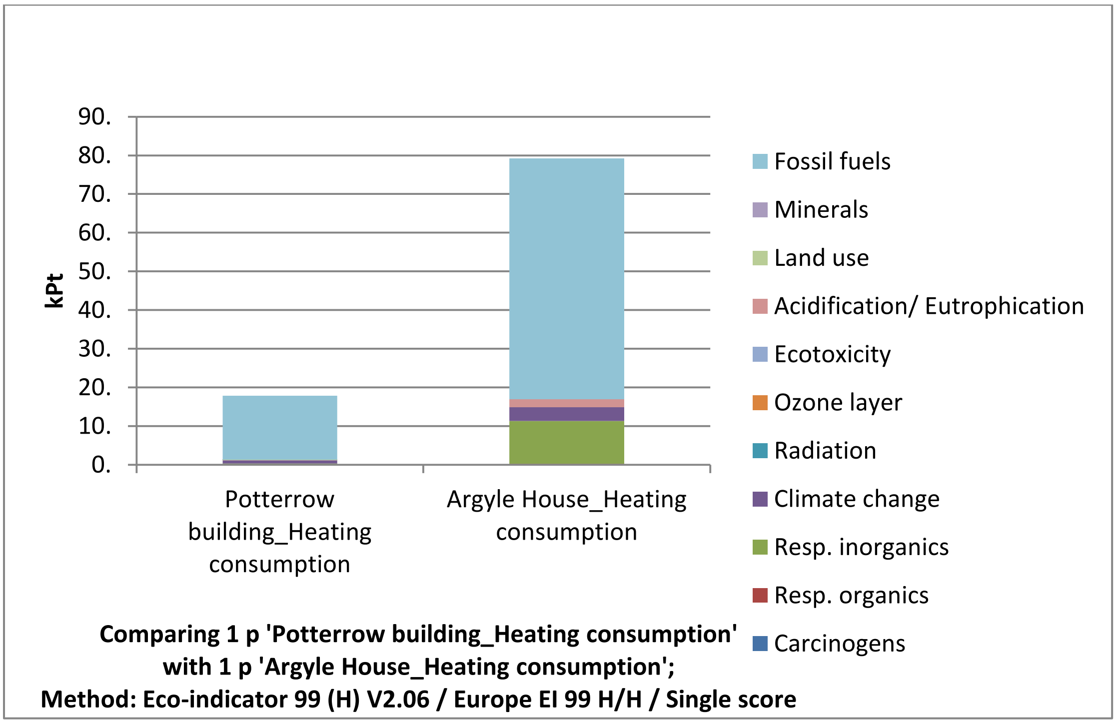


Figure 7.38: Single indicator, comparison evaluation, heating consumption

7.3.3 LCA single score comparison evaluation of the raw-materials on the cooling system

The single score comparison evaluation of the cooling system between the sustainable and the conventional office building (figure 7.39) shows that the sustainable new office building has higher impacts than the conventional office building.

The dominant impacts of the Potterrow building are in minerals 8.8kPt, in respiratory inorganics 2.69kPt, in fossil fuels 2.74 kPt, in ecotoxicity 0.926kPt, in climate change 0.311kPt, in acidification/eutrophication 0.209kPt, in land use 0.252kPt and in carcinogens 0.126kPt. Argyle House contributes to minerals by 0.804kPt, to respiratory inorganics 0.245kPt and to fossil fuels 0.228kPt.

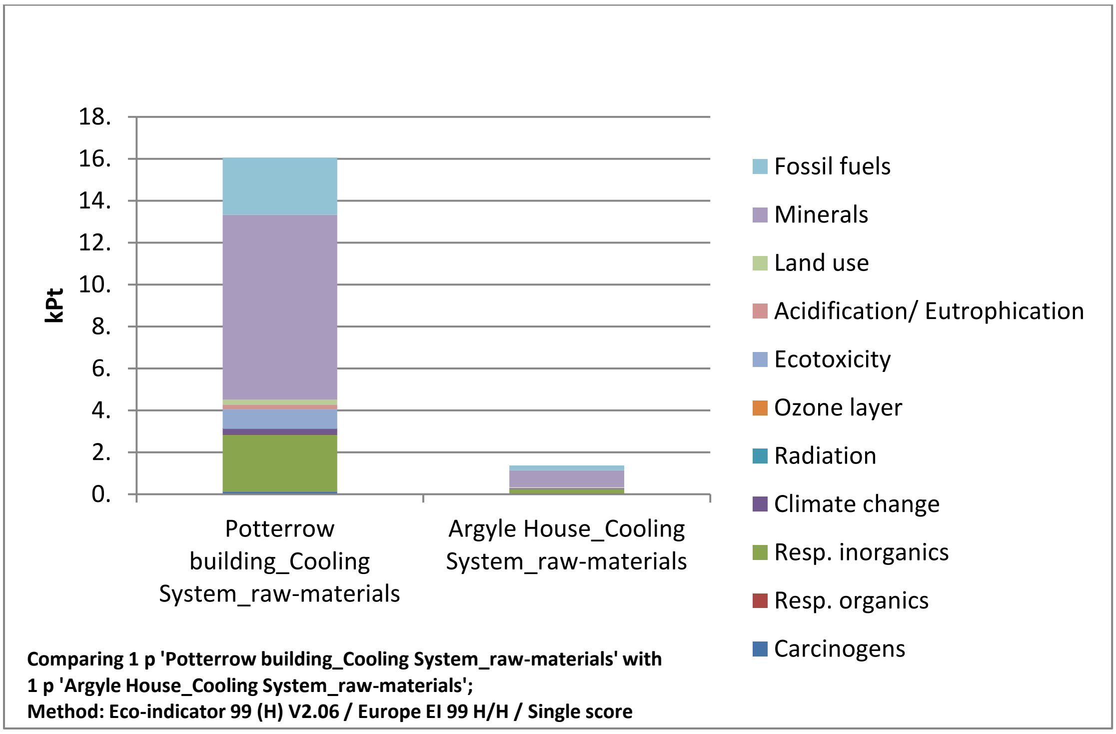


Figure 7.3938: Single indicator score, comparison evaluation, raw-materials, cooling system

7.3.4 LCA single score comparison evaluation on the cooling consumption

The single indicator evaluation (figure 7.40) presents the weighted results of the Potterrow building in comparison to Argyle House. The impact contributions of the Potterrow building are in fossil fuels 1.02kPt, in minerals 0.0315kPt, in ecotoxicity 0.0226kPt, in ozone layer 0.0366 in climate change 0.102kPt and in respiratory inorganics 0.0905kPt. The impacts of Argyle House are fewer, with more contributions to fossil fuels 0.0278kPt. In general the results of the comparison analysis for the cooling consumption as well as for the cooling raw- materials indicator, have smaller values than the results of the heating and that are not particularly significant.

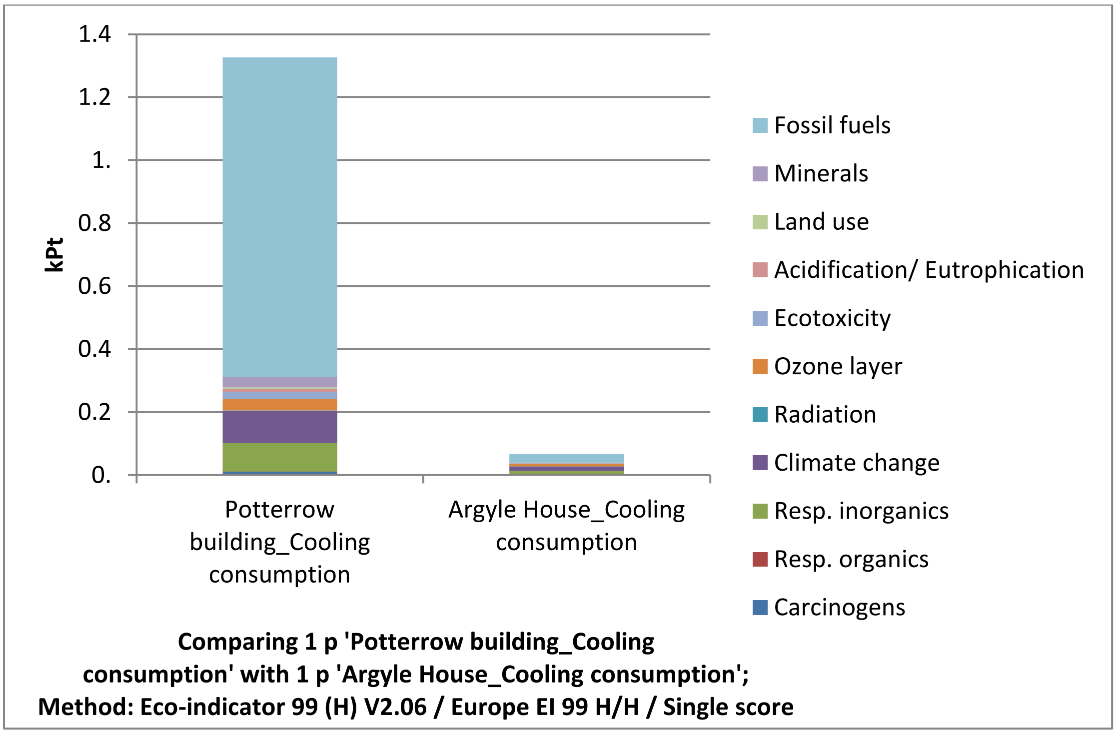


Figure 7.40: Single indicator score cooling consumption

7.4 LCA comparison evaluation between sustainable and conventional office buildings: case study 2

7.4.1 LCA single score comparison evaluation of the raw-materials on the heating system

The single score comparison evaluation (figure 7.41) shows that the sustainable refurbished office building Elizabeth Courts II has less impact than the conventional office building. The dominant impacts of the conventional office building are in minerals 4.34 kPt, followed by respiratory inorganics 2.58 kPt and fossil fuels 1.52 kPt. Fewer impacts appeared in land use 0.244 kPt, acidification/eutrophication 0.244 kPt and climate change 0.127 kPt. The dominant impacts of the sustainable refurbished building are in minerals 2.84 kPt, followed by fossil fuels 1.29 kPt and respiratory inorganics 0.841 kPt with fewer impacts in land use 0.069 kPt, in acidification/eutrophication 0.071 kPt, in ecotoxicity 0.145 kPt and in climate change 0.14 kPt.

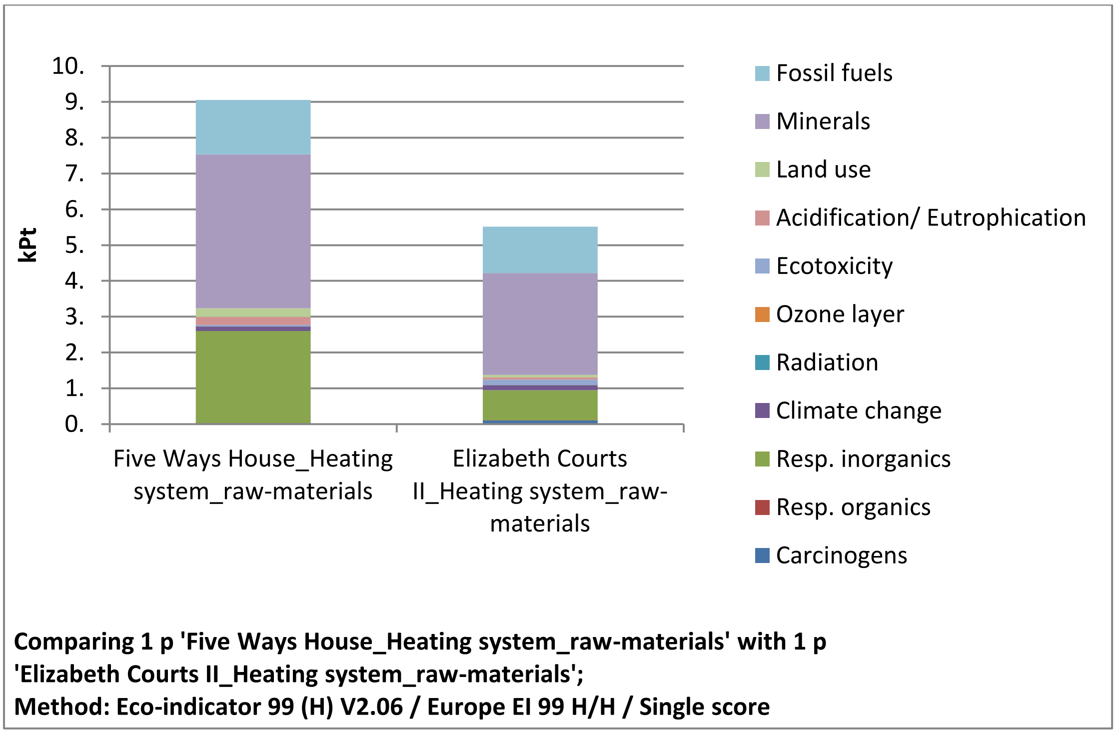


Figure 7.41: Single score, comparison evaluation, raw-material, heating system

7.4.2 LCA single score comparison evaluation of the heating consumption

The single score comparison evaluation (figure 7.42) shows that the heating consumption of the conventional office buildings is responsible for higher impacts than the sustainable refurbished office buildings, shown in fossil fuels 124 kPt, climate change 6.41 kPt and respiratory inorganics 3.55 kPt. The higher impacts of the sustainable refurbished building are in minerals 8.12 kPt.

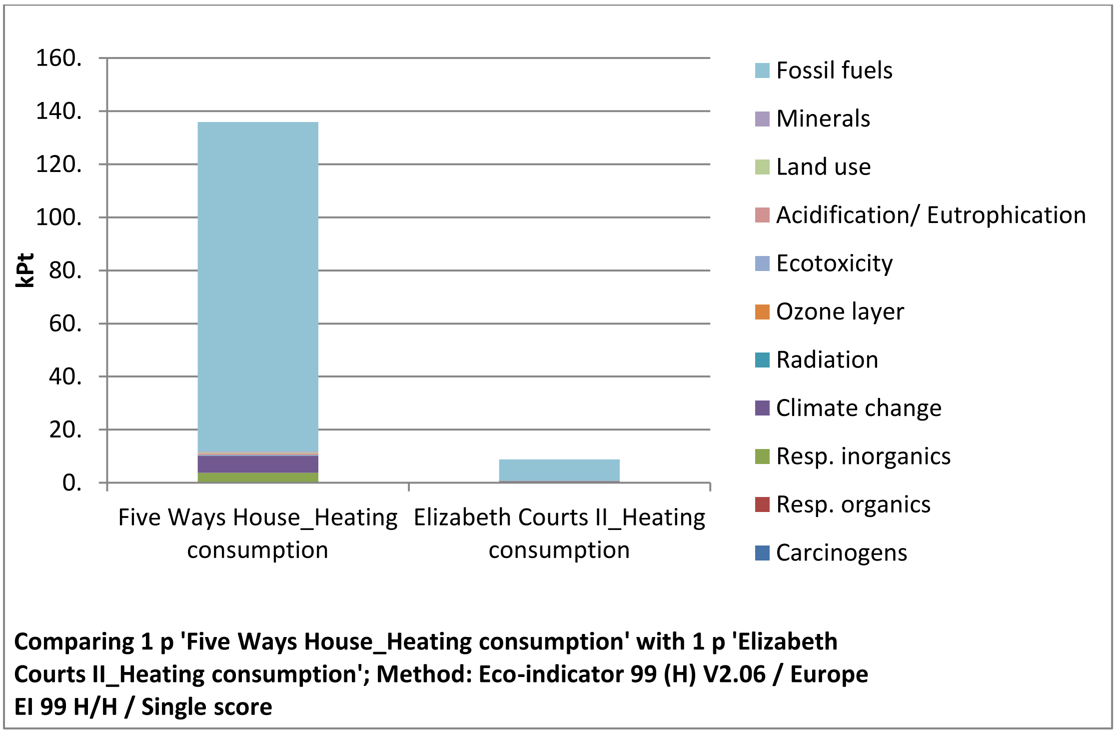


Figure 7.42: Single score, comparison evaluation, heating consumption

7.4.3 LCA single score comparison evaluation of the raw-materials oi the cooling system

The single score comparison evaluation (figure 7.43) shows that the sustainable refurbished office building has higher impacts than the conventional office building. The dominant impact categories of Elizabeth Court are in minerals 10.7 kPt, in respiratory inorganics 6.36 kPt, in fossil fuels 4.24 kPt, in land use 0.599 Kpt, in acidification/eutrophication 0.551 kPt and in climate change 0.357 kPt.

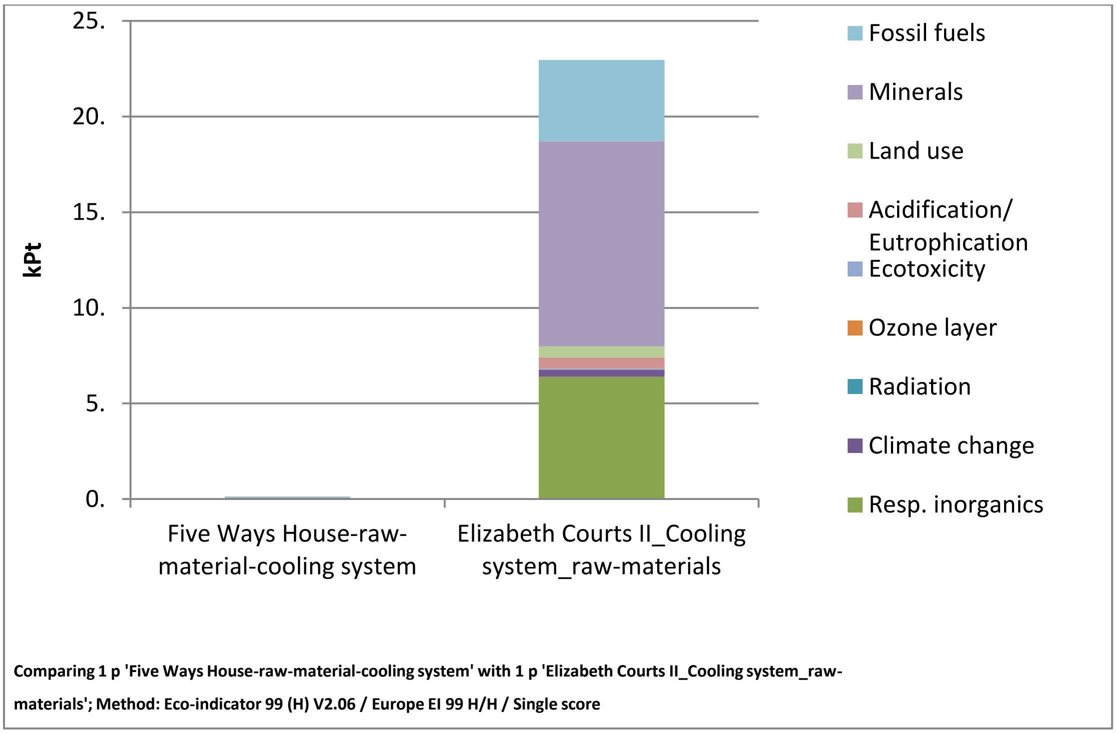


Figure 7.4339: Single score comparison evaluation of the raw-material of the cooling system, case study 2

7.4.4 LCA single score comparison evaluation on the cooling consumption

The single-indicator comparison evaluation on the cooling consumption (figure 7.44) shows the weighted impacts with higher impact outputs from the sustainable office building, in fossil fuels 469 Pt, followed by climate change 205 Pt, respiratory inorgancs 184 Pt, ozone layer 140 Pt, acidification/eutrophication 17.8 Pt, carcinogens 12 Pt and in minerals 8.15 Pt. The most significant weighted impacts of the conventional building are in fossil fuels 27.7 Pt, in climate change 12.1 Pt, in respiratory inorgancs 11.7 Pt and in ozone layer 7.9 Pt.

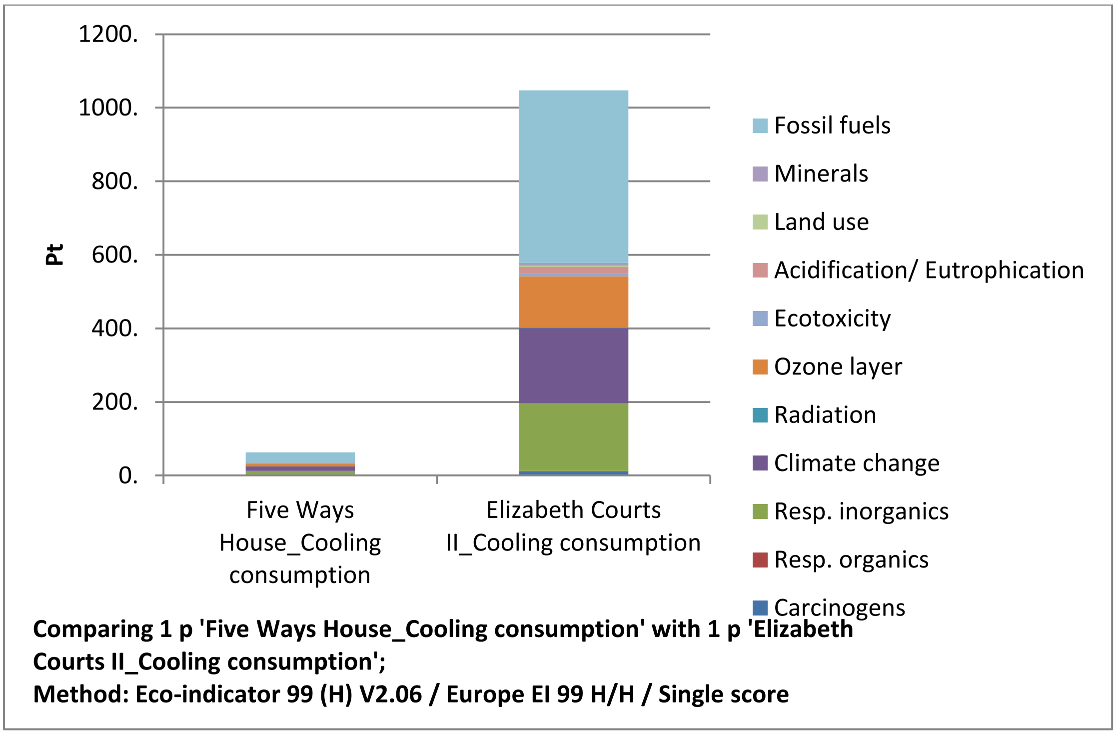


Figure 7.4440: Single score, comparison evaluation, cooling consumption

7.5 LCA comparison evaluation between the sustainable new and the sustainable refurbished office building

7.5.1 LCA single score evaluation of the raw-materials of the heating system

The single score evaluation (figure 7.45) shows that the Potterow building has higher embodied emissions in terms of the raw-materials used in the heating system. The dominant impacts of the Potterrow building are in minerals 1.2 MPt, in fossil fuels 0.84 MPt, in respiratory inorganics 0.807 MPt, in climate change 0.11 MPt, in ecotoxicity 0.807 MPt, in acidification/eutropichation 0.698 MPt, in land use 0.0785 MPt and in carcinogens 0.0485 MPt.

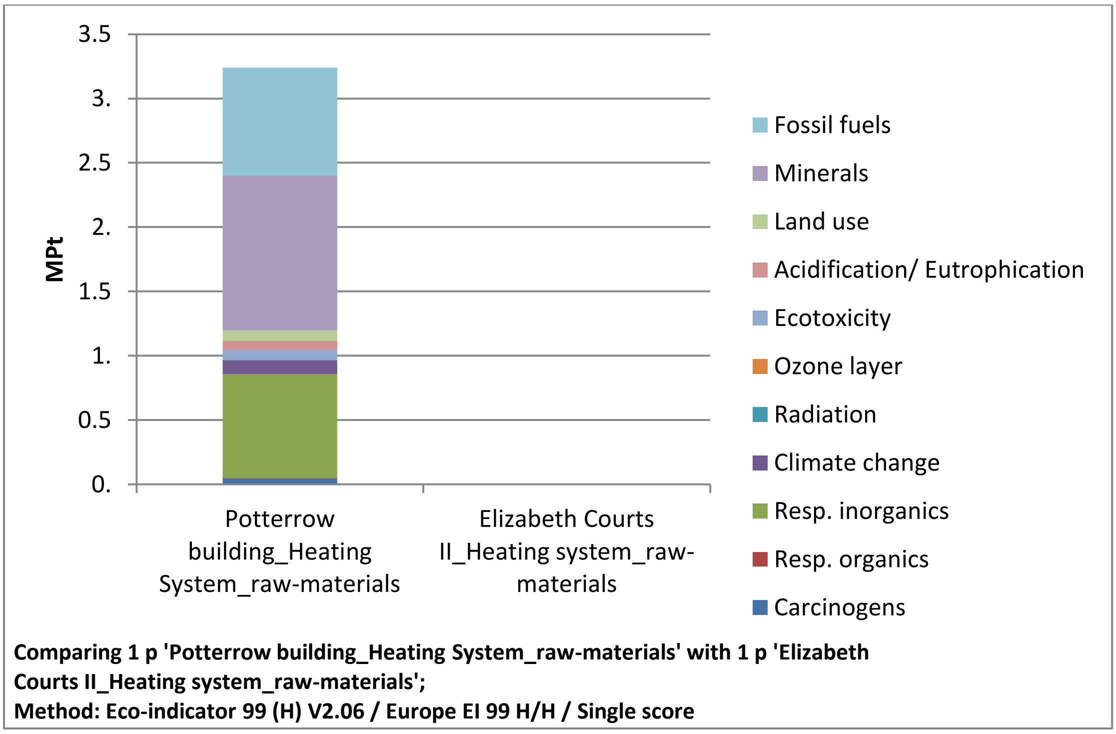


Figure 7.4541: Single score, comparison evaluation, raw-materials, heating system

7.5.2 LCA single score evaluation of the heating consumption

The single indicates that the heating consumption of the sustainable new office buildings has more impacts than the sustainable refurbished office building. The impacts from fossil fuels is the dominant impact category; for the Potterrow building it is 16.6 kPt while from the Elizabeth Courts it is 8.12 kPt. The impacts on climate change from the Potterrow building are 0.802 kPt while from the Elizabeth Courts 0.404 kPt. The impacts on respiratory inorganics from the Potterrow buildings are 0.323 kPt while from the Elizabeth Courts 0.206 kPt (figure 7.46).

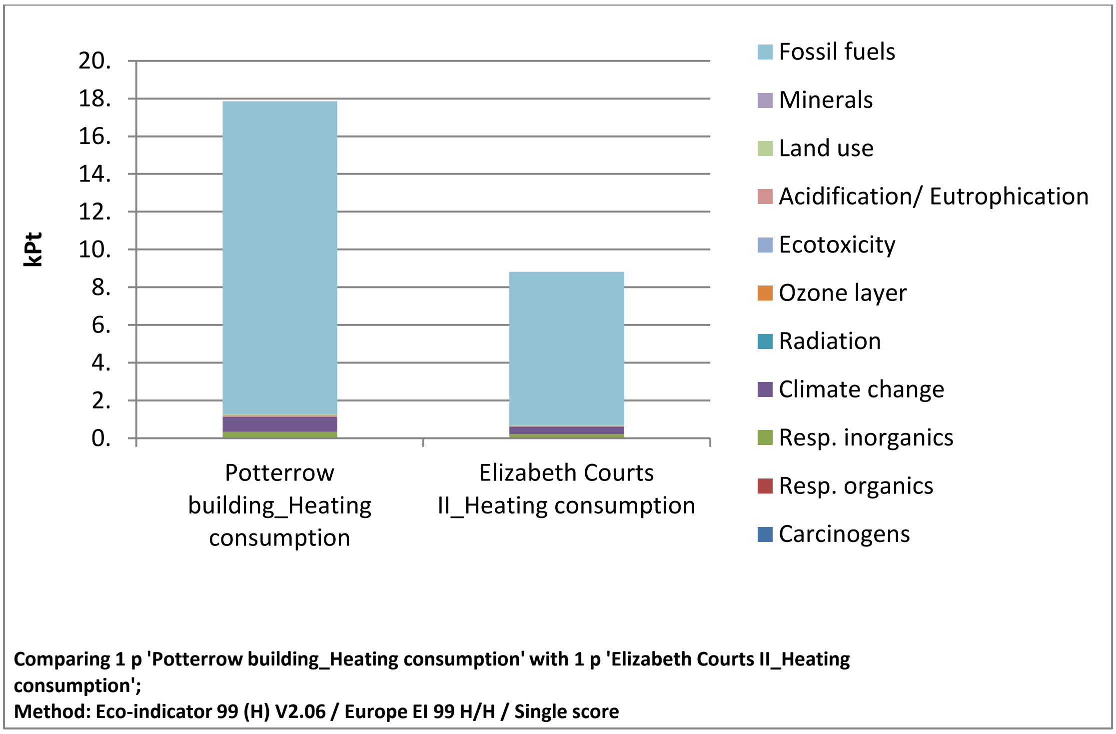


Figure 7.46: Single score, comparison evaluation, heating consumption

7.5.3 LCA single score evaluation of the raw-materials of the cooling system

The single score comparison of the raw-materials of the cooling system between the sustainable offices (figure 7.47) shows that the Elizabeth Courts has more impacts than the Potterrow building. The impacts of the Elizabeth Courts are in minerals 10.7 kPt, in respiratory inorganics 6.36 kPt, in fossil fuels 4.24 kPt, in land use 0.599 kPt, in acidification/eutropichation 0.551 kPt and in climate change 0.357 kPt. The impact of the Potterow building in minerals is 8.8 kPt, in respiratory inorganics 2.69 kPt, in fossil fuels 2.74 kPt, in ecotoxicity 0.926 kPt, in climate change 0.311 kPt, in land use 0.252 kPt and in acidification/eutropichation 0.209 kPt.

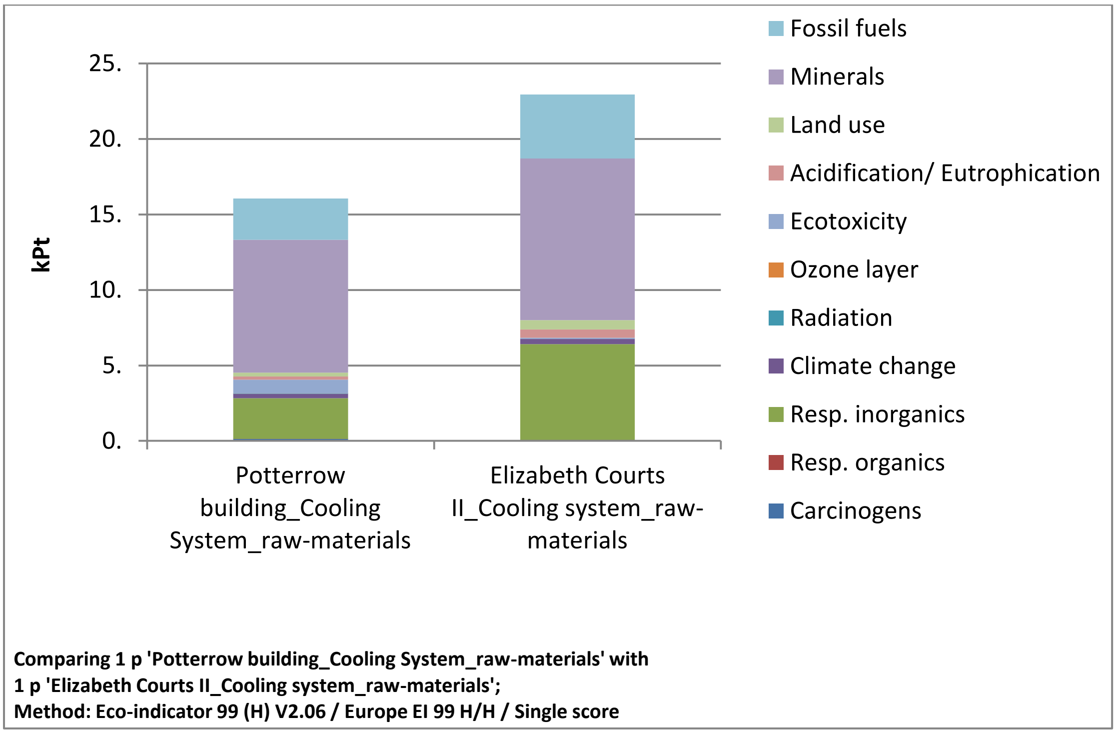


Figure 7.47: Single score, comparison evaluation, raw-materials, cooling system

7.5.4 LCA single score evaluation of the raw-materials of the cooling system

The single score on the cooling system between the sustainable office buildings (figure 7.48) has shown that the Potterrow building has higher impacts than the Elizabeth Courts in fossil fuels, with 1.02 kPt as opposed to 0.469 Kpt for the Elizabeth Courts. Fossil fuels is the dominant impact category. On the other hand, in climate change the impact of the Potterrow building is 0.102 kPt while the impact of the Elizabeth Court is 0.205 kPt. In respiratory inorganics the impact of the Potterrow building is 0.0905 kPt and of the Elizabeth Court 0.184 kPt. In addition in ozone layer the impact of the Potterrow building is 0.0366 kPt while of the Elizabeth Courts it is 0.14k Pt. The Potterrow building has further impacts in minerals 0.0315 kPt and in ecotoxocity 0.0226 kPt.

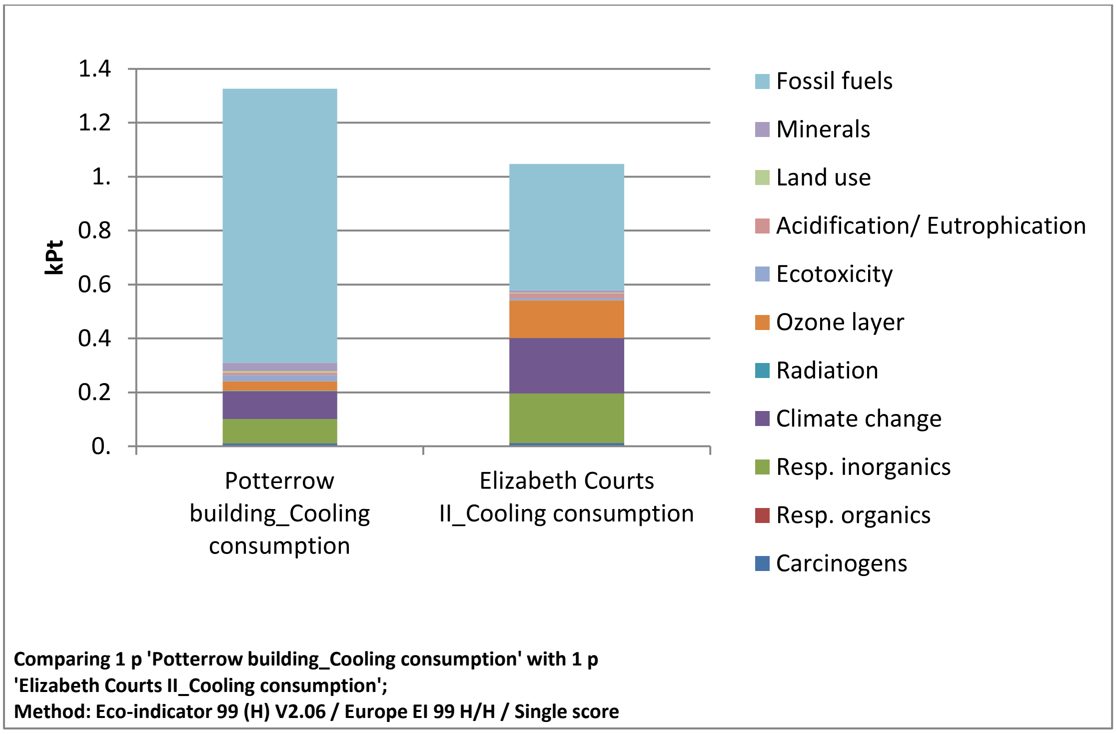


Figure 7.48: Single score, comparison evaluation, cooling consumption

7.6 Hypothetical long run scenarios: case study 1

The heating system in the conventional office building Argyle House is low-energy efficient. An excessive amount of oil is consumed in the cold months, with excessive heat waste due to the central heating system operating in the whole building every time the heating is switched on, even in the unoccupied office spaces. This system has performed in that way for years under frequent maintenance. There have been no replacements-refurbishments on the heating equipment since first installation in the 1960s. This is beneficial in terms of not increasing the embodied emissions but not so for the operational emissions. On the contrary the life span of the sustainable new office building Potterrow is only in the beginning, as the building is today (2013) four years old (two years old at the time of the survey (2009-2010).

From the empirical research conducted it has been realised that the heating system fed from the CHP is highly energy efficient with much lower environmental impacts when compared with the conventional office building Argyle House. A concern is whether in the long run, the energy efficiency as shown today will remain the same. There is no standard answer to that; whether there will be changes, replacements in the long run or whether the maintenance service will become more frequent and what the life span for the heating equipment will be is not known. Faults in the equipment can happen for various reasons and their performance is driven by various mechanical and technical factors.

The reason that it is important to consider the life span of the equipment is because replacements or additional equipment in the systems will increase the overall embodied emissions of the building but on the other hand can reduce the operational emissions. For instance, if in the near future, building regulations boost the obligation for renewable fuels and renewable technologies in existing office buildings, additional technology will increase their existing embodied raw-material emissions but the operational emissions might be towards zero, which seems to be more significant. Further, an online questionnaire survey was conducted (appendix 21) to collect further opinions from various experts about the life span of various heating equipment and about the significance of the embodied emissions and the operational emissions. In the question about what is usually the life span of specific heating equipment the answer varied between 15 and 30 years.

It is assumed that in the long run, which comes into the hypothesis of the thesis, the existing heating technology could lose its energy-efficiency; in the conventional heating system for instance, after 51 years of heating operation, energy-efficiency appears to have decreased. Energy efficiency has to do with the recovery of wasted thermal energy to produce heat (power and cooling in the CHP). The HOVAL manufacturers of the boilers in Argyle House were asked to comment on the efficiency of the boilers, and they mentioned that they have low efficiency. Low efficiency in an oil-fired boiler of that age could be between 45-75%. Apart from that the boilers operate today as they used to operate when the building was fully occupied, to provide heating in the whole building. This increases the waste of fuel, waste of heat, the exhaust gases and the environmental impacts contribution. There the energy-efficiency of the building has decreased.

The heating system in the sustainable office building, Potterrow building, is in operation since 2009. The claimed efficiency of the heating systems is more than 89%. It has been assumed that during the winter periods, energy-efficiency could remain efficient. The efficiency, though, depends also on the efficiency of the CHP as well; if the CHP is used properly to provide heating and it operates daily in the required hours with the appropriate return temperatures, then its efficiency is enhanced. If there is excess production of unused heat, then the heat is stored in the thermal store. If the heat from the thermal store is not recovered, then heat becomes waste and that decreases the efficiency of the CHP, but this is not usually the case in the winter. For a long run hypothetical comparison see figure 7.49.

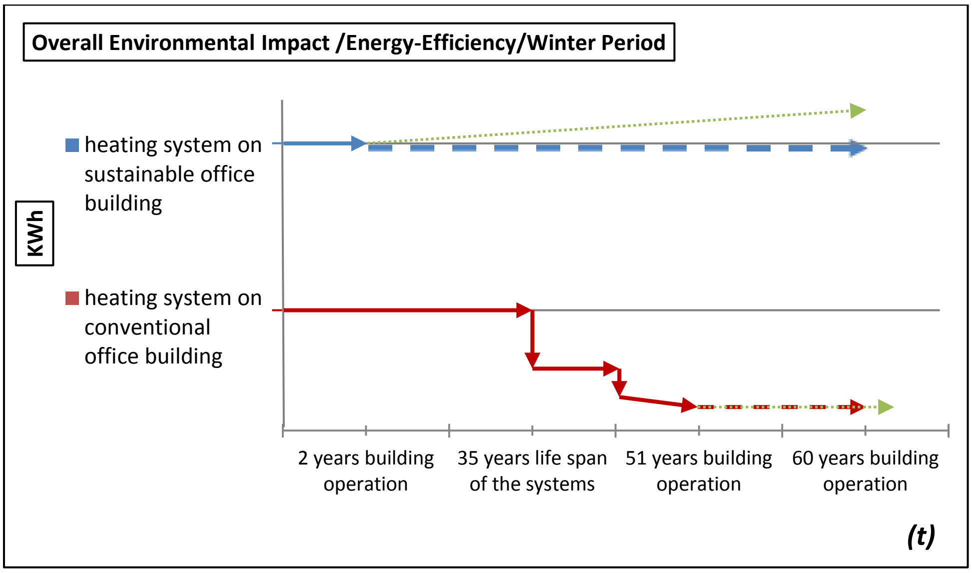


Figure 7.4942: Scenario on the environmental impacts of the energy efficiency of the heating systems, during the winter period, in the long run. The green arrows show potential improvement. The dashed arrows show what could happen with no change. The non-dashed lines show the situation so far.

The hypothetical scenarios developed have considered the potential increase or decrease of the energy efficiency or material efficiency in the next 35,51 and 60 years of operation.

The next hypothetical scenario is for the cooling system in the conventional office building (figure 7.50). The office building space is naturally ventilated which is an advantage for less environmental impacts, as mechanical cooling is only used in the IT server rooms, meaning less cooling equipment and less refrigerant. Since 2006 there has been a reduction in the occupancy, therefore less demand for cooling in the server rooms. On the other hand, in the sustainable office building, the fact that stored heat is not recovered properly and excess heat is produced which is not used for cooling in the summer, means that heat is then rejected in the outdoor environment.

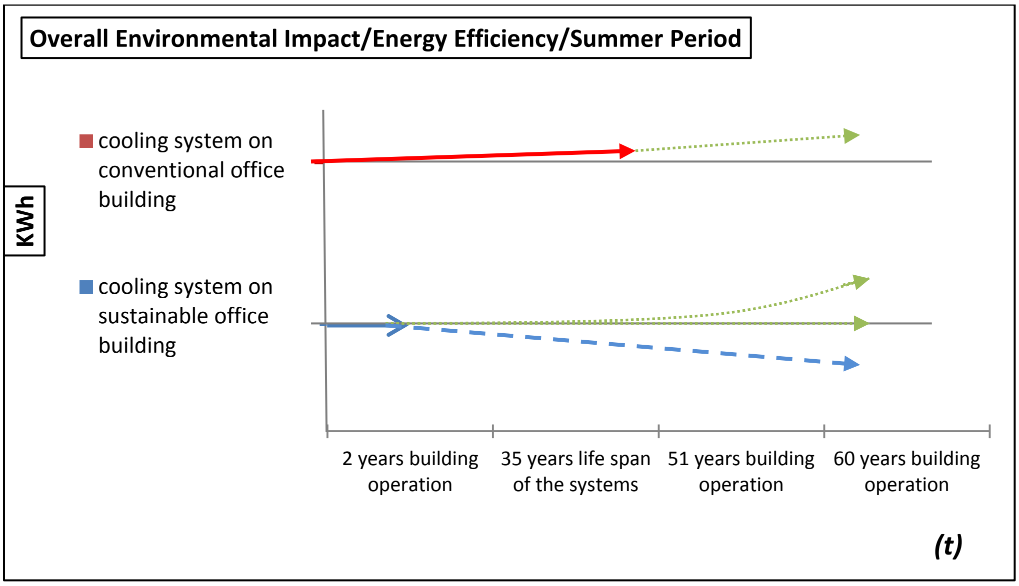


Figure 7.5043: Scenario of the environmental impact indicator for the energy efficiency of the cooling systems, during the summer period, in the long run.

The overall environmental impact indicator in terms of the material efficiency unfolds some important areas for further consideration. The overall material content of the heating-cooling system on the conventional office building has not changed all these years, as there have been no replacemants.

In the case of the sustainable office building, the builing is only 2 years old, so it is too soon to know whether there will be replacements in the future. It has been assumed that after 10-35 years of the building service's life time, there might be changes (refurbishements, replacements). It is also anticipated that in the next 15 years there is a scenario that the outside temperatures might change and therefore the current demand for heating and cooling might change.

There is also another scenario (figure 7.51) that the building will be extended into a 3rd phase where additional equipment will be added in the h/c system. The need for adding up renewables in the existing office building to lower the carbon emissions is also a possibility. No matter what the future scenario, extra equipment will increase the overall environmental impacts and this is the whole point. Another scenario would be to not replace the existing technology and to undertake constant repairs and maintainance as in the conventional office building. However, what has to be avoided is the service costs that Argyle House had and cannot afford in the long run, which is one of the factors that has influenced the decrease of the occupancy. This also plays an important role in lowering energy efficiency. Something has to be done about it and there is a need or a substantial change to improve the energy efficiency for heating in Argyle House. This change could involve whole building refurbishment (see Elizabeth Courts II).

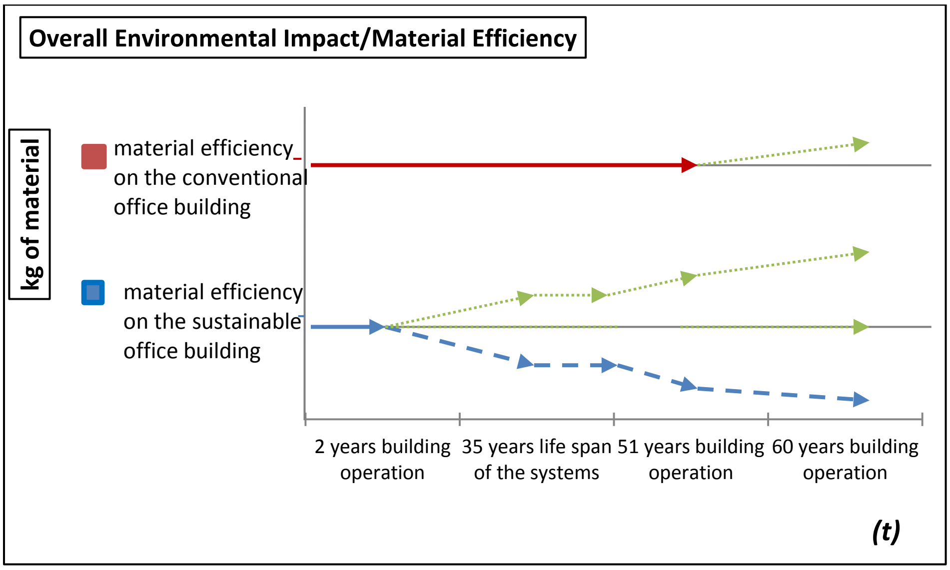


Figure 7.51: Scenario of the environmental impact indicator for the material efficiency

The discussion on the hypothetical scenarios in this section has underpinned that different scenarios are beneficial for the energy efficiency and different for the material efficiency. It is a question of which scenario is more significant for a change either in energy efficiency or in material efficiency and then what the risk will be in the selection of a scenario, as presented in the following table 7.1.

Table 7.1: The importance of long run hypothetical scenarios and their risk for energy efficiency and material efficiency

Long run hypothetical scenarios		
Scenario	**Risk for energy efficiency**	**Risk for material efficiency**
Maintainance	Medium	Low
Replacement	-	-
Re-used	Medium	Low
Recycled	Low	Low
New	Low	High
Additional equipment	-	-
Re-used	Medium	Low
Recycled	Low	Low
New	Low	High
Adding renewables	Low	High
Switch off CHP equipment in the summer	Assumed to be low (see comments from the online survey, appendix 21)	Low

Considering the overall environmental impact indicator of the technologies, in terms of the energy efficiency and the material efficiency in the long run (figure 7.52) it can be realised that the sustainable office building will not be energy efficient unless consideration is taken of the hypothetical scenarios to enhance energy-efficiency in the summer period. However in the winter the energy-efficiency improves as there is a constant heating demand. It could be said that according to the existing situation, the conventional office building becomes more environmentally friendly over time and the sustainable office building could become less so.

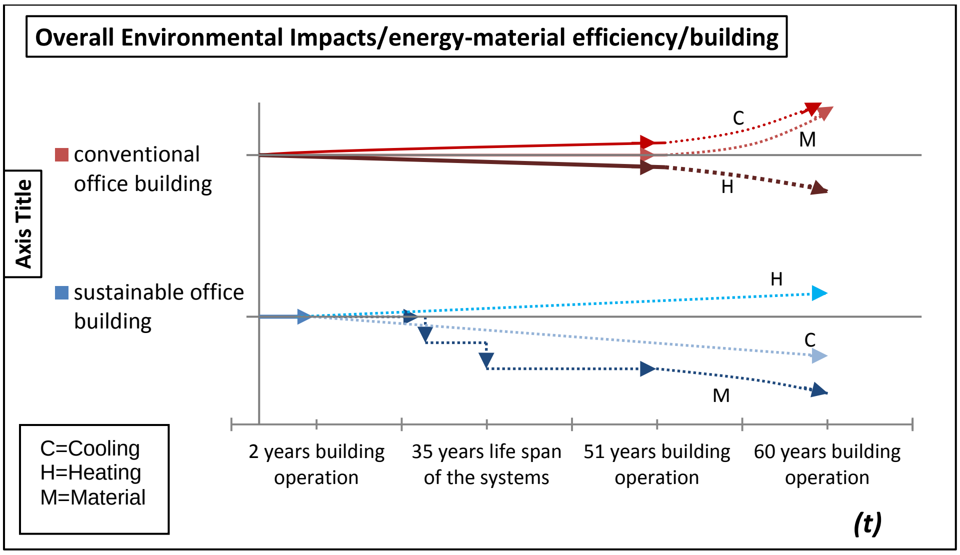


Figure 7.52: Overall environmental impact scenario for energy efficiency and material efficiency.

From the above hypothetical scenarios, the development for the new sustainability indicator, the 'Overall Long Run Life Cycle Impact Indicator' (OLRLCII), can address the relations presented in table 7.2. From this information the development of the new indicator can address the effectiveness of the indicators to determine whether conventional or BREEAM office buildings are better now and in the long run.

Table 7.228: OLRLCII for the case study 1

OLRLCII of Case Study 1
OLRLCII for Energy efficiency-Winter months Heating on the sustainable office building **>** to the conventional office building
OLRLCII for Energy efficiency-Summer months Cooling on the sustainable office building **<** to the conventional office building
OLRLCII for Material efficiency Technology on the sustainable office building **<**to the conventional office building
OLRLCII Overall Sustainable office building **<**to the conventional office building

7.7 Hypothetical long run scenarios: case study 2

In this section the hypothetical scenarios of case study 2 have been developed. The heating system of the conventional office building Five Ways House had a refurbishment in 2001 in the plantroom, where the old boilers were replaced with high energy efficient natural gas boilers. Some of the radiators were also replaced. Hence, at the time of the study, the boilers were 11 years old.

The FM team has stated that there have been no issues with the boilers. They undertake frequent maintenance services and they have used a life cycle management approach (appendix 12), as explained previously. The previous heating equipment must be 51 years old. There are no data in the archives about whether there have been other refurbishments in the past. In terms of the energy efficiency it has been claimed that the new boilers achieve around 92% efficiency, although this depends on the building heating performance also. The thermographic survey has shown heat losses and air-leakages, while lack of insulation increases the heating demand in maintaining the indoor temperature to meet the set point parameters of 28^{0}C. This temperature parameter is quite high and requires more operational watt/hours for heating. If these issues remain as they are, it is assumed that the efficiency of the heating over the winter in the long run will decrease further (figure 7.53).

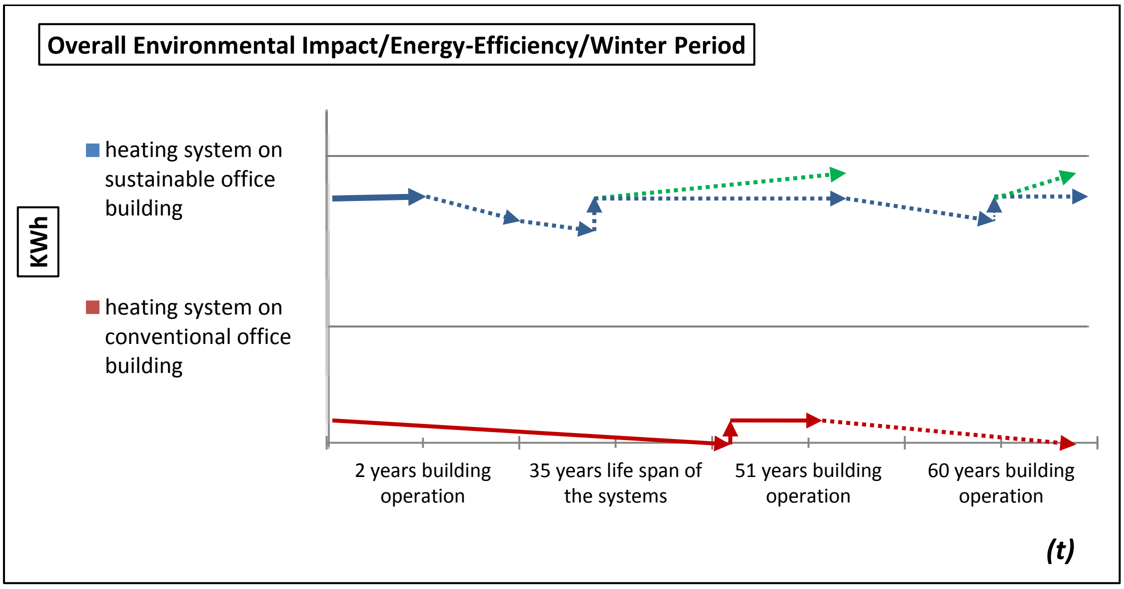


Figure 7.53: Overall environmental impact, energy efficiency in winter

On the other hand the newly installed heating equipment in the Elizabeth Courts II is 2 years old and few issues have emerged about the efficiency that has from the post-occupancy evaluation.

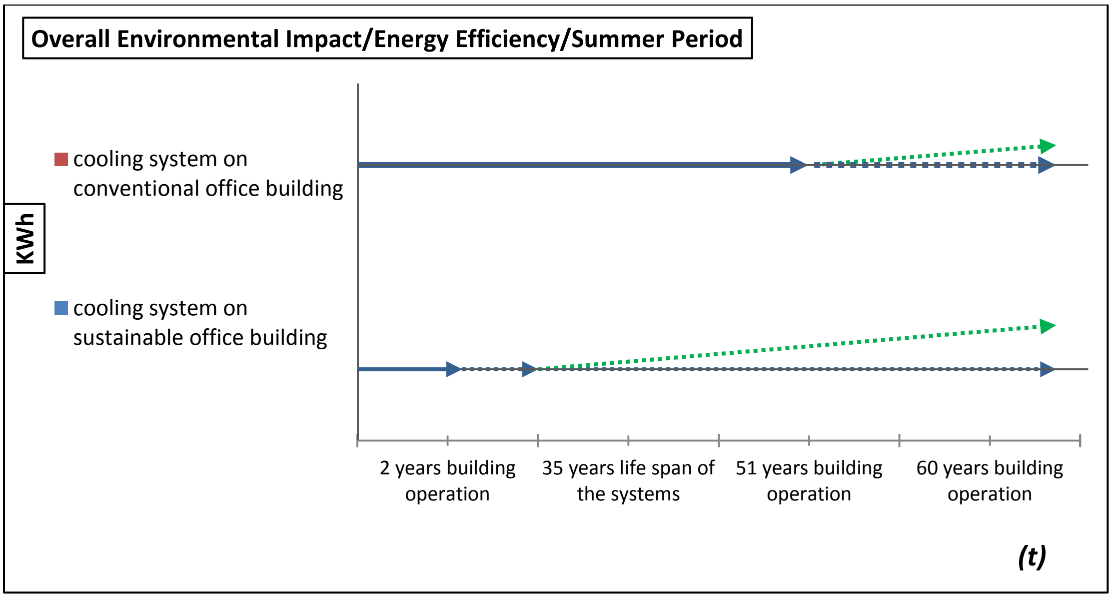


Figure 7.54: Overall environmental impact, energy efficiency in summer

The hypothetical scenario about the cooling system in the conventional office building shows that since the office building area is naturally ventilated, the energy efficiency will basically remain as is with possible increase in the long run (figure 7.54). The cooling system in the rest of the building is fed from the outdoor heat pumps and no heat from the boiler systems is used as a medium to generate cooling, as in the CHP technology in case study 6. This is seen as a positive approach as heating operates in the summer only to heat water and mechanical cooling is not used in the office space.

In terms of the cooling system in the sustainable office building during the summer months, two scenarios have been taken into account. Most possibly, since cooling consumption contributes about 0.763% overall, due to the energy efficient technology, it is assumed that the energy efficiency will either remain as is or improve in the long run (figure 7.55).

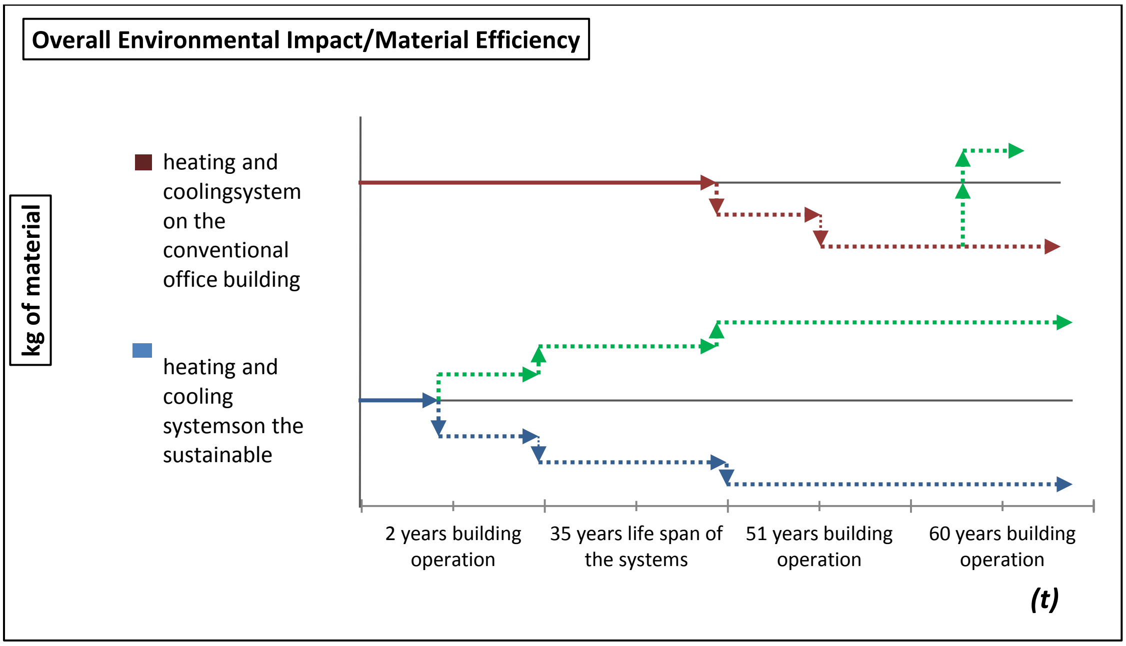


Figure 7.55: Overall environmental impact, material efficiency

The hypothetical scenarios for the material efficiency in the long run (figure 7.55) of the heating and cooling systems in the conventional office building, the building already had plantroom refurbishment in 2001 and radiator replacement, 10 years when the building was 51 years old. Consequently new technologies mean more components and more materials with more embodied emissions added to the overall building life material consumption by the heating and cooling systems. As mentioned before, it is not known what percentage of recycling content is in the new mechanical systems. The materials selected and analysed with LCA have been found from the existing literature, heating-cooling equipment specification, from other LCA studies, and advice has been taken from experts in engineering bearing in mind the total weight and the measurements of individual heating and cooling equipment. The final material selection from the available inventory libraries at the LCA software SimaPro has been chosen based on material specific characteristics, choosing those which have some recycling material content and preferably mixed types from primary and secondary material contents. The scenario for the long run for the technology used on the conventional office building assumes that added technologies means more material content therefore more production and embodied emissions. Considering the LCA results on the selected metals, several environmental impacts occur. So it makes sense to say that material efficiency has decreased although in a few years' time, if equipment replacement takes place to reduce further the energy consumption and recycling content, it is considered that this could increase the material efficiency.

About the sustainable office building which has been operated fully the past two years, it is difficult to predict the lifetime of the heating and cooling equipment. However two scenarios can be explained: either the material efficiency will increase or decrease. Assuming that by the time a replacement will be needed technologies of lower embodied emissions will be available in the market, material efficiency has the potential to increase.

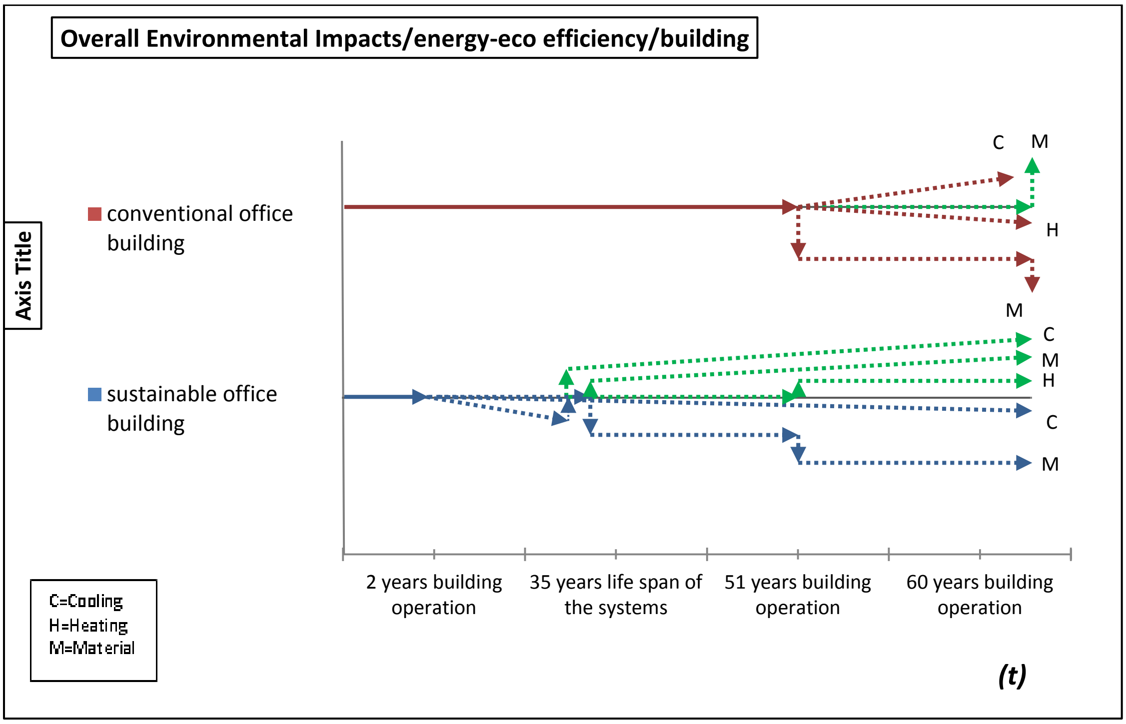


Figure 7.56: Overall environmental impact, energy efficiency and eco-efficiency

By considering and combining the previous hypothetical scenarios the OLRLCII can be determined for the conventional office building and for the sustainable office building. Table 7.3 presents a summary of the scenarios discussed.

Table 7.3: Long run comparisons

OLRLCII of Case Study 2
OLRLCII for Energy efficiency-Winter months Technology on the sustainable office building **>** to the conventional office building
OLRLCII for Energy efficiency-Summer months Technology on the sustainable office building **>** to the conventional office building
OLRLCII for Material efficiency Technology on the sustainable office building **>** to the conventional office building
OLRLCII Overall sustainable office building **>** to the conventional office building

7.8 Sensitivity analysis

It is a common approach to use sensitivity analysis in Life Cycle Assessment studies. although it is not mandatory. Sensitivity analysis is an additional LCIA data quality analysis, a procedure to determine how changes in data and methodological choices affect the results of the LCIA (ISO 14044 2006 p.22). There are different tools for approaching sensitivity analysis (Budavari et al. 2011 p.7) depending on the goal and scope definition and on what the sensitivity needs to show. In this thesis the sensitivity analysis has been used to:

a) calculate different scenarios, to analyse the influence of discrete input parameters on either output parameter values or priorities (Budavari, Szalay, Bown, Malmqvist, Peuportier, Zabalza, Krigsvoll, Wtzel, Cai, Staller, & Tritthart 2011 p.7).

b) simplify data collection and analysis without compromising the robustness of a result or to identify crucial data that must be thoroughly investigated (International Energy Agency et al. 2004 p.1).

The sensitivity analysis (figure 7.57) considers 1 KWh of energy for heating from different sources in an attempt to get a better understanding of the environmental impacts of the technologies that have been evaluated so far, compared to alternative technologies that could be used to support the decision-making in the long run. By simplifying the value of the KWh the difference in the impacts caused can be better realized. The alternative technologies that have been evaluated and compared to the technologies of the selected case study buildings with LCA are:

- electricity from wind power
- heat with hardwood chips from forests at furnace
- heat geothermal
- heat lignite briquette at stove
- electricity from nuclear power
- electricity from hydropower
- electricity from PV
- electricity wood

- heat at cogen with biogas engine

The normalisation evaluation has shown that impacts in fossil fuels, consuming 1 KWh of electricity for heating come from cogen 8.51E-05, from hydropower 9.51E-05, from natural gas at low-NOx boiler 7.62E-05 (Elizabeth Courts), from natural gas at modulating boilers 6.68E-05 (Five Ways House). Impacts in respiratory inorganics come from heat lignite briquette 1.88E-05, from hydropower 2.2E-05, hardwood chips from forests 1.58E-05. Geothermal power and hydropower impact climate change.

The selection of the alternatives has to do with the current demand for heating. Commercial buildings usually switch to energy efficient technology. However, only with renewable technology such as PV, wind power and nuclear will there be a transition into zero carbon emissions. Another phenomenon in low-income countries switching to traditional cheap methods, using stoves in commercial buildings that burn briquettes, wood logs and chips from forests, pellets which produce smog that damages the environment and human health.

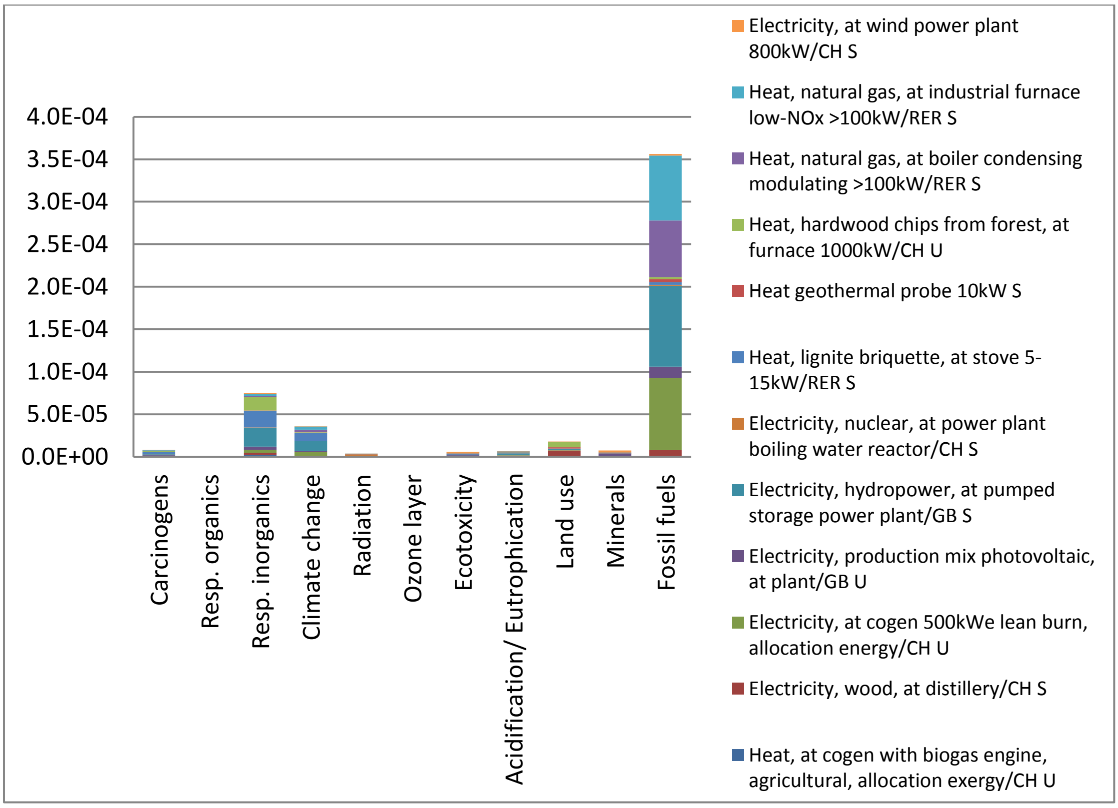


Figure 7.57: Environmental impacts of 1 kWh of electricity from different low/zero carbon technologies

Renewable seems to be the current-state-of the art technology and the best option towards zero greenhouse emissions, although the hypothetical scenarios have underpinned the influences that this choice can have in increasing embodied emissions. It is fundamental to consider disposal scenarios as well as production scenarios of renewable technology so that during the production life cycle phase, they can be as friendly to the environment as possible. In the coming years the production of renewable technology is expected to increase significantly so considering embodied emissions from the conceptualization stage of decision making is apparent. Several studies have taken alternatives into consideration (Theodosiou et al. 2005;Witson 2002).

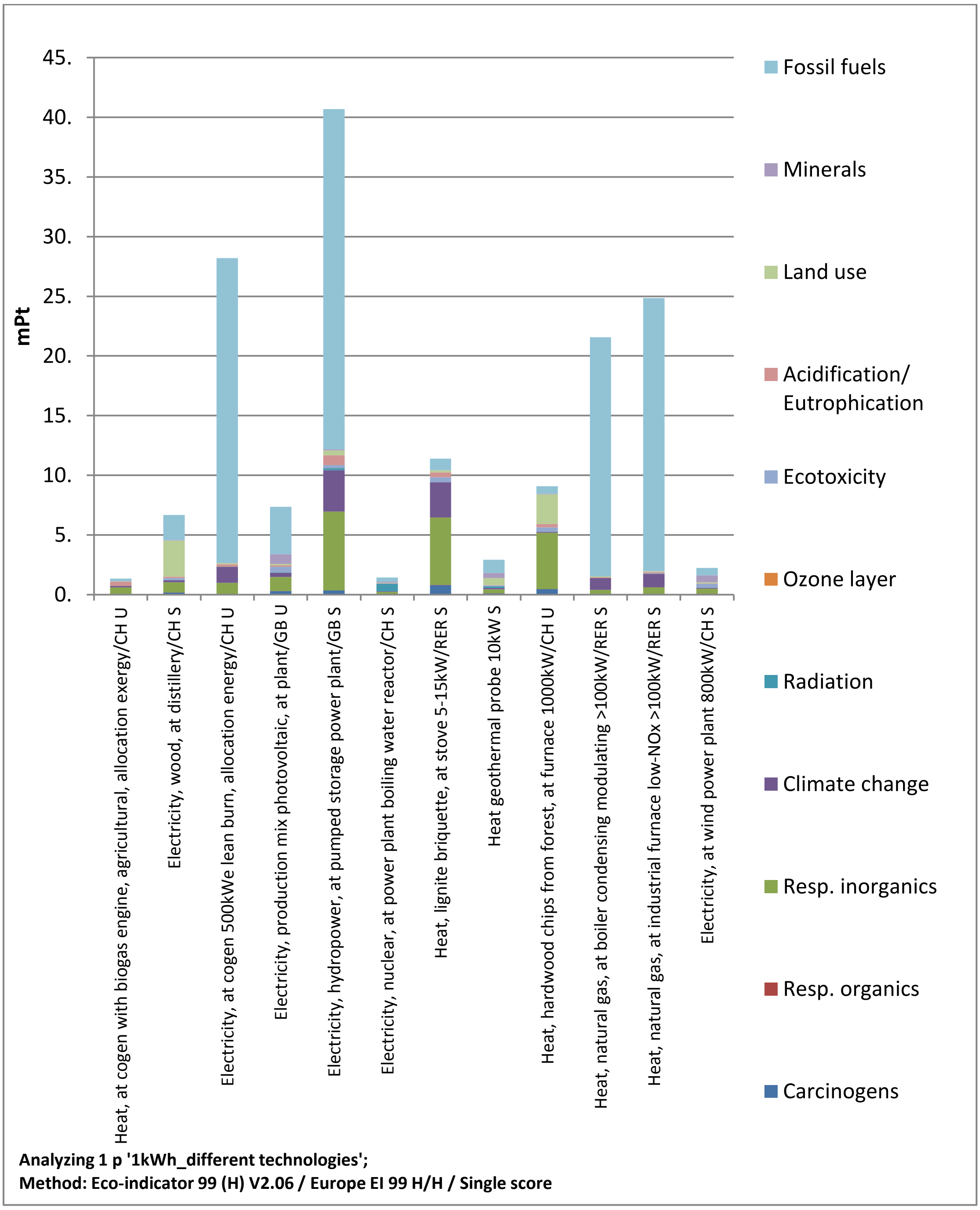


Figure 7.58: single score evaluation of 1 KWh of energy by different technologies

The single indicator evaluation (figure 7.58) shows that fossil fuels have the greatest impact, produced from 1 KWh of hydropower electricity 28.51 mPt, from electricity production at cogen 25.53 mPt, heat at natural gas low-NOx boilers 22.87 mPt and from heat at natural gas in condensing-modulating boilers 20.03 mPt. Impacts on respiratory inorganics are caused by hydropower 6.6m Pt, from briquettes in stoves 5.6 mPt and from hardwood chips in stoves 4.7 mPt. Impacts on climate change are produced by hydropower 3.4 mPt and from briquettes 2.9 mPt. Impacts on land use are caused by the use of hardwood chips. From these results it can be seen that there are worse choices than the technologies been used in the selected case study building in terms of environmental impact, but there are also better choices such as pvs, geothermal, nuclear power and wind power. Cogeneration (CHP) seems to be one of the best options if biofuels-biogas is used instead of fossil fuels-natural gas.

7.9 Discussion

This chapter has shown the influence of building designs on the demand of heating and cooling systems in the mechanical engineering market. Building design has determined the selection of building services; the amount of equipment, the size, the capacity, the needed space, the efficiency, which therefore determines the type and amount of raw-material . From the literature review, it was found that the previous BREEAM schemes (before 2009) and the existing schemes do not include a category about embodied raw-material emissions. This is a highly important indicator that is influenced significantly by the building design, as it unfolded in this study. It can be further realised that the need for energy efficient technologies to enhance overall energy efficiency of the building system (see CHP at Potterrow and VRV air-conditioning in EIIC) actually increases the embodied raw-material emissions. If nothing is done about it in the near future when the existing UK office building stock will have to be renovated (existing 1950s-60s office buildings), embodied raw-material emissions will further increase. Also within the next 25 and 50 years existing BREEAM buildings will go to some form of renovation or upgrade. This is why the development of the new sustainability indicator has been important, so that the embodied raw-material emission indicator can be considered in environmental decision making.

The LCA evaluations on the heating and cooling systems in this study have shown that copper, aluminium and different types of steel, such as galvanised steel and stainless steel, are the dominant metals used in heating and cooling systems. Based on the assumptions used and based on the literature research about heating and cooling equipment material, it has been found that the highest metal content in the heating and cooling systems in the case study buildings is copper. This leads to high extraction of resources through extractions of fossil fuels and minerals and its manufacturing can cause respiratory (inorganics) health issues.

Looking at the inventory data in the conventional office building in Edinburgh, Argyle House, the main components of the heating system are two large conventional old boilers and 1892 perimeter old type radiators. Overall copper contributes 97.9toin the total environmental impact compared to the other material content (see network evaluations). In the Potterrow building copper contributes 71.5% and aluminium 27.9%, with 522 radiators in the whole building, 22 pumps and 69 pieces of trench heating equipment, including the three turbines. The contribution of copper in Elizabeth Court is similar to the Potterrow building, with 73.1%, and further impacts from stainless steel 12.6%, included in 434 radiators, three boilers and 16 pumps within the heating system. The content of copper in the heating system of Five Ways House is 78.1% with further impacts from cast iron 20.7% included in 1185 radiators, in 3 boilers and in 15 pumps. As the use of copper and other steels increase, the impacts in minerals, respiratory inorganics and in fossil fuels increase accordingly.

From the single indicator results it is clear that the conventional office buildings have higher impacts than the sustainable office buildings in terms of the raw-material content in their heating systems, due to the large amount of equipment used in the heating systems.

The associated impacts from the sustainable office building in Elizabeth Court show that size of equipment also plays a significant role in the increase of environmental impacts. The Potterrow building has the advantage that the boilers as well as the turbines and most of the pumps are included in the CHP unit installed outside of the building within a district network feeding other buildings that belong to the University of Edinburgh campus. Therefore the only associated impacts related to the building and not to the heating system are from the equipment installed inside the building. This type of heating system lowers the embodied emissions of the building. Even if we look at the embodied emissions of the heating system, and not of the building, again the heating system of the Potterrow building has less embodied emissions than the heating system in Argyle House.

In the embodied emissions of the cooling system, copper is also the predominant material with 75% contribution in Argyle House, from the mostly unused cooling mechanical equipment as the office building space is natural ventilated. In the Potterrow building ferronickel has a higher impact of 61.6% compared to copper 36.8%, used in three chillers and in five air-conditioners, causing impacts on minerals, fossil fuels, respiratory inorganics and in ecotoxicity. The highest metal content in

Elizabeth Court is from copper, 93.6%, with fewer contents from stainless steel, 12.6%, used in three chillers and 40 air-conditioners. The amount of the equipment explains the difference in embodied emissions of the cooling system in the comparison evaluation between the sustainable office buildings (section 9.4). In Five Ways House, which is naturally ventilated, it has been found that cold-rolled steel has the highest impact with 53.6% contribution, with fewer impacts from galvanized steel, from copper and from aluminium, used in 17 air-conditioners and in seven heat pumps. These impacts damage resources and human health, with less detrimental effect on ecosystem quality.

In the case of the cooling system in the case study buildings, the results have shown that the sustainable office buildings have higher embodied emissions than the conventional office buildings. From the LCA evaluation, it can be seen that energy-efficient technology means additional equipment to enhance energy efficiency. For instance in order for CHP to be energy-efficient, unused heat is recovered and used from chillers; similarly waste heat from the data centre of Elizabeth Courts is recovered and used as cooling. If there was no mechanical cooling and there was also natural ventilation in the sustainable buildings, there would have been issues with high exhaust heat with CO_2 and other emission released into the atmosphere. So the increase of embodied emissions has an influential factor on the 'energy-efficiency', which is the main focus of sustainable office buildings in reducing carbon emission targets. Certainly the carbon emissions targets have to be achieved but should not embodied emissions also be a concern? In the online questionnaire survey (appendix 21), in the question', "is it more important to reduce operational or embodied emissions? Or both?'', different experts from the building sector have answered that both operational and embodied emissions are equally important.

In terms of the operational emissions, it was found that the conventional office buildings have higher environmental impact contributions, about double the emissions of the sustainable office buildings. This was expected considering the passive design characteristics and the energy efficiencies of the sustainable buildings. The oil consumption of Argyle House had significant impact on fossil fuels, respiratory inorganics and climate change due to the huge heating demand to provide heating in the areas that are unoccupied.

Between the sustainable office buildings, the Potterrow building has higher impacts than the Elizabeth Courts. Both buildings have been designed with passive design principles, and both buildings have been widely recognised and awarded for their achievement in carbon emission reductions. Both buildings have more or less the same energy efficiency in their boiler systems with differences in the set point indoor temperature parameters, in the size of the building, in the building shape, in the heating demand and in the type of equipment in the heating system - see MATRIX appendix 1. Although the CHP trigeneration is the state-of the-art technology for carbon emission reduction, the environmental impacts caused by the CHP and other heating equipment in the Pottterrow building, are higher than the impacts from the condensing and low-NOx boilers and from the other heating equipment in Elizabeth Court II. This is also due to the summer CHP operation.

The cooling consumption indicates that electricity for cooling in the office buildings does not contribute more than 10% of the annual electricity consumption. However the Potterrow building has more impact than Argyle House and Elizabeth Courts II has more emissions than Five Ways House. Should not the sustainable office building have less environmental impacts for cooling than the conventional office buildings? As previously explained, cooling is an important factor for the energy-efficiency of the CHP in the Potterrow building but this increases the emissions from cooling mostly over the summer period in the long run. Since this has been an issue, should not the CHP have been switched off over the summer and the hours that the office building is not in daily use (office building daily operational hours in the UK are 9-5)? Or should cooling have been provided from the CHP, since it has been found that the mechanical cooling installed in the conventional office buildings has less cooling consumption and therefore less environmental impact? From the online questionnaire survey results, it has been highlighted that switching off the CHP over the summer should be an option. Further recommendations are provided in chapter 8.

In the evaluation of the operational emissions for cooling, the emissions of the refrigerant have also been evaluated and the results show that potentially (during installation and maintenance, or during replacement), significant emissions are produced by the alternative refrigerant R134-a which are higher than the emission produced from cooling consumption. This is an important area for consideration.

The hypothetical scenarios have discussed the extent of the current issues in the long run. Currently the sustainable office buildings have less embodied emissions for heating and less operational emissions for heating consumption than the conventional. On the other hand the scenarios demonstrate that the sustainable office buildings have higher embodied emissions for cooling and higher operational emissions for cooling consumption than the conventional office buildings. Potentially the existing situation could increase thus, considering the long run situation in an attempt to avoid worse case scenarios is highly important.

The sensitivity analysis in this chapter shows that 1 KWh of energy consumption for heating has no emissions from the renewable and low emissions from the cogenerations that burn biofuels instead of natural gas. This evaluation can be used to support decision making for future changes in case study buildings or for new office building development.

The major research findings have shown that the environmental impact consequences of the extreme use of copper and of other metals in the whole heating systems depend mainly on building characteristics, external climate conditions, operational building standards and occupancy rate, which then influences the heating demands. This therefore influences the amount of heating or cooling equipment needed in the buildings as well as the size of the equipment and the life span. The sustainable office buildings are good practices for environmental performance of heating although further improvements are still needed. In terms of the cooling consumption, actions must be taken to improve energy efficiency (recommended in chapter 8). Table 7.4 presents a summary of the outcomes from the LCA comparison evaluation and table 54 presents a summary of the OLRLCII outcome.

Table 7.4: LCA comparison oucome

LCA comparison outcome
Operation phase-Heating-energy consumption sustainable office building **<** to the conventional office building
Operation phase-Cooling-energy consumption and refrigerant sustainable office building **>** to the conventional office building
Production phase-raw-materials of heating sustainable office building **<**to the conventional office building
Production phase-raw-materials of cooling sustainable office building **>**to the conventional office building
Overall sustainable office building **<**to the conventional office building in heating sustainable office building **>**to the conventional office building in cooling

Table 7.5 OLRLCII outcome

OLRLCII Outcome	
OLRLCII for Energy efficiency-Winter months	
Case study 1	Technology on the sustainable office building **>** to the conventional office building
Case Study 2	Technology on the sustainable office building **>** to the conventional office building
OLRLCII for Energy efficiency-Summer months	
Case study 1	Technology on the sustainable office building**<** to the conventional office building
Case study 2	Technology on the sustainable office building **>** to the conventional office building
OLRLCII for Material efficiency-Heating system	
Case study 1	Technology on the sustainable office building**>** to the conventional office building
Case study 2	Technology on the sustainable office building**<** to the conventional office building
OLRLCII for Material efficiency-Cooling system	
Case study 1	Technology on the sustainable office building **>** to the conventional office building
Case study 2	Technology on the sustainable office building **>** to the conventional office building
OLRLCII Overall	
Case study 1	Sustainable office building **<** to the conventional office building
Case study 2	Sustainable office building **>** to the conventional office building
Better Practice	Case study 2**>**Case Study 1

Tables 7.6-7.9 summarise the LCA single score results from the comparison evaluation. These tables will be used as a reference for the discussion chapter.

Table 7.629: Single score heating system, case study 1

ENVIRONMENTAL IMPACT CATEGORIES FROM Eco-Indicatpr99		SINGLE INDICATOR SCORE (in kPt)				NORMALISATION VALUE				CHARACTERISATION (in %)			
		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building	
Heating Systems	**Units**	mPt	kPt	mPt	kPt	n/a	n/a	n/a	n/a	%	%	%	%
	Raw-materials (R.M), energy (E) and refrigerant (R)	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R
	Carcinogens	-		0.0501	-	167	-		-	100	100	15.2	8.74
	Respiratory Organics	-		-	-	-	-		-	100	100	65.5	1.49
	Respiratory Inorganics	1.18	113.56	0.813	-	2.71E3	36.7	3.94E3	1.08	68.7	100	100	2.93
	Climate Change	0.0655		0.113	0.802	376	11.9	218	2.67	100	100	58	22.5
	Radiation	-		-	-	-	-		-	100	-	3.61	100
	Ozone Layer	-		-	-	-	-		-	100	5.66	29.1	100
	Ecotoxicity	-		0.0826	-	207	-	92.2	-	100	100	44.6	64.2
	Acidification/Eutropichation	0.105	2.09	0.0703	-	176	5.22	263	-	66.8	100	100	3.08
	Land Use	0.119		0.0791	-	198	-	297	-	66.6	-	100	100
	Minerals	2.06		1.21	-	4.02E3	-	6.87E3	-	58.5	-	100	100
	Fossil Fuels	0.796	62.2	0.854	16.6	2.83E3	2.07	2.65E3	55.2	100	100	93.2	26.6

Table 7.730: Single score cooling system, case study 1

: ENVIRONMENTAL IMPACT CATEGORIES FROM Eco-Indicatpr99		SINGLE INDICATOR SCORE (in kPt)				NORMALISATION VALUE				CHARACTERISATION (in %)			
		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building	
Cooling Systems	Units	kPt	kPt	kPt	kPt	n/a	n/a	n/a	n/a	%	%	%	%
	Raw-materials (R.M), energy (E) and refrigerant (R)	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R
	Carcinogens	-	-	0.114	0.0109	-	-	0.379	0.422	5.09	0.683	100	100
	Respiratory Organics	-	-	-	-	-	-	-	-	12.7	0.673	100	100
	Respiratory Inorganics	0.261	0.0128	2.58	0.0905	0.872	-	8.59	2.55	10.1	1.67	100	100
	Climate Change	-	0.0138	0.29	0.102	-	-	0.967	2.86	9.02	1.61	100	100
	Radiation	-	-	-	-	-	-	-	-	1.41	100	100	100
	Ozone Layer	-	0.00943	-	0.0366	-	-	-	-	3.73	25.4	100	100
	Ecotoxicity	-	-	0.908	0.0226	0.332	-	2.27	0.83	1.79	100	100	100
	Acidification/Eutropichation	-	-	-	-	0.202	-	0.506	-	11.4	1.36	100	100
	Land Use	-	-	0.236	-	-	-	0.59	-	14.9	100	100	100
	Minerals	0.837	-	8.75	0.0315	2.79	-	29.2	1.58	9.57	100	100	100
	Fossil Fuels	0.235	0.0278	2.6	1.02	0.783	-	8.67	49.7	9.03	100	100	100

Table 7.831: Single score heating system, case study 2

ENVIRONMENTAL IMPACT CATEGORIES FROM Eco-Indicatpr99		SINGLE INDICATOR SCORE (in kPt)				NORMALISATION VALUE				CHARACTERISATION (in %)			
		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building	
Heating Systems	**Units**	kPt	kPt	kPt	kPt	n/a	n/a	n/a	n/a	%	%	%	%
	Raw-materials (R.M), energy (E) and refrigerant (R)	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R
	Carcinogens	0.153	-	0.0755	-	0.511	-	0.252	-	100	100	49.2	14.9
	Respiratory Organics	-	-	-	-	-	-	-	-	100	100	92.2	7.57
	Respiratory Inorganics	3.46	2.08	0.701	-	11.5	6.93	2.34	-	100	100	20.2	9.92
	Climate Change	0.256	5.29	-	-	0.854	17.6	0.356	-	100	100	41.7	7.64
	Radiation	-	-	0.107	-	-	-	-	-	68.7	100	100	22.1
	Ozone Layer	-	-	-	-	-	-	-	-	16.3	100	100	7.53
	Ecotoxicity	0.238	-	0.111	-	0.596	-	0.277	-	100	100	46.5	13.4
	Acidification/Eutropichation	0.257	-	0.0725	-	0.643	-	0.181	-	100	100	28.2	10
	Land Use	0.27	-	0.0828	-	0.674	-	0.207	-	100	100	30.7	7.88
	Minerals	4.34	-	2.77	-	14.5	-	9.24	-	100	100	63.9	12.3
	Fossil Fuels	2.19	108	1.11	8.12	7.29	360	3.69	27.1	100	100	50.5	7.51

Table 7.9: Single score cooling system, case study 2

ENVIRONMENTAL IMPACT CATEGORIES FROM Eco-Indicatpr99		SINGLE INDICATOR SCORE (in kPt)				NORMALISATION VALUE				CHARACTERISATION (in %)			
		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building		Conventional office building		Sustainable claimed office building	
Cooling Systems	Units	kPt	kPt	kPt	kPt	n/a	n/a	n/a	n/a	%	%	%	%
	Raw-materials (R.M), energy (E) and refrigerant (R)	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R	R.M	E,R
	Carcinogens	-	-	-	-	-	-	-	-	7.16	-	100	-
	Respiratory Organics	-	-	-	-	-	-	-	-	10.4	-	100	-
	Respiratory Inorganics	-	-	5.97	-	0.189	-	19.9	-	0.952	-	100	-
	Climate Change	-	-	0.342	-	-	-	1.14	-	2.24	-	100	-
	Radiation	-	-	-	-	-	-	-	-	90.2	-	100	-
	Ozone Layer	-	-	-	-	-	-	-	-	0.732	-	100	-
	Ecotoxicity	-	-	-	-	-	-	0.19	-	3.88	-	100	-
	Acidification/Eutropichation	-	-	0.528	-	-	-	1.32	-	1.76	-	100	-
	Land Use	-	-	0.599	-	-	-	1.5	-	0.668	-	100	-
	Minerals	-	-	10.1	-	-	-	33.8	-		-	100	-
	Fossil Fuels	-	-	4.07	-	0.236	-	13.6	-	1.74	-	100	-

7.10 Summary

In this chapter the environmental impacts of the heating and cooling systems on office buildings have been evaluated using Life Cycle Assessment. Interesting research outcomes demonstrate that sustainable office buildings are more energy efficient with fewer impacts in terms of heating compared to conventional office buildings. However, as the conventional offices are naturally ventilated, the opposite is true in terms of the cooling system. Interestingly, the hypothetical long run scenarios show that energy efficiency of sustainable office buildings still needs improvements and, if this does not happen, it is possible that within the next 50- 100 years, as systems age and are not operated and managed effectively, efficiency could decrease and reach the level of a best practice conventional office building. In parallel, in case of replacement and new technologies being added to the systems, this could potentially increase the embodied raw material emissions. Therefore, the development of the new long run sustainability indicator can play a significant role in studying in parallel these two particularly important indicators.

CHAPTER 8: NEW SUSTAINABILITY INDICATOR

8.1 Introduction

The previous empirical chapters focused on addressing the performance gap related to building design and energy performance by exploring five key dimensions: 1) case study sustainable and conventional building characteristics (presented in a MATRIX table), 2) the key influential parameters and factors of energy efficiency related to heating and cooling, 3) the energy consumption considering local temperatures and the building fabric thermal performance, 4) the environmental impacts caused by the building-energy performance gap, using LCA 'gate-to-gate' to assess the energy and raw-materials of the heating and cooling systems, 5) the long run hypothetical consequences of the LCA results, by developing hypothetical long run scenarios. The above dimensions set up the basis and the requirements for developing a new sustainability indicator that through its application from an early or later phase of an office building project, can bridge the environmental performance gap between building design and energy and its impact on the increase of the embodied raw-material emissions. This chapter suggests that this can be enhanced by developing a new indicator for the raw-materials, by exploring and developing further the energy indicator, by assessing in parallel the relationship of the two indicators and through the integration of the new sustainability indicator into the existing SAMs.

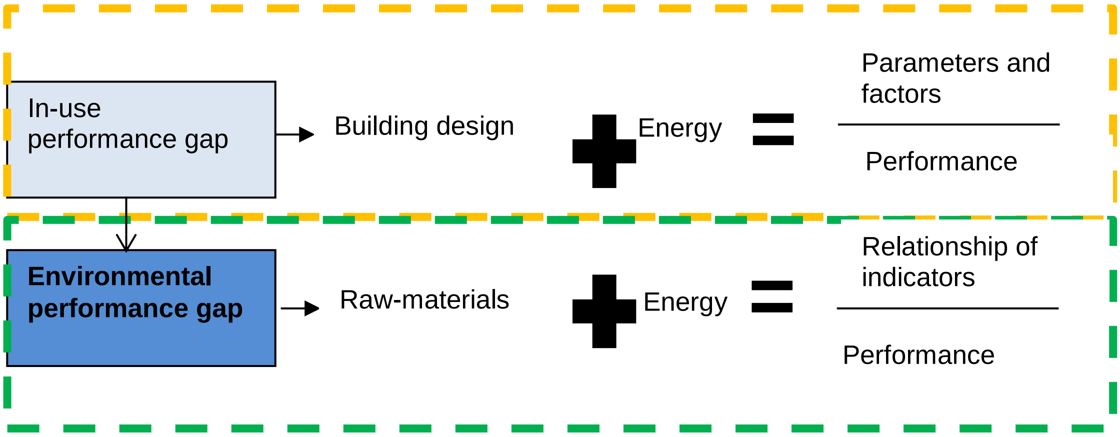


Figure 8.1: The new sustainability indicator's intention in bridging the in-use performance gap in parallel to the environmental performance gap

8.2 Background of the New Sustainability Indicator

The need for the development of a new sustainability indicator has been derived by exploring the above research dimensions.

1) Case study sustainable and conventional building characteristics (presented in a MATRIX table)

The purpose of this exploration was to find out the key differences between sustainable and conventional office buildings in an attempt to understand which characteristics define an office building as sustainable. The result of this analysis was the creation of a MATRIX table that lists all the building characteristics. This allows cross-case comparisons and identifications of sustainable features that could be considered in other office building projects, new or refurbished. This data helped to understand the background context of the energy and raw-material environmental performance. From this study it has been realized that sustainable office buildings have advanced technologies that require large space and are large in size. It is interesting to note that even though sustainable office buildings have been designed in such a way so that mechanical heating and cooling can be operated less, the amount of heating and cooling technologies used within the systems is higher compared to the conventional office buildings. This kind of data is useful to understand the role of building design in increasing energy efficiency but on the other hand in increasing the amount of raw-material used to produce these energy efficient technologies. The new sustainability indicators through this dimension, can assist decision making from the early stages of an office building project, in considering the pros and cons that the building design can have on the heating and cooling systems building requirements and how that could improve the overall environmental performance through sustainable decisions. This could happen by developing a MATRIX table with characteristics from different case study buildings.

2) The key influential parameters and factors of the environmental performance, related to heating and cooling

Through the exploration of the office building characteristics a list of factors and parameters have been unfolded that influence the environmental performance of the office buildings (energy and raw-material environmental impacts). The building design is the most significant influential factor that could play a significant role for reducing energy and embodied raw-material emissions. The key building design influential parameters unfolded are building orientation, volume of indoor office spaces, window surfaces, double-glazing, exposed thermal mass, different façade design according to surroundings (glare and shadowing), U-values and insulation. For instance a large volume of office space has higher demands for heating and cooling, which means that it takes more time to heat up or cool the space, therefore more fuel and electricity consumption. Considering the heating and cooling system consumption of the sustainable office buildings, it appears that energy efficiency has been enhanced due to the building design and the types of heating and cooling systems used, the management and the operation. However it seems that the building design factor needs to be further explored to maximise its potential for less mechanical systems operation. Other influential factors unfolded have to do with maximizing the energy efficiency of the heating and cooling system types and reducing the energy consumption by changing operational and technical parameters, such as reducing the set temperature in the indoor office space by at least 1 degree, close to 20 or 21 degree celsius. This can be enhanced with efficient use of the building while the heating is on, such as closed windows when the heating is on. Another parameter is the on-switch off out of office hours. For instance the CHP unit of the Potterrow building is on during the weekends and evenings after working hours. The new sustainability indicator allows these parameters to be identified and prioritized in order to take energy reduction actions.

3) The energy consumption considering local temperatures and the building fabric thermal performance

The triangulation of the research findings from the POE surveys demonstrated that the building design is the most important influential factor. The thermogarphic survey revealed excessive heat losses from the conventional office building fabrics and some heat losses in parts of the sustainable office buildings, mainly due to missing insulation or improper sealing of window components. The HHD evaluation revealed that the management and operation of the heating systems according to the set temperature and in correlation to the outdoor set local temperatures (degree days) is also important in order to reduce heating or cooling consumption. The need to explore further the energy indicator through a new sustainability indicator is highly important. This study has used current state of the art POE methods, although it is suggested that more energy performance evaluation methods can be added under this dimension. Another significant area for exploration is the occupancy behavior aspect. This has been excluded from this study as explained in the study limitations (chapter 4).

4) The environmental impacts caused by the building-energy performance gap, using LCA ‘gate-to-gate’ to assess the energy and raw-materials of the heating and cooling systems

The application of the LCA in assessing the energy and raw-material environmental impacts of heating and cooling systems has been a highly significant method. In terms of the energy indicator, by exploring the previous dimensions, it was expected to find that in terms of heating, the sustainable office buildings have about half the impact of the conventional office buildings. Surprisingly, in terms of the cooling consumption the sustainable office buildings have more impacts than the conventional office buildings. In terms of the raw-material indicator, the results showed unexpectedly that the sustainable office buildings have overall higher embodied environmental impacts than the conventional. The key message from these findings is that while heating and cooling efficiency increases the embodied emissions of raw-materials increase. This happens due to the amount of heating and cooling equipment used, their size, the material used, and their properties. An improved and more sustainable building design could potentially reflect improvements in the environmental performance of office buildings. This means that the 'environment impact shifting' from out life cycle 'gate' to the other 'gate' can be overcome. This is where the new sustainability indicator is important.

The new indicator is also important in order to overcome some fundamental limitations in data collection and analysis. For instance the SimaPro (the LCA software) has been helpful in providing lists of materials (like alloys) that can be selected and quantified to evaluate the raw-material emissions, although this list is not exhausted and not all the metal types are included. As material specification on heating and cooling systems does not exist it is very difficult to know the exact type of metal used. A structured LCA questionnaire survey sent out to manufacturers was not completed as it requested time and information that was not available at first hand. The importance of evaluating the raw-material of such technologies has not been sufficiently considered, as someone might argue that most steels are recycled. The recyclability content and the impacts caused through different life cycle processes can only be known to a better extent through life cycle assessment. For this indicator to be considered, there is a need for more studies in this area to show its impact and significance on a greater scale. This study suggests the development and integration of this indicator in current SAMs which could be applied through the new sustainability indicator (explained in detail in the following sections).

5) The long run hypothetical consequences of the LCA results, by developing hypothetical long run scenarios

The exploration of this dimension highlights the importance of thinking proactively in terms ofthe long run consequences of the existing environmental performance, as found from the POE and LCA. This helps in avoiding scenarios where energy and raw-material emissions can increase and in thinking what changes are needed to ensure long term sustainability. This can also be used in feasibility studies to include life cycle costing. The new sustainability indicator known as Overall Long Run Life Cycle Impact

Indicator, introduces the development of hypothetical long run scenarios from an early to a later stage of an office building project (before built, during operation, before refurbishment).

8.3 Aim and Objectives of the OLRLCII

The aim of the new indicator is to bridge the gap between building design and in-use performance and its impact on the environmental performance, through a long run life cycle and proactive approach. Through this indicator, the office building benchmarking could improve (identify best practice) and the BREEAM assessment could be upgraded; a conventional office building can become BREEAM excellent and perform better than current BREEAM offices. The long run hypothetical scenarios help to avoid worst case scenarios and to consider potential change for better energy efficiency and material efficiency. How this can be achieved is explained in the following sections. Further, the objectives of the new indicator are:

1. Reassess and upgrade existing BREEAM office buildings.
2. Evaluate existing environmental performance of conventional office buildings.
3. Consider the renovation of a conventional office building to a BREEAM excellent office.
4. Consider whether in the long run raw-material efficiency and energy efficiency will remain efficient.
5. Bring together a way of addressing holistically environmental impacts of building services from cradle to grave, building performance and building design-construction.
6. Develop an assessment tool that can be used by other practitioners in order to evaluate the existing and long run environmental performance of their building projects. Show how to interpret and adapt this indicator to the specific needs of individual projects is an integral part for approach to design.

8.4 Development of the OLRLCII

The development process of the new indicator has been derived throughout the exploration of the five key dimensions mentioned. The stages and the methods used are shown in the flow diagram of the research model presented in chapter 4. The LCA application. which is the most important method to evaluate the environmental performance of the office buildings, has been conducted through three types of analysis:

a) LCA individual office building analysis

Evaluation of the environmental impacts of the sustainable office buildings and of the existing conventional office buildings

b) **LCA case study ccomparison analysis**

Explanations about to what extent sustainable office buildings are better than conventional.

c) **Long run hypothetical scenario evaluation**

The long run hypothetical scenarios considered two aspects:

- the energy efficiency (seasonal)
- the material efficiency

These three types of analysis are suggested as mandatory evaluations for the new indicator. The thesis suggests that the LCA sensitivity analysis is also important for the development of the indicator in order to evaluate alternative hypothetical options (low/zero carbon technologies) and to provide recommendations. It can be used as an optional evaluation method. The uncertainty analysis is also recommended as an optional evaluation method to ensure that uncertainties will have a small impact on the results. The types of analysis and the methods used are presented in figures 8.2, 8.3.

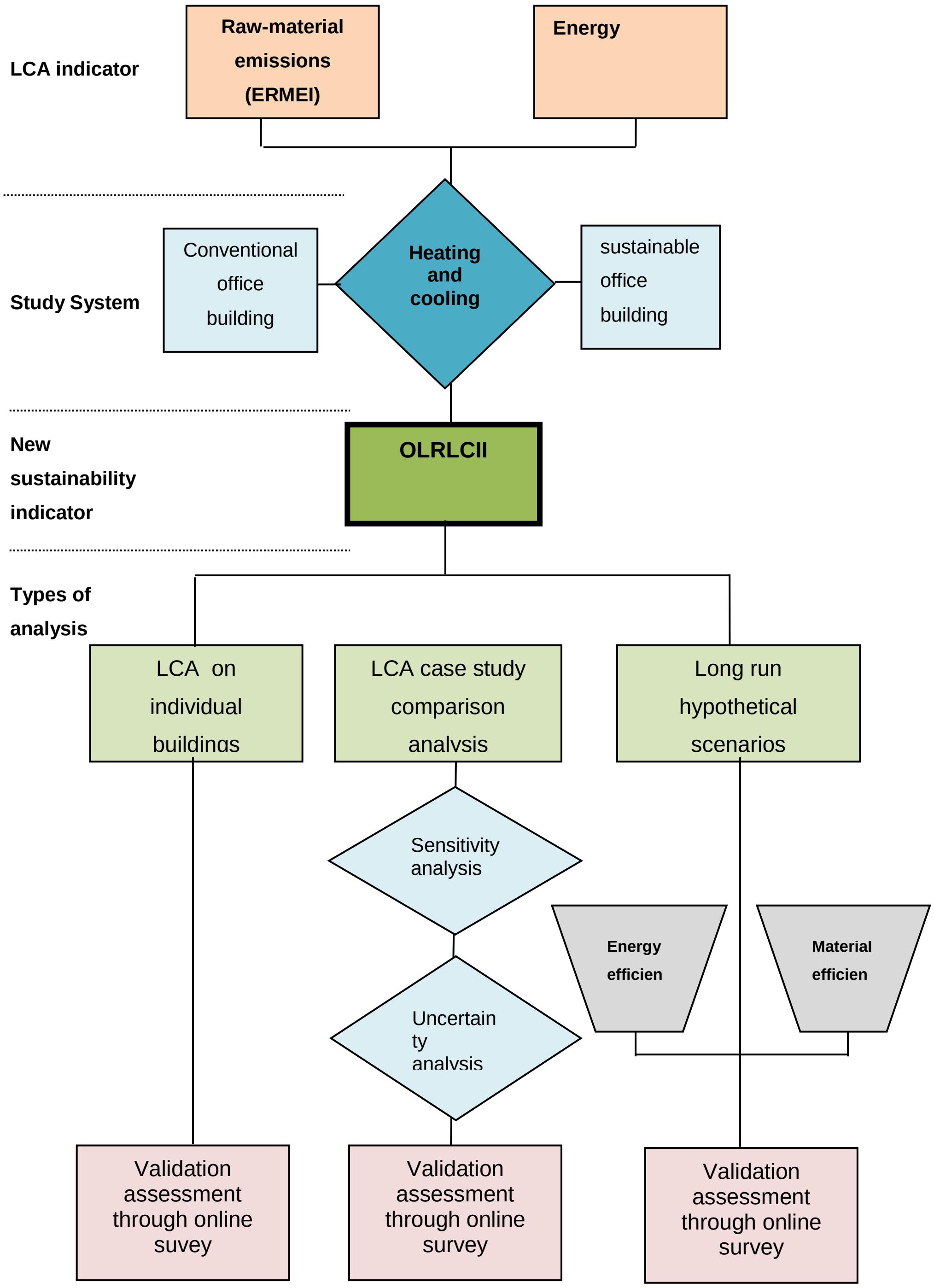


Figure 8.244: OLRLCII diagram

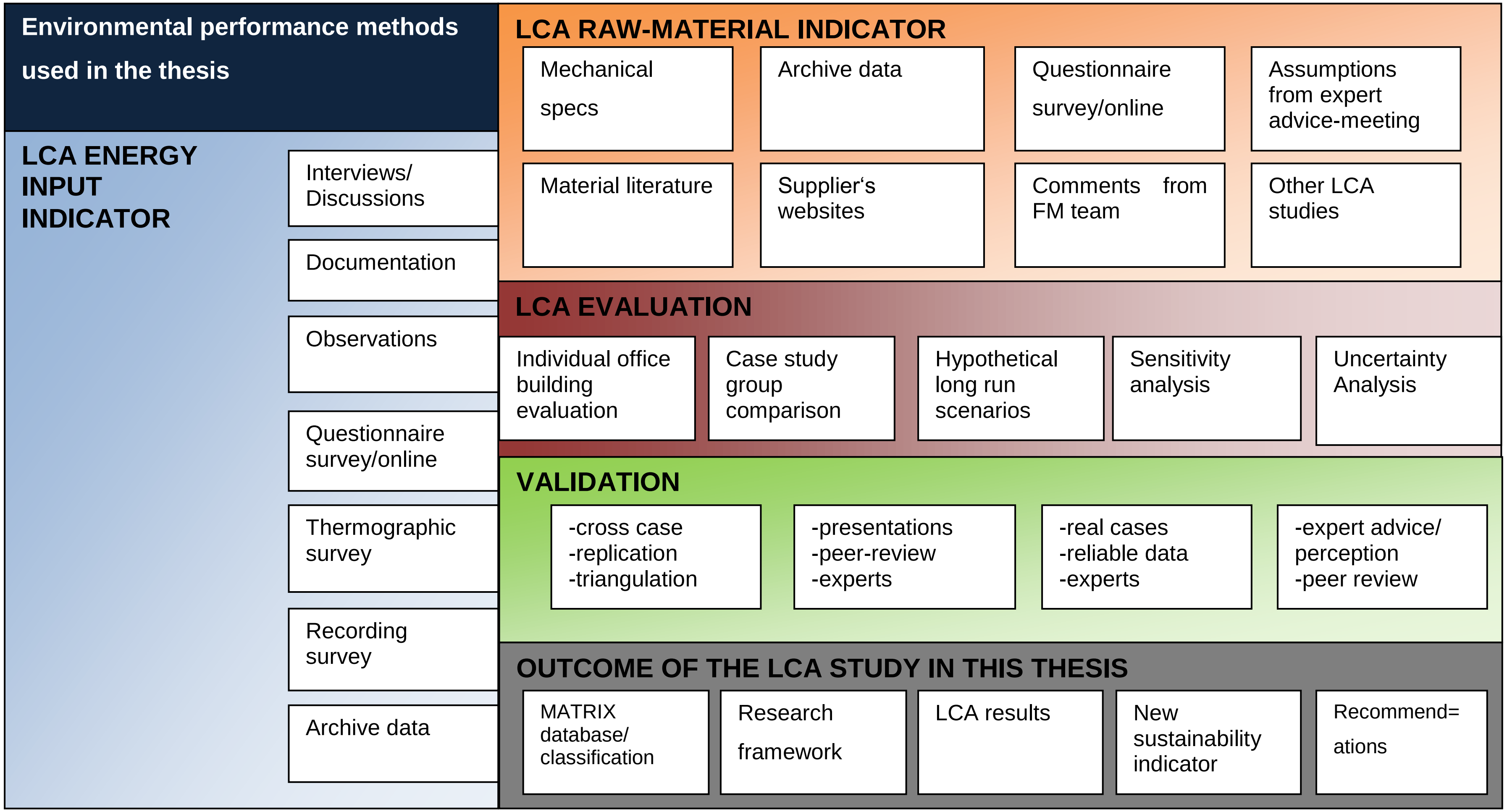


Figure 8.345: Environmental performance methods used in the thesis

8.5 New embodied raw-materials emissions indicator (EMRMEI)

The development of the new OLRLCII requires the inclusion of two indicators, the raw-materials and the energy. Energy has been a worldwide sustainability indicator and in the built environment in the UK, is evaluated by BREEAM. Currently the BREEAM assessment includes nine categories from which energy and the refrigerant pollution are included as separate categories. Each of these categories consists of a list of issues (section 2.7.1). The thesis has also assessed the embodied raw-material emissions of the heating and cooling systems. However this issue is not included as a category in the existing BREEAM assessment. Therefore the thesis suggests that the development of a new indicator is needed to determine this issue. The research work carried out indicates clearly that the new indicator is required to bridge the gap between the design and the operation of new sustainable buildings, of refurbished and of existing conventional buildings. The new indicator is called Embodied Raw-Material Emissions Indicator (ERMEI) and can be used as a separate indicator or under the OLRLCII. This indicator aims to support environmental decision making on eco-efficient building design and selection of eco-efficient heating/cooling equipment.

8.5.1 Background to the indicator

The need for the development of the ERMEI indicator comes out from various LCA studies reviewed in the literature review. The LCA study by Prek (2004) concludes that different heating systems with different construction materials vary the Eco-indicator value. He has also concluded that the Eco-indicator 95 LCIA method, enables environmentally aware design and it is an open working method with a platform on which both industry and science can integrate the environmental aspects into the design process (Prek 2004a p.1027). He also mentioned that the result permits the user to see how much environmental impact design alternatives will have. and the designer may analyse the consequences of an idea effectively and establish clear selection criteria (Prek 2004a p.1027). The thesis questions the way the research findings are discussed. They cannot support decision making clearly. The issues discussed are vague sentences rather than concrete statements of what the issue is and where it originates. Thus the development of the ERMEI intends to provide a solid framework for addressing clearer embodied raw-material emissions in relation to building design and performance. The study of Prek (2004) also makes a case about the dominant impacts and the dominant equipment that contribute to the greatest environmental impact. This is important information to be used in the discussion of the OLRLCII.

Another LCA study by Shah et al (2008) on residential heating and cooling systems in four regions in the US compares the life cycle impacts of three residential heating and cooling systems over a 35 year study period. Simulations and the LCA determine the effect of regional variations in climate, energy mix and the standard building characteristics on the system's environmental impact. These are important influential parameters of heating and cooling system operation. Shah's study explains that cast iron, galvanised steel and copper used in boilers were the most significant impact contributors (figure 8.4). Significant material impacts associated with the air-conditioners were found to be steel, galvanised steel, copper and aluminium. This study has also revealed that high impacts are caused due to the manufacturing of the metals and the system infrastructure (Shah et al. 2007 p. 509).

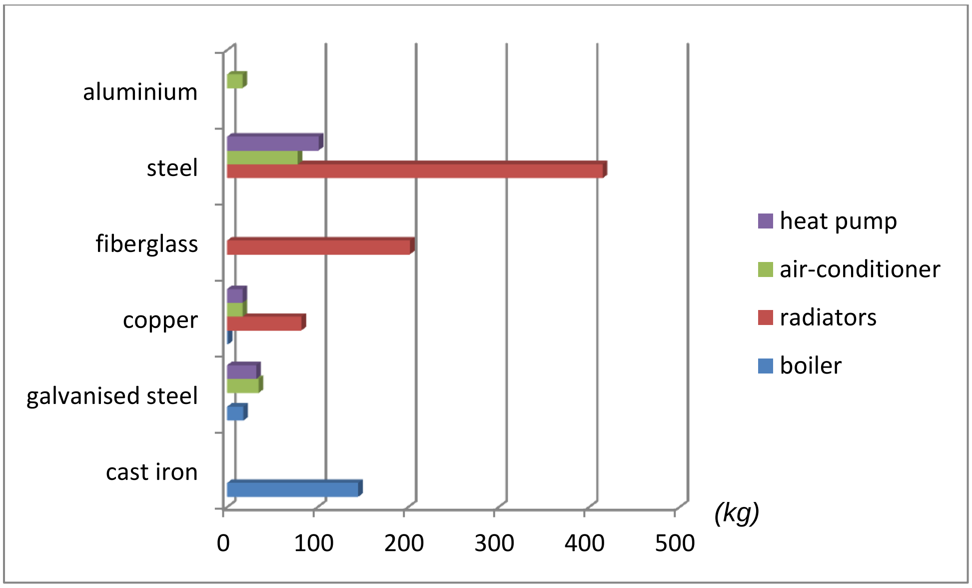


Figure 8.4: The dominant raw-material mass used in the production life cycle phase of heating and cooling systems in a hypothetical residential building.

Source: (Shah, Debella, & Ries 2007)

The study of Shah, Debela & Ries (2007) also shows that the manufacturing of metals is a highly significant environmental impact contributor that needs to be further addressed. Although certain equipment has not been replaced and maintained for 35 years, they can still have higher impacts than other replaced equipments, due to the manufacturing materials and processes. The argument here is that the research findings explained are not related clearly to the external and internal building parameters that influence regionally the raw-material emissions. The use of the proposed ERMEI can help to communicate and to address this issue more clearly.

An LCA study by Heikkila (2008) investigates air-conditioning systems which used a bore-hole heating and cooling. Her study focused on the operation and the production phase of the system. By comparing this system with a reference system that uses a more traditional source of heat (district heating in Sweden) and cooling energy (refrigeration), she has found the bore-hole system performs better in three impact categories; in acidification, in eutrophication and in global warming potential. This happens due to the fact that it uses less material in the production phase. She has concluded that metals such as steel, stainless steel and copper used in the production phase are responsible for the largest impact.

She suggests that the impacts of the production phase can be reduced significantly in the disposal stage by recycling as much as possible all metals and by energy recovery from plastic materials. However the thesis argues that information about the study system and which input indicators were assessed is not provided. The study mentioned the life cycle phases and the production phase as a parameter. The thesis suggests that the ERMEI is the indicator that should be used in LCA studies that assess the production phase, in order to differentiate the environmental impacts from the operational life cycle phase. The ERMEI indicator has used the word ‘embodied’ to make clear that the impacts embedded in the system are from the previous extraction and manufacturing life cycle phases. The embodied raw-material emission is what has actually been assessed in this study.

8.5.2 Integration of the ERMEI in the environmental consultation and in the BREEAM assessment

The development of the ERMEI is important to inform and to support environmental decision making for low embodied raw-material emissions related to buildings services on buildings. For the ERMEI to be applied, the thesis suggests its integration as an:

1. **individual LCA input indicator in the OLRLCII**

   For this to happen, it is suggested that the OLRLCII be integrated in the BREEAM assessment (explained in detail in section 10.5).
2. **Additional issue category in the existing BREEAM assessment**

   This integration will help to push forward embodied raw-material reductions; with this integration from the early stages before the building design stage, considerations can be taken for choosing low embodied emission building services. This decision will further assist the environmental design of the buildings (how this integration can work is shown in section 10.4.3)
3. **A separate assessment indicator toolkit for building services**

   This indicator can also be used to support environmental decision making by different stakeholders.

For the ERMEI to be used as an additional issue category in the existing BREEAM assessment, the current BREEAM assessment final report of the sustainable case study office buildings (Elizabeth Courts II and Potterrow building) have been reviewed (appendix 11). Currently the existing BREEAM assessment for office buildings includes nine issue categories. Each category includes a list of issues upon which the achievement of the buildings is weighted and scored (table 52).

8.5.3 Integration of the ERMEI in BREEAM assessment, in Eco-labelling and in existing energy efficiency rating EPCs.

The thesis proposes that the assessment of the ERMEI can take the form of:

1. **Eco-label13**

This suggestion has been evaluated in the online questionnaire survey. The participants of the survey have commented that:

- Competition will enhance eco-efficiency although it might cause confusion in the market if the industrial sector will have to meet standard criteria-targets.
- The introduction of such labeling will encourage more industries to compete with regards to the ecological impact of their products, driving a more ecologically conscious market place.
- Any additional information which assists the designer or specifies choice of a product will be beneficial.
- Comparison will encourage the industrial market to take seriously the eco-indicator for marketing purposes.
- Good but ambitious.

The information provided on the ecolable will have to be evaluated using a life cycle approach as with the EU Ecolabel suggested by the European Commission (European Commission 2013). Through this approach it can be guaranteed that the environmental impacts are reduced in comparison to similar products in the market.

The EU Ecolabel on a heat pump, for example, provides information that:

- The product has improved energy efficiency during heating and cooling modes.
- The product reduces or prevents the risks for the environment and for human health related to the use of hazardous substances.

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[13] The EU Ecolabel helps identify products and services that have a reduced environmental impact throughout their life cycle, from the extraction of raw material through to production, use and disposal. Recognised throughout Europe, EU Ecolabel is a voluntary label promoting environmental excellence which can be trusted (European Commission 2013).

- The product has a lower global warming impact.

2. BREEAM assessment integration

The thesis suggests that the ERMEI must be included after the material and waste category. The ERMEI new category will include the folowing:

- The content in the material specification
- The result of the environmental impact life cycle single score evaluation
- The recyclability material content
- The re-usability of the equipment and
- The life span given for the equipment

The proposed category weighting is proposed to have the same significant value as the materials and waste category: 7.5%. The ERMEI indicator could also replace the existing material category and waste could be a separate issue category. As the overall BREEAM should be 100%, it cannot be said which weighting issue is to be reduced from other categories, as the significance of these impacts have not been evaluated in this study. This study can only suggest the significant value for the raw-material embodied emissions.

The thesis suggests ways that ERMEI could be integrated in the BREEAM scheme but it is up to the decision making of the scheme to decide further on the method of the integration.

Table 8.1: Integration of the ERMEI in the existing BREEAM assessment categories

BREEAM existing categories		
Issue category	**Issue weighting %**	**Issues**
Management	12	Commissioning Considerate constructors Construction site impacts Building user guide Life cycle costing
Health and wellbeing	15	Daylighting View out Glare control High frequency lighting Internal and external lighting levels Lighting zones and controls Potential for natural ventilation Indoor air quality Volatile organic compounds Thermal comfort Thermal zoning Microbial contamination Acoustic performance Office space
Energy	19	Reduction of C02 emissions Sub-metering of substantial energy uses Sub metering of high energy load and tenancy areas External lighting Low or zero carbon technologies Building fabric performance & avoidance of air infiltration Cold storage Lifts Escalators & travelling walkways
Transport	8	Provision of public transport Proximity to amenities Cyclists facilities Pedestrian and cyclist safety Travel plan Maximum car parking capacity Travel information point Deliveries and manoeuvring
Energy and transport	6	
Water	12.5	Water consumption Water meter Major leak detection Sanitary supply shut-off Water recycling Irrigation systems Vehicle wash Sustainable on-site water treatment systems

BREEAM existing categories		
Materials & Waste	7.5	Materials specifications (major building elements) Hard landscaping and boundary protection Reuse of building facade Reuse of building structure Responsible sourcing of materials Insulation Desiging for robustness
		Construction site waste management Recycled aggregates Recyclable waste storage Compactor/Baler Composting Floor finishes
ERMEI	7.5 (proposed) is the available score to be achieved in the existing BREEAM assessment (appendix 10)	Material specifications (size, types, weight) Environmental impact life cycle single score Recyclability material content Re-usability of the equipment Life span
Land use and ecology	10	Reuse of land Contaminated land Ecological value of site AND Protection of ecological features Impact on site ecology Long term impact on biodiversity
Pollution	10	Refrigerant GWP-Building services Preventing refrigerant leaks Refrigerant GWP-Cold storage NOx emissions from heating sources Flood risks Minimising watercourse pollution Reduction of night time light pollution Noise attenuation

3. Material-Efficiency Rating

The thesis also suggests that the ERMEI evaluation could take the form of rating, as with the Energy Performance Certificate (EPC) (figure 8.5, see example of the full certificate in appendix 23). Material-efficiency ratings of the case study buildings are presented in section 10.7

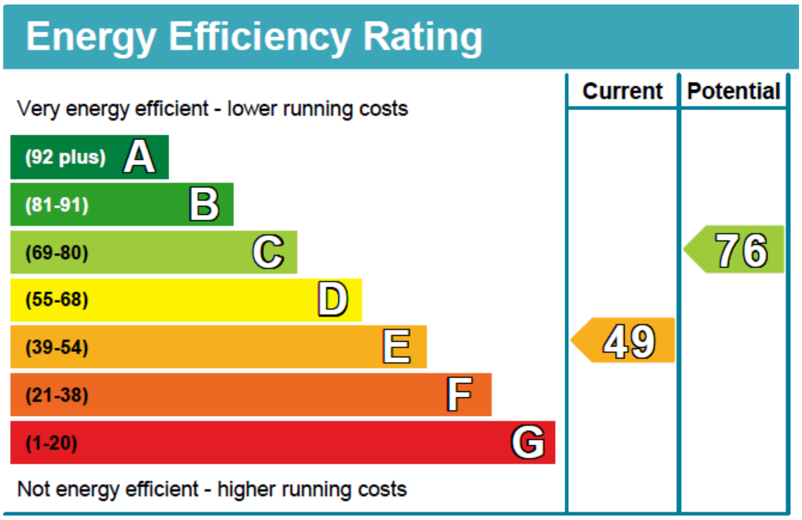

Figure 8.546: Example of an Energy Performance Certificate

Source: GOV.UK

8.5.4 ERMEI in practice

This section and the following sub-sections provide discussion on the practical applications of the ERMEI in this study and on what it has revealed. The results have shown significant environmental impact contributions associated with raw-materials from the production phase of the systems (chapter 9). There are a number of factors that influence this result. Through the empirical research and analysis (chapter 6, 7, 8, 9), this study demonstrates that the embodied raw-material emissions depend on several parameters, internal and external (related to local temperatures, building design and conventional-current heating-cooling technologies). These parameters are mainly concerns for the operational life cycle phase of the systems although they also influence the increase or decrease of the embodied raw-material emissions.

Determination of the raw-material environmental issue

At first it is important to explain what the results of the ERMEI evaluation mean. By looking at the summary results, different interrelations related to the environmental impact categories can be discussed. In the summary tables the single indicator scores can be compared between raw-material emissions and energy. So it can be seen that the life cycle phase is more responsible for causing higher environmental impacts. Initially it can be seen that the unit of the score is different; MPt (million eco-points) for raw-materials and kPt (killo eco-points) for the energy. This means that the raw-material emissions of the heating system, on Argyle House and on the Potterrow building, are higher than the energy emissions. In order to check why this is happening, it is necessary to look at the inventory data (chapter 9) which presents the weight of the raw-materials used in which equipment type, the number of each equipment installed in the heating-cooling system, in the building.

From the inventory data it can be seen that in the heating system of Argyle House there are 1892 perimeter radiators that increase the raw-material emissions, 2 large tanks, 2 large boilers and 3 overdoor heaters. Each of these pieces of equipment is made out of different raw-materials, mainly from metals. In the heating system of the Potterrow building (figure 251) 2 systems are included: inside of the building and outside of the building (the CHP). The CHP includes the 3 turbines and the 3 boilers which are large in size and heavy. Inside the building there are 522 radiators, 69 trench heaters, 3 over-door heaters and 4 underfloor heaters. From the Potterrow office building it can be seen that a mixture of different equipment types have been used to serve the sustainable office building with heating, different from the conventional office building. The number of radiators in the Potterrow building is about 1/3 less than the 1892 radiators used in Argyle House.

Similarly the heating system of the Five Ways House includes 1185 upgraded radiators, perimeter of the building, 3 large boilers, 1 feed and expansion tank and 15 pumps. The amount of the upgraded radiators and of the upgraded boilers, have increased the initial embodied raw-material emissions of the building. On the other hand the heating system of the EIIC (figure 266) has 434 radiators which are smaller in size compared to the Five Ways House. Therefore the EIIC uses about 1/3 of the radiators that the Five Ways House has installed. The heating system of the EIIC includes 2 boilers (smaller size compared to the Five Ways) and different types of heating equipments not used in the Five Ways, like 1 pressurisation unit, 2 heat exchangers, 1 underfloor heater and 1 overdoor heater.

An important area for consideration is therefore the amount of equipment used in office buildings to provide heating. It can be assumed that a reduction in the amount of the equipment and a reduction in the size of the equipment would lower the embodied raw-material emissions. But could this reduction influence the energy efficiency of the systems-building? The concerns start when considering the energy efficiency of the heating-cooling systems that must be enhanced. A well designed building helps in improving energy efficiency as seen from the LCA case study comparison analysis (chapter 8). f For certain systems like the CHP to be energy efficient the installation of other services such as trench system and underfloor heating is especially significant. Similarly the cooling system of the EIIC included supplementary back up air-conditioners for cooling (VRV/VRF technology). The additional equipment increases the embodied raw-material emissions but enhances energy efficiency and human comfort if needed and where needed.

The embodied raw-material emissions of the cooling systems of the sustainable office buildings are high due to the use of chillers which are large and heavy. The office spaces of the conventional office buildings are only naturally ventilated and air-conditioners are only used in the comms rooms. This tactic reduces the embodied raw-material emissions although cooling comfort of the occupants if needed is an issue. Therefore it could be said that energy efficiency causes raw-material emissions or that energy-efficiency overlaps material efficiency. In the online survey the importance between the two has been raised (appendix 21, question 10) and out of the 7 responses by experts in the field, 6 responses agree that both are very important.

Further, for energy-efficiency to be improved in the long run, in the next 25 and 50 years of operation of the sustainable buildings, it is assumed that the heating-cooling systems will be upgraded (as shown from the hypothetical scenarios developed, chapter 8). Consequently, if new emerging equipment will replace the existing (see the Five Ways House case), so that energy efficiency can be enhanced, that means additional overall embodied raw-material emissions. From the summarised results (tables 45-47), other interrelations that can be discussed are the comparison of the single indicator scores for the raw-material emissions of the heating and of the cooling system between the conventional and the sustainable office buildings. The most significant interrelations are presented in table 8.2:

Table 8.2: Interrelations that emerge from the ERMEI application

ERMEI interrelations	**Single indicator scores**	**Relations to the inventory data and fieldwork**
	Argyle House (AH), Potterrow building (PB), Raw-Materials (RM), Energy (E)	
Comparison between raw-material and energy, per heating system, per office building	AH-E>AH-RM in respiratory inorganics AH-E>AH-RM in acidification/eutrophication AH-E>AH-RM in fossil fuels PB-E>PB RM in climate change PB-E>PB RM in fossil fuels	***In relation to Energy***
		Heating operational hours, building thermal performance, energy efficiency, fuel consumption, occupancy, building envelope structure, building design (orientation, shape, floors, layout)
		In relation to raw-materials
		Long maintenance service lowers embodied emissions, reduced amount of the equipment and reduced size of the equipment
Comparison between raw-materials per heating system, per case study office buildings	AH-RM>PB in respiratory inorganics AH-E>PB in respiratory inorganics PB-RM>AH in climate change AH-RM>PB in acidification/eutrophication AH-RM>PB in land use AH-RM>PB in minerals AH-RM about the same with PB in fossil fuels AH-E>PB in fossil fuels	

By adding up the weight of each material type, per system, per office building, it can be seen that across the four office buildings the Potterrow building has the highest amount in aluminium, in copper and in stainless steel in its heating system. The amount of aluminium is higher compared to copper and stainless steel (figure 8.6). However the LCA results showed that copper has higher and more significant impacts than aluminium.

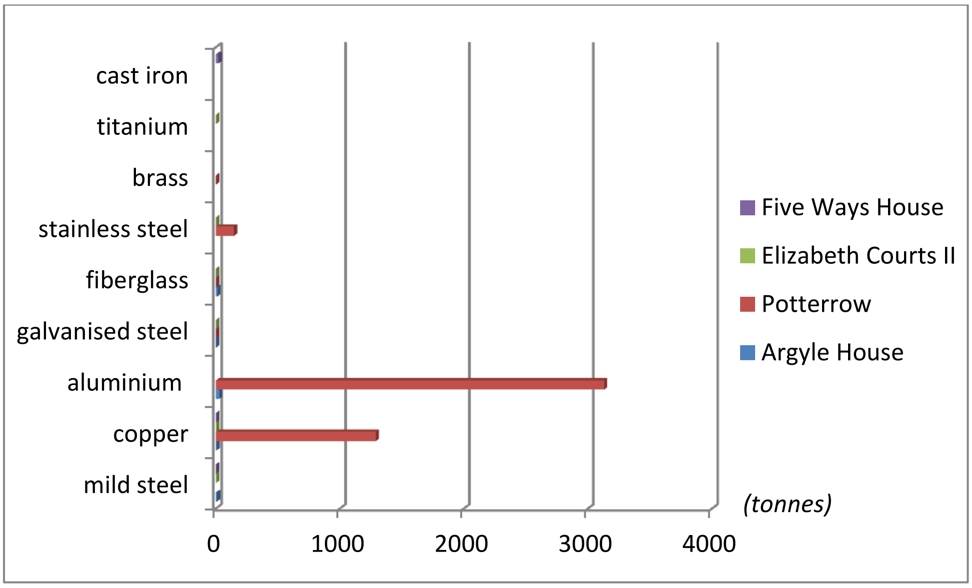

Figure 8.6: The dominant raw-material mass used in the production life cycle phase of the heating system across the case study office buildings.

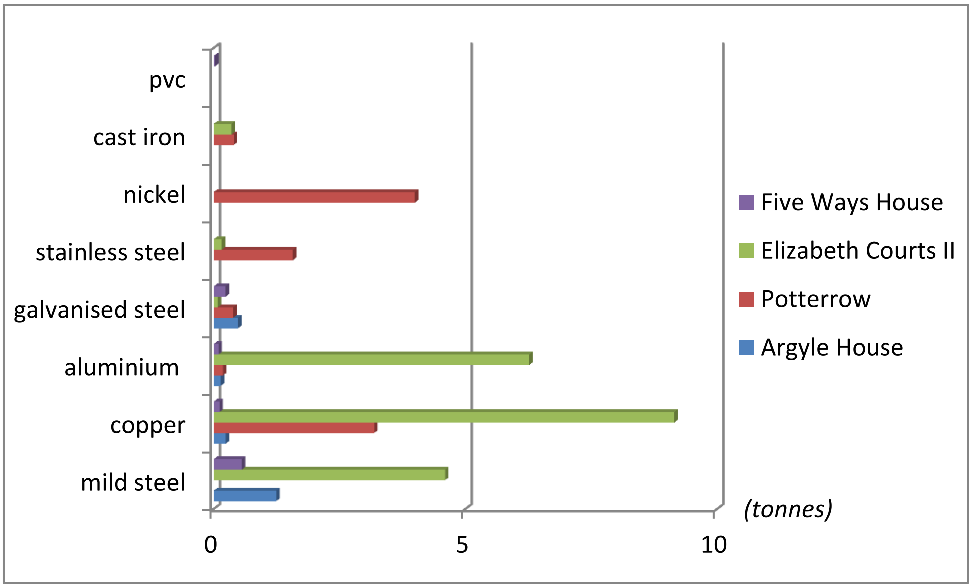

Figure 8.7: The dominant raw-material mass used in the production life cycle phase of the cooling system across the case study office buildings.

Figure 8.9 indicates that the cooling system of the EIIC has the highest amount of copper, aluminium and mild steel plate than all the office buildings. This affects the environmental impacts. The cooling system of the Potterrow building has the highest amount of nickel and stainless steel compared to the other buildings. It can also be seen that the cooling systems of the sustainable office buildings have higher raw-material contents compared to the conventional office buildings. This happens due to the fact that cooling in the office spaces of the conventional buildings is naturally ventilated. In the Potterrow building the high material content is related to the chillers connected to the CHP and to the air-conditioners installed in the comms rooms. In the EIIC the high material contents is related to the backup VRV cooling supply installed in the office spaces and also to the air conditioners installed in the comms rooms, and the chillers. This technology is energy efficient as it operated autonomously only when needed and in the room needed without the need for all the VRV cooling equipment to be on at the same time. This technology has helped to satisfy indoor temperature in the warm months as the building is located in the south of England. However this technology has increased the raw-material content.

In general, the increase of the embodied raw-material emissions depends on the engineering requirement in order for raw-materials to address the mechanical and technical needs of specific equipments; durability, corrosion, energy efficiency-fuel efficiency. For instance from the inventory data, it can be seen that mild steel is a common material for the energy-efficient boiler systems.

8.6 The role of office buildings ENERGY USE in reducing EMBODIED raw-material emissions

The research findings revealed that for energy efficiency to be enhanced in office buildings, at some point of the building life time, upgrade on the heating or cooling system or refurbishment of the whole building and replacement of old systems will be required. However, these measures can increase substantially the embodied raw-material emissions in the long run.

Argyle House, for instance, has low energy efficiency but lower embodied raw-material emissions, considering the full life span of the building, as the heating system has not changed since it was first installed. In Five Ways House there was an upgrade on the heating systems where old equipment was replaced. This has added embodied raw-material emissions to the first embodied raw-material emissions from the first installation.

A slightly different case is the refurbishment of Elizabeth Courts II and this is because the building has been through a whole building refurbishment. This kind of refurbishment extends the original building life span. This is actually the role of the refurbishment; otherwise it would have been a new building. All the old systems were removed from the building and new heating and cooling systems were installed. So in that case, it would make sense to say that the new systems installed add up raw-material emissions to the existing since the first installation of the former building in 1950. The argument here is that the refurbished building now performs differently as the building envelope is entirely new with new facades and with a natural ventilation system built on the roof with the ducts. The building now has double glazed windows, with lower glazing ratio, shading systems on the south, and insulation. Therefore it is as if the building starts operating from zero with an entirely new energy efficient heating-cooling system. In that case the embodied raw-material emissions should count since the new systems were installed in the refurbished building.

A sustainable office building that has to achieve high energy efficiencies with energy reductions over 70%, such as the EIIC and the Potterrow building, requires heating equipment that is mainly durable, well sealed, insulated and made from raw-materials that enhance energy efficiency. The dominant impact category of the heating consumption of the EIIC is in fossil fuels (8.12 kPt) which is about 13 times lower than the impact concentration in fossil fuels of the conventional office building in Birmingham. In order to better understand whether energy efficiency improvements had or are going to have an impact on the raw-material emissions of office buildings, it is important to discuss this further by explaining the relationship that:

> **If energy efficiency improves will that decrease (<) or increase embodied raw-material emissions (>).**

This is why the development of the OLRLCII and of the ERMEI is so important. Starting from the broader picture, the heating-cooling consumption depends mainly on the building characteristics. A well-passive-solar-designed building theoretically should have less need for mechanical heating and cooling supply therefore, less equipment and less raw-material content. The passive solar buildings have the attribute to be less prone to exterior temperatures and to retain the set indoor temperatures longer without the need for long operations of the mechanical heating and cooling. However the achievement of the energy efficiency targets depends also on other influential parameters and factors, as discussed in sections 5.6 and 6.6. How these parameters can influence embodied raw-material emissions is discussed as follows:

Energy efficiency and thermal-cooling performance of office buildings depends highly on the use of the buildings by the occupants and the facility management. The occupancy level and behaviour is a significant influential factor. The energy consumption depends on how the occupants feel-perceive indoor set temperatures in the office building. Some can feel at the same time cooler or warmer than others. Thus zone temperature control systems are important to serve different indoor thermal-cooling comforts in large office buildings. If such a system is not used this will certainly increase energy consumption and can also destroy the mechanical systems that need to operate on different modes during a day. For instance, imagine an air conditioner where occupants change temperatures a few times during a day making the system consume more so that the fans can have a higher speed. Improper use of the systems can not only increase energy consumption but also destroy a system and therefore a replacement will increase sooner than later the embodied raw-material emissions.

In these cases it is better if the heating and cooling system modes are only changed by the facility management office building services. The only interaction that the occupant should have with the system in an office building is in switching on/off the equipment, if the rooms where they work are enclosed spaces and not open plan spaces. For instance, in terms of cooling consumption, sustainable office buildings have higher impacts than conventional buildings due to the extra hours operational backup cooling supply out of office hours and also due to the way the system is used by the occupants. The occupancy satisfaction survey provided by the FM of the EIIC showed the occupancy satisfaction levels responsible for the energy consumption levels that are still not a great deal better from the existing good practice benchmark levels.

Some of the classic mistakes that the occupants make that influence to a great extent the indoor temperatures are leaving mechanical equipment on and leaving windows and doors open. This can be seen from the thermographic survey which has detected several windows open while heating was still on. This means that the occupants need to be better informed about the consequences of making these classic mistakes. Also the occupant must inform their FM team about issues that they might have with colleagues about the indoor temperatures in their office space. The consequences of the issues mentioned are increased operational cooling emissions compared to the conventional offices. This should not happen as the sustainable office building spaces were supposed to be naturally ventilated. Therefore, the dominant impacts of the cooling consumption on the sustainable new office building in fossil fuels were (1.02 kPt), in climate change (0.102 kPt) and in respiratory inorganic (0.0905 kPt) while the dominant impacts of the cooling consumption of Argyle House in fossil fuels were (0.0278 kPt). The dominant impacts of the Elizabeth Courts in fossil fuels were 469 Pt, in climate change (205 Pt), in respiratory inorganics (204 Pt) and in ozone layer (140 Pt) while the higher impacts of the Five Ways House in fossil fuels were (27.7 Pt).

Another important influential factor raised in chapter 6 was the control of the building services in term of temperature, operation and maintenance. According to the HDD evaluation it has been found that the heating consumption of the sustainable office buildings does not correlate with the exterior base temperatures. This means that heating operates above the heating degree base temperature. The current heating systems are usually operated according to the outside-inside sensors. So the heating or cooling must perform according to the set point parameters but in correlation with the heating or cooling base temperatures. The indoor office set temperature is usually set at 21^{0}C for summer and winter. This should change according to the outside base temperature. Depending on the climate, sufficient insulation keeps the indoor temperature higher than the outdoor temperature with little or no heating.

The facility management must ensure that all the equipment operates appropriately; with the proper amount of fuel, without mechanical faults, according to the indoor set temperatures and the external climate temperatures, in the appropriate building hours. The improper use of the heating-cooling system reduces the life span of the equipment. In the long run this could mean replacements with other equipment and therefore more embodied raw-material emissions. On the other hand, from the online survey, it has been suggested that short life spans of 15-20 years and replacements will enhance energy-efficiency anyway. However, what the case will actually be is not known.

From the fieldwork research it has also been discovered that energy efficiency is enhanced by the use of different types of equipment that vary in shape, in size, located on the floor, ceiling and on the walls and windows so that different heating or cooling demands in different areas-zones of the building are served autonomously.

The CHP technology installed outside of the Potterrow building, in order to be high energy efficient, must operate certain hours per year and on-off office hours. Further, in order for this type of technology to perform efficiently, the installation of the LTHW underfloor heating, the trench systems and the radiators are important. The associated dominant impacts of the heating consumption of the Potterrow building are in fossil fuels (16.6 kPt) with lower impacts in climate change (0.802 kPt), and in respiratory inorganics (0.323 kPt) (see table 48). The heating consumption contribution in fossil fuels is about 4 times less compared to the conventional office building. In the sustainable office buildings the amount and the size of the radiators have been reduced compared to the conventional office buildings, although their source of energy. such as the CHP boilers and chillers, are large in size and heavy which means high raw-material content. Here the need to achieve high energy efficiency increases the embodied raw-material emissions. This should not be the case. It would have been interesting if the amount of the equipment used compared to a conventional office buildings was less than the half.

The LCA research findings have shown that Argyle House has the lowest embodied raw-material emissions than all the buildings. The two oil-fired boilers exist in the building since the 1960s with frequent maintenance services, as with the rest of the heating equipment. In combination with the building fabric and the occupancy levels, the building is at risk due to its high energy costs for heating. In order for the 21^{0}C indoor temperature to be achieved, the boilers are on from 6am to 5pm weekly (see

MATRIX appendix 7) and they perform constantly to provide heating in the whole building, even in the large unoccupied areas. In this example the fact that the first heating equipment installed in the building has maintained until today, has not increased further the embodied raw-material emissions.

Long maintenance service is highly important to maintain existing-initial embodied raw-material emissions but it is not the only way and the best way. It is extremely important to maintain high energy efficiencies as well. From the online survey it has been revealed that energy efficiency should have short life spans, no more than 20-30 years of operation. Upgrades in the heating system or cooling are important for enhancing energy efficiency and for reduction energy consumption. As the systems get older, their efficiency drops.

The associated dominant environmental impacts of the heating consumption of Argyle House were in fossil fuels (62.2 kPt), with lower impacts in climate change (3.56 kPt), in respiratory inorganics (11 kPt) and in acidification-eurtophication (2.09 kPt) (see table 48). In comparison to the Potterrow building, the fossil fuel contribution is significantly higher. The dominant impacts of the heating consumption of Five Ways House are in fossil fuels (124 kPt), in climate change (6.41 kPt) and in respiratory inorganics (3.55 kPt) (table 50). This building had an upgrade in the heating system so that the energy efficiency and the heating consumption costs could be improved. However it still consumes high amounts of energy compared to the current refurbished office building EIIC. Even though the boilers are highly efficient (net 92% and calorific 83%), the building still consumes high amounts of energy for heating.

The high heating consumption has to do with the fact that the upgraded natural gas boilers are not condensing, which means that there are no heat exchangers and lower heat return temperatures become waste and rejected into the atmosphere. High heat losses from the building have been detected (see thermographic survey, chapter 7) due to its poor building fabric with single-glazed windows and no insulation on the construction walls, floors, roof, north orientation with large open-plan office spaces, all of which does not support energy efficiency of heating. So in this example energy-efficiency has not improved as it should have and the overall embodied raw-material emissions of the building have increased due to the heating system upgrade. The thesis argues that there is no point in investing in energy efficient technology that cannot be supported by its building context and which therefore increases raw-material emissions.

The conventional office spaces are natural ventilated without any back up mechanical cooling supply. In the conventional buildings air conditioners are installed in the comms rooms (meeting rooms) and they do not operate often. Only the air conditioners that are installed in the server rooms operate 24/hours/day. From the overall electricity of office buildings, electricity for cooling accounts for about 10%. In the online survey the participants have agreed that both energy efficiency and material efficiency are very important aspects to be considered, although energy efficiency is crucial in order for carbon reduction targets to be met. This thesis suggests that with the use of the ERMEI the research gap between different sectors and areas in the life cycle could be bridged for reducing raw-material emissions. Figure 8.8 presents the key areas that influence the embodied environmental load.

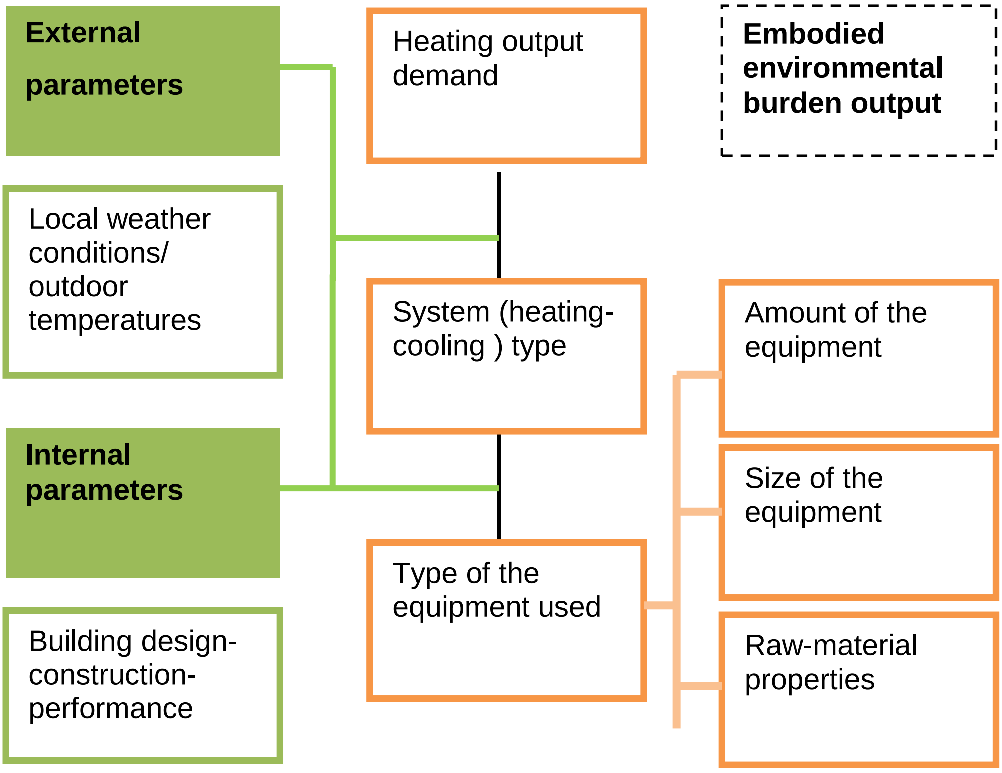

Figure 8.847: The embodied environmental load influences

8.7 Use of the OLRLCII and BREAM on the longevity of a sustainable building

In order for the OLRLCII to be applied, the thesis suggests its integration in the BREEAM assessment for office buildings and for other building types as:

- a new stage of assessment
- integrated in the Green Guide to Specifications[14]

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[14] The Green Guide to Specification assesses materials and components in terms of their environmental impacts, within comparable specifications, across their entire life cycles (BRE 2012). The Guide presents this information by a rating system, A+ to E (BRE 2012). These

Currently BREEAM has three stages of certification:

1. **Design and procurement**
   The sustainable case study office buildings in the thesis have been assessed in this stage (Elizabeth Courts II in 2006 and the Potterrow building in 2004).
2. **Post construction**
3. **Operation**
   This stage is currently under development (since 2012) (BRE 2013b)

The thesis proposes an additional stage that can be called Long Run stage. The long run stage could be used before the design and the procurement stage, so that long run considerations are taken well in advance in the conceptualisation. It could also be applied during the operation stage of the building to evaluate existing issues in the long run. This will provide feedback for appropriate actions in order for worst case scenarios to be avoided. The operation stage could also be followed or replaced by another stage that could be called Post-Occupancy stage, as the evaluation taking place after a building has been fully occupied and operated involved post-occupancy evaluation methods.

No matter in which stage the OLRLCII will be used, the form of the assessment is suggested to be developed according to the existing Design & Procurement stage (appendix 11), as shown in table 8.3.

Table 8.3: Proposed OLRLCII assessment rating

INPUT CATEGORY	**LIST OF EXISTING ISSUES**	**% WEIGHTING**		**SOLUTION**	**POTENTIAL**	**TO BE RE-ASSESSED**
		Credits acheived	Credits available	For immediate low cost action	Action to be considered for the long run	Given the UK target and the year to be re-assessed
ERMEI	Impacts of the system					
ENERGY	Impacts of the system					
(it can be extended with further issue categories)	-	-	-	-	-	-

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environmental ratings are based on life cycle assessment (LCA), using BRE Global's Environmental Profiles Methodology (BRE 2012). These are generic ratings that illustrate a range of typical materials (BRE 2012).

Further to the way of applying the new sustainability indicator, the thesis has also looked at the possibility of having a new Green Guide to Specification for building services that can be used to inform and to support decision making regarding environmental credentials of the materials used in the building services. As in the Green Guide to Specifications for buildings materials and building products the key areas for concern are (BRE 2012):

- Where do the materials come from?
- Have they been extracted and processed in an environmentally sensitive manner?
- Have the highest levels of ethics been demonstrated within the supply chain?
- Has the workforce involved in their extraction and production been treated fairly?
- Have all stakeholders in the supply chain been effectively consulted?
- Are communities local to the extraction and manufacture adequately considered?

The role of the new sustainability indicator is to:

- Upgrade existing BREEAM assessment results
- Consider existing issues and consequences in the long run
- Consider potential changes and what that can bring in the long run
- Improve and maintain current energy efficiency and material efficiency according to long run targets (depending on externalities and UK government targets)

8.7.1 Development of the long run hypothetical scenarios

The development of the long run hypothetical scenarios is the fundamental component of the OLRLCII. The OLRLCII is to consider hypothetical scenarios according to the existing issues revealed from the LCA and the POE evaluation. The scenarios being developed in this study (section 9.4) reflect on:

- Climate change in the future and increase of the outside temperature.
- Change in the carbon emission target.
- Building refurbishment.
- Building new construction-extension (Potterrow building phase 3).
- System upgrade-plantroom refurbishment.

No matter what the future scenario will be the goal for the long run is for energy efficiency to be improved to a level where the energy reduction targets can be achieved and the raw-material emissions reduced. Thus it is important to consider in the long run good case, medium case and worst case scenarios. The good case scenario is the assumption that energy emissions and raw-material emissions will be reduced. This could be achieved with the use of additional technology, or with upgrading existing systems and with good maintenance service. It really depends on the carbon emission reduction target; if the current low-carbon new or refurbished office buildings will have to be zero carbon in the future, then renewable fuels or technologies will have to be used. The medium case scenario is that the existing situation improves with good maintenance and proper control and with simple none-cost measures, for as long as the systems can be maintained, but also be energy efficient.

The worst case scenario in where both energy emissions and raw-material emissions will increase in the long run. This could happen if the current situation of the sustainable building is not considered. It could also happen if the systems get old or if there is poor maintenance, control and use of the buildings. In the case where there will be a need for additional technology in either the heating or cooling system, if the materials used are not recycled to a great extent then, overall, during the building life span the raw-material emissions will increase. So the worst case scenario is really what must be avoided and to be avoided additional measures must be taken into account.

To get a better understanding of what the situation could be like if energy consumption for heating and cooling increases in the long run, the hypothetical scenario considers the potential increase in the next 20,50 and 100 years (figure 8.9, 8.10). From the MWh of heating consumption in the long run, it can be seen that Argyle House in not an environmentally viable building and urgent actions must take place. In terms of the cooling consumption in the long run, the Potterrow building will have larger cooling consumptions, much higher from Elizabeth Courts.

Office Building	**Hypothetical heating operation in the long run**			
	2	**20**	**50**	**100**
PB (MWh)	761,6	7616	19040	38080
AH (MWh)	3.307	33066,94	82.667.360	165.335
EC (MWh)	354,884	3548,84	8872,1	17744,2
FW (MWh)	5392	53920	134800	269600

Figure 8.9: Long run heating consumption of the case study buildings in the next 20, 50 and 100 years

Office Buildings	**Hypothetical cooling operation in the long run**			
	2	**20**	**50**	**100**
PB (MWh)	60,76	607,6	1519	3038
AH (MWh)	0,22641	2,2641	5,66025	11,3205
EC (MWh)	8,08079	8,08079	202,019	404,0395
FW (MWh)	0,4095	4,095	10,2375	20,475

Figure 8.10: Long run cooling consumption of the case study buildings in the next 20, 50 and 100 years

If the energy consumption for heating and cooling remains as is in the long run, supplementary LCA results (appendix 24) show that in 50 years, the operational life cycle phase of the sustainable office buildings will have higher environmental impacts from the production life cycle phase. Therefore, it can be said that energy reduction during operation is highly significant even if this means additional technologies in the long run or replacement or refurbishment. However revealed from the LCA the production phase has more significant impacts compared to the operational phase at present. Thus critical attention must also be given in the reduction of the embodied raw-material emissions. Tables 8.4-8.6 summarise the hypothetical scenarios considered for each case study office building.

Table 8.4 ORLCII hypothetical scenarios

Case study office building		PB	AH	ECII	FWH
Years old in 2010		2	50	2	60
Life span building scenario (approximately)		60 or more	2,3 years	60 or more	8-10 years
Life span h/c system life span (approximately)		15-30 years or more	2,3 years	15-30 years or more	20 years or more
	Hypothetical Scenarios				
Energy efficiency In the winter	**Best case**	Increase if actions for energy reduction are not implemented	n/a	Increase if actions for energy reduction are not implemented	-Increase if actions for energy reduction are not implemented
	Medium case	Remain the same due to frequent maintenance	n/a	Remain the same due to frequent maintenance	-Remain the same due to frequent maintenance
	Worst case	Decrease as system gets old or due to inappropriate operations-use	Building has reached its life span. Evacuation plan. Discussion for building demolition	Decrease as system gets old or due to inappropriate operations-use	-Decrease if existing situation remains as is
	Issues	-Excess production of heat -Low temperature return -Off-office hours operations -Heat losses -HDD -occupancy information/feedback	-Old oil fired boilers and old radiators -Central heating -poor building thermal (heat losses)performance -no zone control -off-office hours operations - occupancy information/feedback	-Off-office hours operations -Heat losses -HDD -set indoor temperature parameter -occupancy satisfaction/ understanding - occupancy information/feedback	-low temperature returns (non-condensing boilers) -set indoor temperature parameter Poor thermal performance (heat losses) -occupancy Satisfaction/ understanding - occupancy information/feedback

Table 8.532: ORLCII hypothetical scenarios

Case study office building		**PB**	**AH**	**ECII**	**FWH**
Years old in 2010		2	50	2	60
Life span building scenario (approximately)		60 or more	2,3 years	60 or more	8-10 years
Life span h/c system life span (approximately)		15-30 years or more	2,3 years	15-30 years or more	20 years or more
Hypothetical Scenarios					
Energy efficiency In the summer	**Best case**	Increase if actions for energy reduction are not implemented	n/a	Increase if actions for energy reduction are not implemented	Increase if actions for energy reduction are not implemented
	Medium case	Remain the same due to frequent maintenance	n/a	Remain the same due to frequent maintenance	Remain the same due to frequent maintenance
	Worst case	-Decrease as system gets old or due to inappropriate operations-use	n/a	-Decrease as system gets old or due to inappropriate operations-use	-Decrease as system gets old or due to inappropriate operations-use
	Issues	-indoor set temperatures - practical use of stored heat for cooling -constant CHP -operation in off-office hours -office space natural ventilation not enhanced and used properly -occupancy information/feedback	-Old systems constantly maintained -no zone control -no back up supply -no sensors and thermostats --occupancy information/feedback	-indoor set temperatures - operation in off-office hours -office space natural ventilation not enhanced and used properly -occupancy information/feedback	-mix of old and current equipment - no zone control -no sensors and thermostats -Occupancy information/feedback

Table 8.6: ORLCII hypothetical scenarios

Case study office building		**PB**	**AH**	**ECII**	**FWH**
Years old in 2010		2	50	2	60
Life span building scenario (approximately)		60 or more	2, 3 years	60 or more	8-10 years
Life span h/c system life span (approximately)		15-30 years or more	2, 3 years	15-30 years or more	20 years or more
Hypothetical Scenarios					
Material efficiency	**Best case**	Increase if actions are implemented	n/a		Might decrease further in the future
	Medium case	Remain the same since first installation(it depends from maintenance)	Remained the same since first installation	Remain the same since first installation (it depends on maintenance)	Remain the same since second installation (it depends from maintenance)
	Worst case	-Decrease if actions are not implemented -future plan for a 3rd building construction phase	n/a	Decrease if actions are not implemented	Upgrade has increased embodied raw-material emissions
	Issues	-Raw-materials extractions -type of materials -property of materials -use of primary materials -ongoing production of new equipment -impacts in fossil fuels, minerals, land use, respiratory inorganics	-Raw-materials extractions -type of materials -property of materials -use of primary materials -ongoing production of new equipment -impacts in fossil fuels, minerals, land use, respiratory inorganics	-Raw-materials extractions -type of materials -property of materials -use of primary materials -ongoing production of new equipments -impacts in fossil fuels, minerals, land use, respiratory inorganics	-Raw-materials extractions -type of materials -property of materials -use of primary materials -ongoing production of new equipment -impacts on fossil fuels, minerals, land use, respiratory inorganics

8.7.2 Influential parameter considerations for the effectiveness of BREEAM

This study also demonstrates that the environmental performance of the BREEAM office buildings depends on various parameters; technical, mechanical, control and occupancy parameters (chapter 6, 7). The empirical work in this thesis reveals that the energy-efficiency indicator of the heating and cooling systems has different seasonal results. A building that is energy efficient in the winter is not necessarily energy efficient in the summer. This has been the case with the CHP seasonal efficiency of the Potterrow building. The seasonal efficiency of the CHP is influenced by other technical and operational parameters. The online questionnaire surveys have helped to put these parameters into a hierarchy of importance (figures 8.11, 8.12).

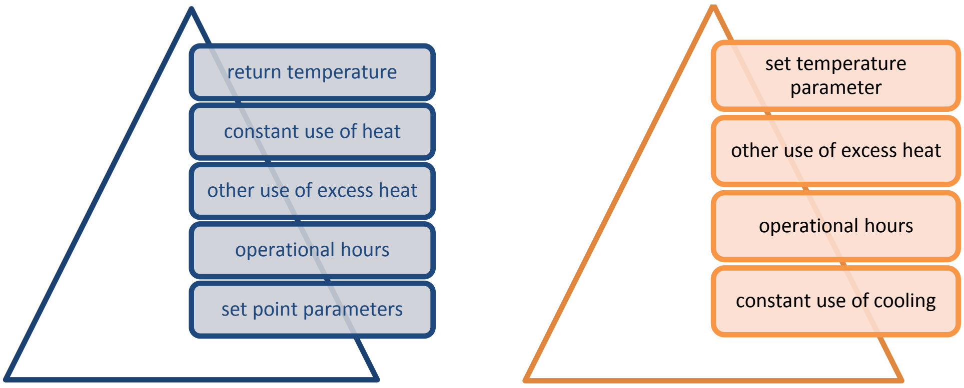

Figure 8.11: Influential parameters of the energy efficiency of the CHP in the winter (left pyramid) and in the summer (right pyramid). The top parameters are the most important.

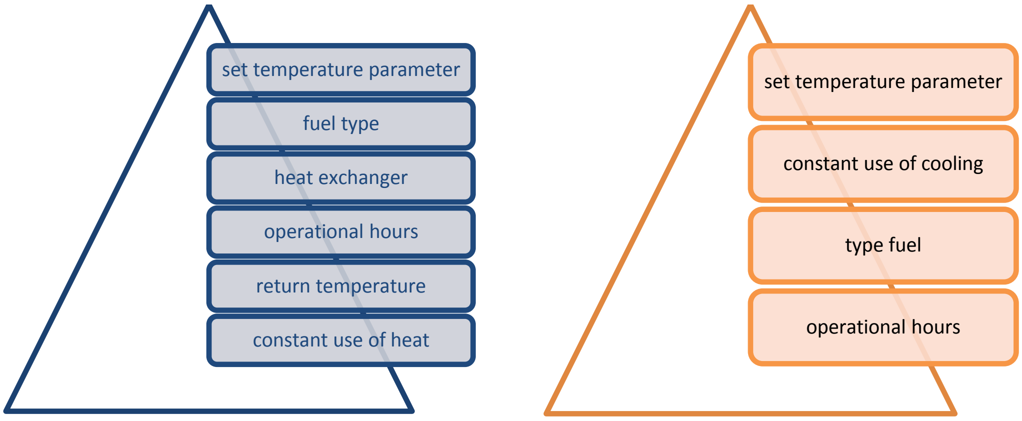

Figure 8.12: Influential parameters of the energy efficiency of the CHP in the winter (left pyramid) and in the summer (right pyramid). The top parameters are the most important.

In the winter, the return temperature of the fuel gas plays a significant role in the efficiency of the CHP and thus the heat exchanger type is a highly important consideration. Another parameter that is important to consider is the constant use of heat which is closely related to the operational hours of the CHP. The CHP operate throughout 2009 and 2010, non-stop, 24 hours per day. This means that the CHP operation is not consistent with the daily operational working hours of the building. It has been found that during off-office hours (during weekends and bank holidays) there is some energy heating consumption. The excess amount of heat produced is stored in the heat storage tank. If this heat is not used properly (return temperature and practical use) by the system either as heating or as cooling, the excess heat will be rejected from the chimney flues into the outside environment. Thus the use of excess heat is also a significant parameter to be further considered. By reducing the operational hours of the CHP energy consumption can potentially be further reduced. The same factors apply for the energy efficiency of the system in the summer. Another highly significant parameter for reducing heating and cooling consumption is the set point parameter. The office buildings in the UK must achieve the standard set point parameter of 21^0C. This parameter has been applied in the new sustainable office building and in the conventional office building in Edinburgh. The set point temperature of the sustainable refurbished building varies between 22-24^0C and of the conventional building in Birmingham at 28^0C. In order for a heating system to achieve a temperature higher than the base set temperature of 21^0C in the winter the system will have to operate longer to meet these temperatures, therefore increased heating consumption. The same applies for cooling in the summer: for the cooling system to achieve 21^0C it means long hours of the cooling system, therefore increased cooling consumption. For instance, in comparing Elizabeth Courts and the Potterrow building, the cooling system of Elizabeth Courts operates less hours for 24^0C to be achieved in the summer.

In Kofoworola and Gheewala (2009) LCA study of a commercial office building in Thailand, it was found that air-conditioning was the major load of the building as there were no provisions for individual temperature controls. A similar pattern was observed in other office building surveys (Aun 2004; Ayuni 2004;Chirarattananon et al. 2006; Department of Alternative Energy Development and Efficiency 2005; National University of Singapore 2006), as mentioned in Kofoworola’s study. Likewise, the set-point parameter of the building was as low as 23-24^0C, even in the summer, which is lower than the standard indoor air set-point temperature of 26^0C. The result of the optimization analysis of increasing the indoor air set-point temperature indicates that a mean energy consumption reduction of about 7% can be achieved per 1^0C increase in the set point temperature (Kofoworola & Gheewala 2009).

Further to these research findings, the PhD research has also conducted post-occupancy evaluation survey using thermographic survey and HDD evaluation, to evaluate the office building thermal and energy performance. Through the POE, it can be explained why the energy achievements of the BREEAM office buildings are still at benchmark levels. The HDD evaluation indicates positive correlations between the energy consumption and the degree days for the conventional office buildings and for the refurbished BREEAM office building. Negative correlation has been found between the BREEAM new building and the degree days. This can be explained due to the fact that energy metering readings are not taken on a specific date and time (eg, at the end of the month). Another reason for this could be that the CHP does not operate according to the degree days parameter as in order for energy efficiency to be enhanced the CHP works off-working days of the building.

From the thermographic survey it has been detected that the BREEAM office buildings have some heat losses and air-leakages which are not as great as in the conventional office building, although important to be considered for lowering the energy consumption.

In terms of the embodied raw-material emissions of the cooling system, the sustainable office buildings have more impacts than the conventional office buildings. In terms of the embodied raw-material emissions of the heating system the conventional office building in Birmingham has higher impacts than the sustainable refurbished office building in respiratory inorganics and in fossil fuels while the impacts in minerals are slightly higher. This is a significant achievement considering the amount of heating equipment used in the heating system of the sustainable new office building and in the other conventional buildings. The study of cells (2002) explains that heating systems in the conventional buildings takes less space than in the high-tech buildings.

The sustainable office buildings that have the advantage of the passive solar building characteristics have more complex heating and cooling systems but less heating-cooling equipment installed. The increase in the emissions has to do with the size of the equipment, its weight and the type of raw-material used. Certainly the demand for the amount of equipment needed in a building has to do with the building gross floor area and with the indoor space layout. The sustainable office building in Edinburgh is 16,100 m^2 and the conventional office building in Edinburgh is 20,472 m^2. Elizabeth Courts could be seen as a current benchmark in achieving lower embodied raw-material emissions and heating consumption. However, its back up cooling supply via the VRV air-conditioning system increases the overall embodied emissions of the building, compared to the other case study buildings. Between the cooling indoor temperature comfort of the occupants when needed and the increase in the embodied raw-material emissions, having the back up supply is more important. However, it is also important in order to better control the cooling consumption. The Potterrow building could have benefited from the VRV system more than it has with the CHP operation in the summer.

Another highly significant finding is that in the sustainable office buildings more weight is in the refrigerant used in the air-conditioners, and in the chillers. The use of the R-134A refrigerant type is an alternative to the R-22 but it still contributes to the ozone layer and to climate change. The old cooling equipment in the conventional office buildings are more risky as issues can occur during the installation of the equipment, when leakages occur, in maintenance and when the equipment is removed. Therefore, the effectiveness of the BREEAM sustainable office building environmental performance depends on the unfolded parameters as shown in figure 8.13.

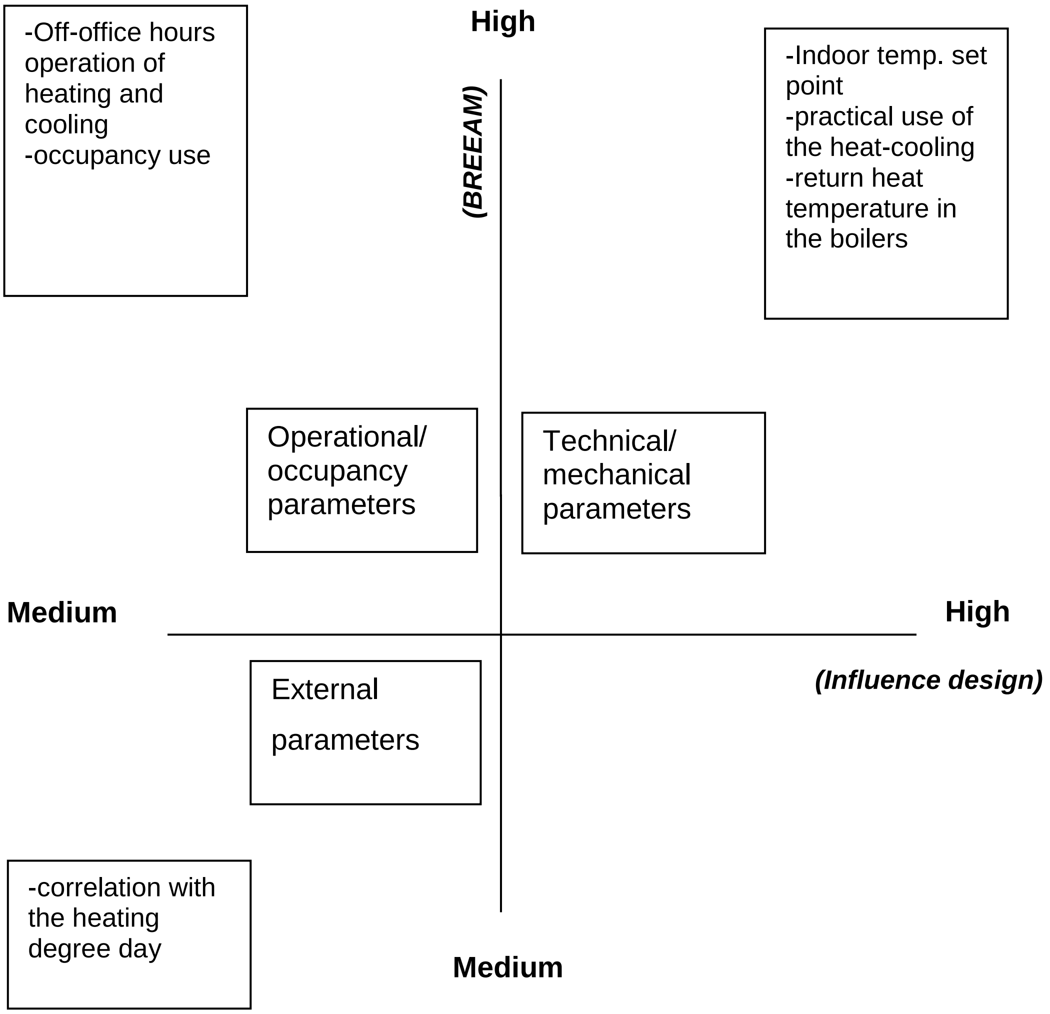

Figure 8.13: Significance of the parameters that influence the effectiveness of the BREEAM office buildings and their associated issues in the BREEAM axis and in the Influence design axis.

8.8 Recommendations

This section shows what change the OLRLCII can bring according to the issues revealed from the LCA, the POE and the hypothetical long run scenarios. The third step of OLRLCII is the recommendations. A particular course of action is suggested for energy consumption and embodied raw-material emissions to be reduced.

Prior to the course of action, the study has produced energy-efficient and material efficient ratings (figures 8.14-8.21) for the case study office buildings, which represent the former, the current and the potential situation of the four buildings. Upon these ratings, the recommendations in tables 8.7, 8.8 are provided. The colours illustrated in the ratings and the colours shown in the tables were chosen to match the level of the current and the potential measures needed with the current and the potential situation of the buildings. The ratings show the former situation (before refurbishment and upgrade), the current situation and the potential achievement. The green arrows indicate lower and zero carbon emission on the top (rating A). The coloured office building image on the right of the figure indicates the status of the building: green=sustainable, amber=conventional with upgrades, red=conventional with no upgrades.

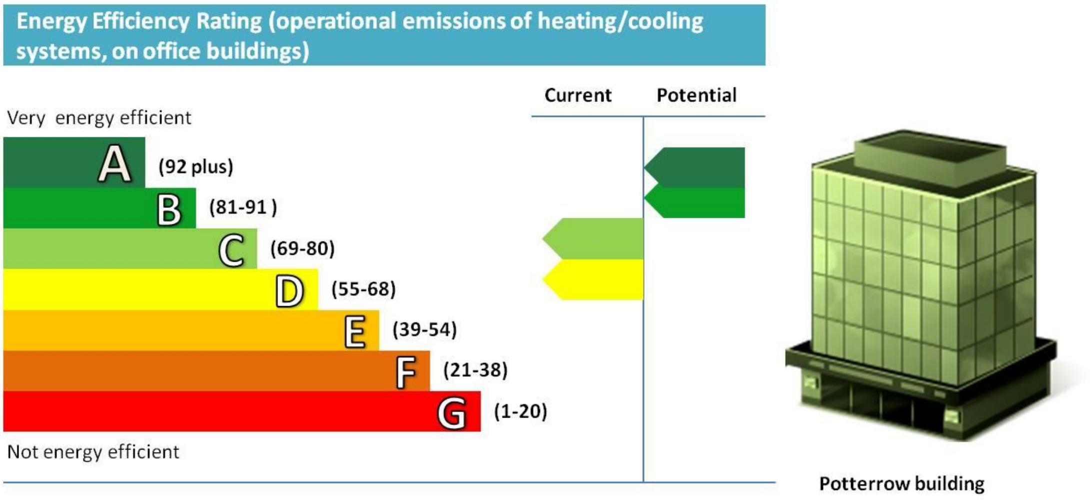

Figure 8.1448: Energy efficiency rating for the Potterrow building

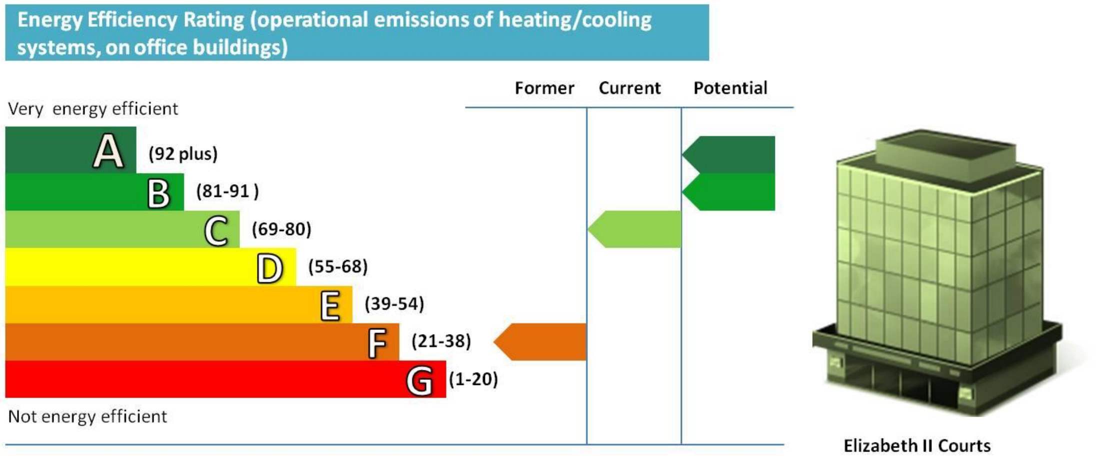

Figure 8.15: Energy efficiency rating for the Elizabeth II Courts

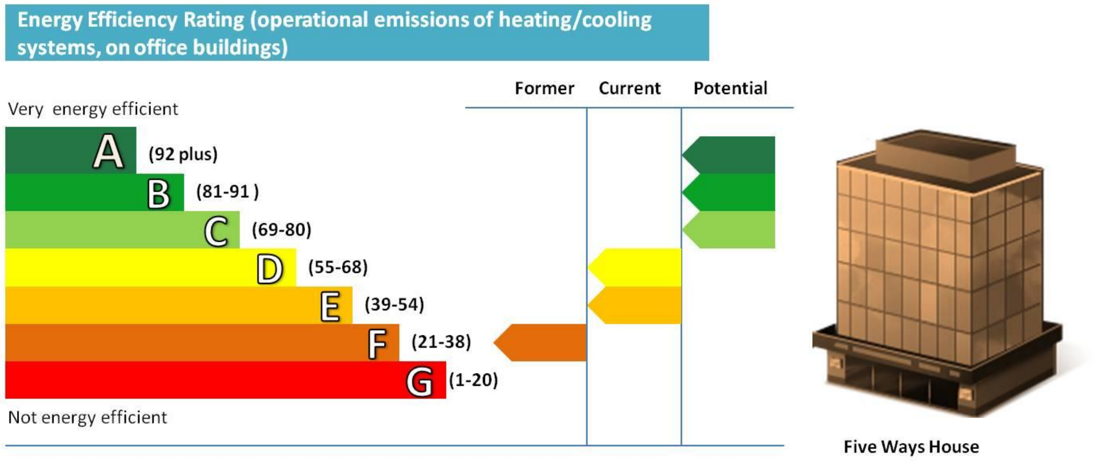

Figure 8.16: Energy efficiency rating for Five Ways House

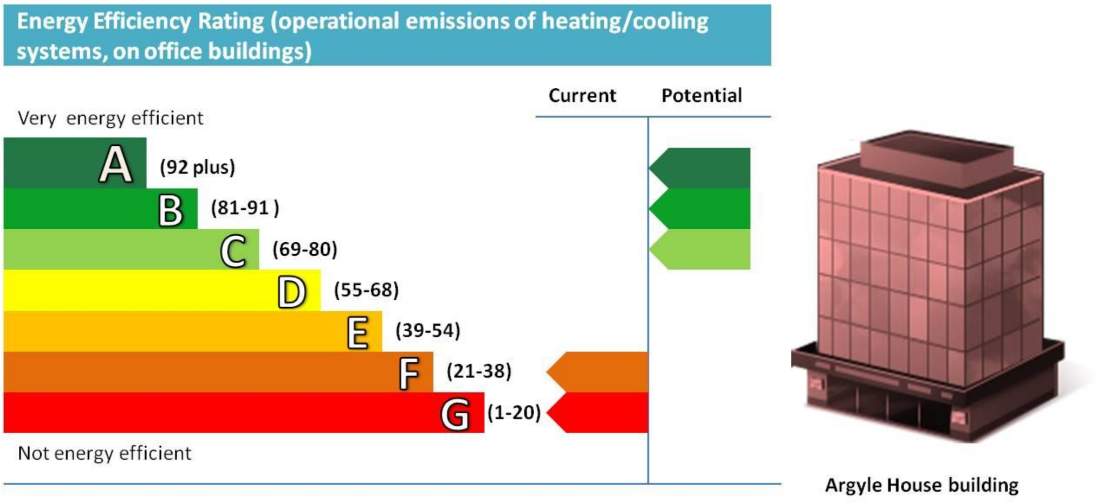

Figure 8.17: Energy efficiency rating for Argyle House

The rating system for the material efficiency of the heating/cooling system shows the current rating according to whether the system has reached its end of life, whether it had an upgrade within the 50 or 20-25 years of life time and since their first installation.

It also shows the potential rating according to what needs to be achieved in the future. The green arrows represent that raw-materials have been assessed and are eco-efficient, in other words, friendly to the environment. This means that the raw-material contents have low embodied emissions. The recommendations provided in tables 58, 59 explain how this could be achieved.

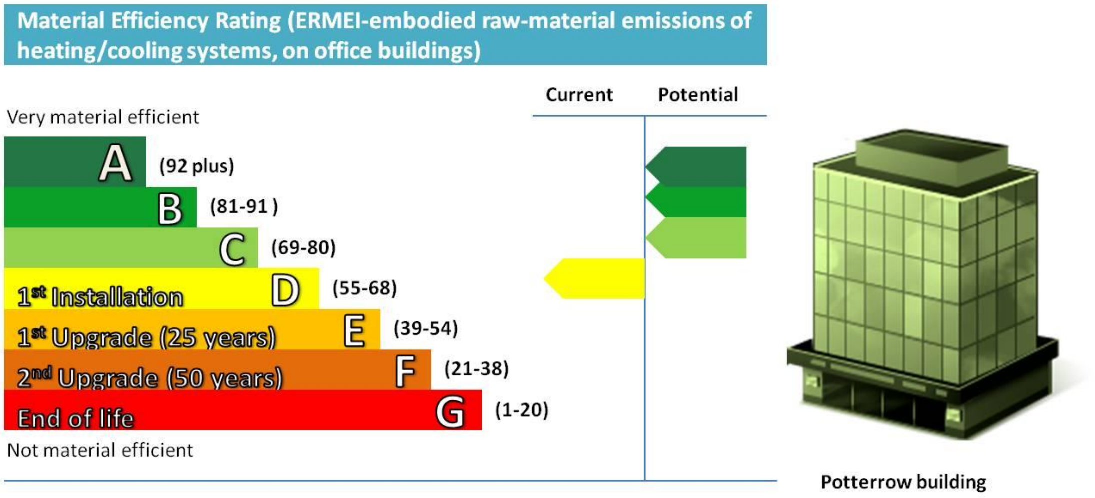

Figure 8.18: Material efficiency rating for the Potterrow building

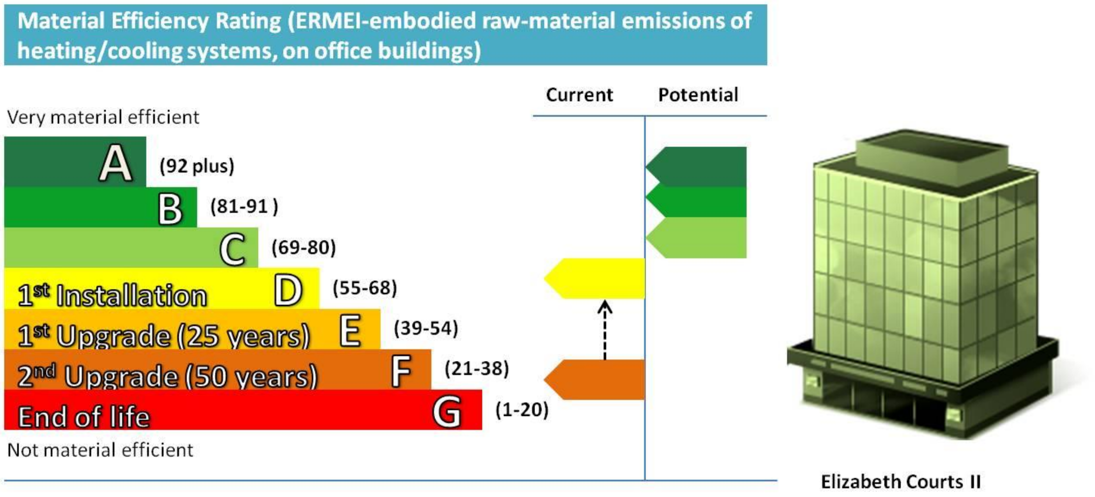

Figure 8.19: Material efficiency rating for the Elizabeth II Courts

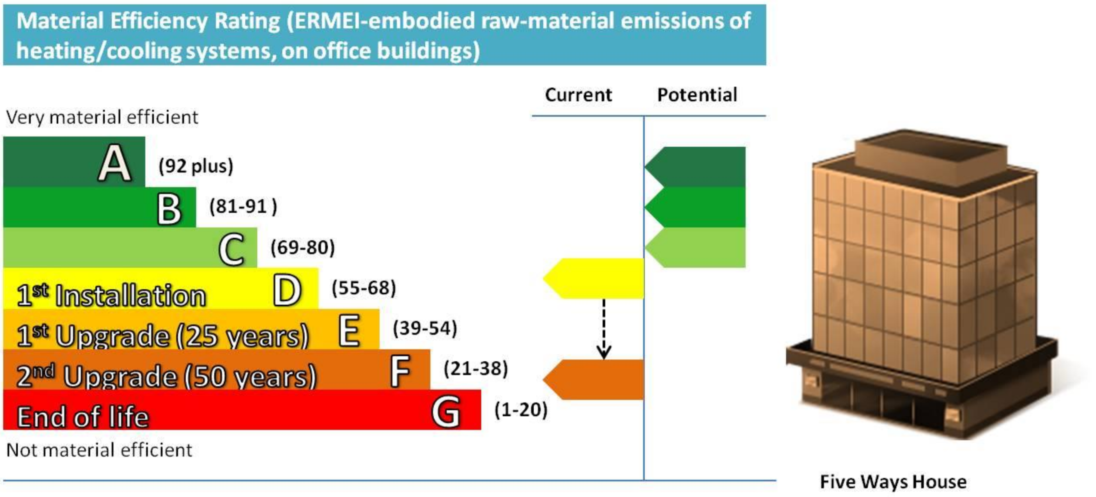

Figure 8.2049: Material efficiency rating for Five Ways House

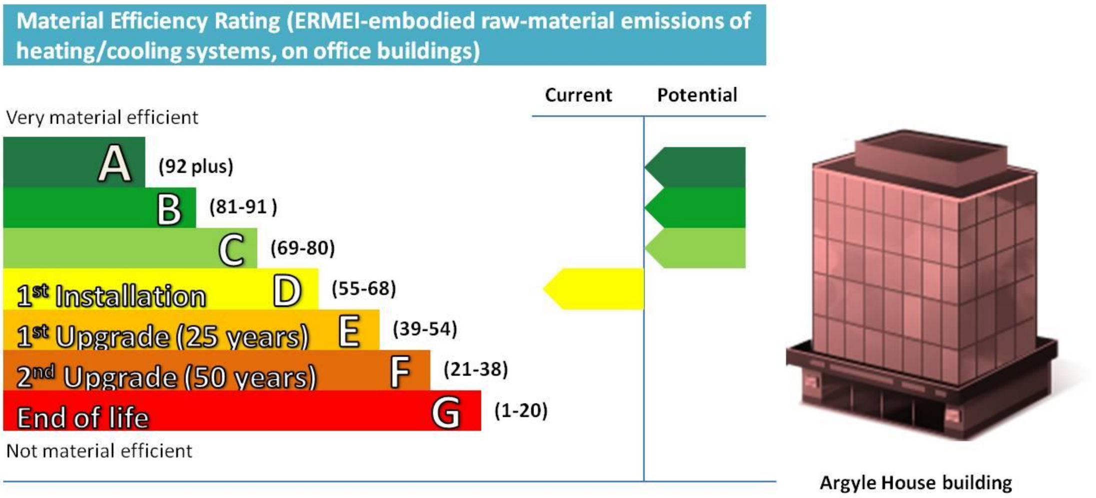

Figure 8.2150: Material efficiency rating for Argyle House

Following the rating systems, recommendations are provided in the tables (58) to respond to the potential changes of the buildings, considering the hypothetical long run scenarios developed in this study. The suggested measures have been categorised as none-cost, low cost and medium cost. This is to demonstrate that with simple technical-control based measures; there can be significant changes in terms of the heating-cooling consumption. On this occasion, not a great deal of non-cost change can happen in the conventional office buildings. By using the OLRLCII as part of the BREEAM system (tables 8.7, 8.8), worst case hypothetical scenarios can be avoided. The recommendations aim that the conventional office buildings can also achieve BREEAM excellent score in near future. Through these suggestions, this study is trying to emphasize that the existing conventional office buildings need retrofitting and that with the range of measures provided, they can have a crucial contribution in reducing UK non-domestic greenhouse emissions.

In order to support the recommendations for lower-zero carbon upgrades in heating-cooling energy consumption, this study has used LCA sensitivity analysis that allows comparison between the technologies that were assessed. In the near future it is expected that the demand for replacements with renewable fuels and upgrades with renewable technology in existing buildings will increase significantly from the current situation. The use of renewable fuels or technologies could upgrade existing BREAAM scores of the existing sustainable office buildings.

Currently, Elizabeth II Courts could be distinguished as being the best practice in terms of energy efficiency. Therefore it is suggested that this be used as a benchmark when compared to other office building practices that intend to undergo refurbishment.

The thesis reveals that by using the OLRLCII this rating of the case study buildings could change. Since the current BREEAM buildings will be existing buildings in few years time, if the conventional office buildings are transformed to passive solar buildings, according to the recommendations, the rating could change. It is anticipated that Five Ways House and Argyle House will be better than the current benchmark levels.

The recommendations provided in the tables can be used by first identifying the characteristics of the building and its status: conventional existing, conventional with upgrade, sustainable new and sustainable refurbished. Location is also an important criterion for a building. These buildings are located in the UK. In parallel, the MATRIX table produced in the appendices can be checked. The tables have been split into current and long run measures.

Table 8.733: Recommendation of the case study buildings at present considering none-cost, low cost and medium cost measures. A rating system has been used, using highlights: best practice with deep green, good practice with light green, bad practice with amber, worst practice with red.

None-cost, low cost and medium cost measures that can be taken today	**Low-medium and none-cost**	**Low-medium and none-cost**	**Low-medium and none-cost**	**Low-medium and none-cost**
Buildings	**Potterrow building**	**Argyle House**	**Five Ways House**	**Elizabeth Courts II**
Location	**Edinburgh (northeast)**	**Edinburgh (northeast)**	**Birmingham (midlands)**	**Winchester (southeast)**
Building age in 2010	**2**	**60**	**50**	**2**
	New	**Existing**	**Existing with an upgrade in the heating system**	**Refurbished**
BREEAM score	**Excellent**	**-**	**-**	**Excellent**
Architectural	☐ **Reduce further heat losses recorded from the thermography survey** ☐ **Increase/repair insulation around the window cases** ☐ **Check the sealing of windows** ☐ **Consider extensive building performance monitoring**	☐ **Insulation**	☐ **Insulation** ☐ **Double or triple glazed windows where needed**	☐ **Reduce further heat losses recorded from the thermography survey** ☐ **Increase/repair insulation around the window cases** ☐ **Check the sealing of windows** ☐ **Consider extensive building performance monitoring**

Heating consumption	Switch off CHP in off-office hours (summer, weekends, bank holidays, after office hours) Reduce the set point parameter by 1^0C Consider back up electric heating Keep doors properly shut to maintain the heat temperatures longer inside the office room-spaces Post occupancy Evaluation and energy monitoring Optimise start times	Reduce the set point parameter by 1^0C Switch off the boilers in off-office hours Reduce heat losses when boiler heating is on Keep doors properly shut to maintain the heat temperatures longer inside the office room-spaces Optimise start times	Upgrade to condensing boilers natural gas or biomass Reduce the set point parameter by 1^0C Consider electric heating instead of using boilers Switch off the boilers in off-office hours Reduce heat losses when boiler heating is on Keep doors properly shut to maintain the heat temperatures longer inside the office room-spaces Optimise start times	Switch off boiler heating in off-office hours (summer, weekends, bank holidays, after office hours) Reduce the set point parameter by 1^0C Consider back up electric heating Keep doors properly shut to maintain the heat temperatures longer inside the office room-spaces Optimise start times
Cooling consumption	Practical use of the CHP for cooling so that efficiency is enhanced. Switch of CHP in off-office hours (summer, weekends, bank holidays, after office hours) Increase indoor set temperature parameter Switch off cooling in off-office hours	Use of night cooling via natural ventilation	Use of night cooling via natural ventilation	Reduce operational hours of cooling equipment Increase indoor set temperature parameter Switch off cooling in off-office hours

Control	☐ **Better control of heating consumption according to the heating degree days** ☐ **Correct metering readings in a standard day of each month**	☐ **Maintain HDD data correlation** ***(Not a great deal of control measurements can be recommended)***	☐ **Programmable thermostats** ☐ **Maintain HDD data correlation**	☐ **Better control of heating consumption according to the heating degree days** ☐ **Correct metering readings in a standard day of each month**
Occupancy awareness	☐ **Feedback or meetings end of the month/announcements** ☐ **Monitor/display of the KWh consumption** ☐ **Sensors for guiding the occupants when to close/open the windows** ☐ **Display EPC** ☐ **Occupancy monitoring/behaviour** ☐ **Satisfaction survey**	☐ **Feedback or meetings end of the month/announcements** ☐ **Display EPC**	☐ **Feedback or meetings end of the month/announcements**	☐ **Feedback or meetings end of the monthannouncements** ☐ **Monitor/display of the KWh consumption** ☐ **Sensors for guiding the occupants when to close/open the windows** ☐ **Display EPC** ☐ **Occupancy monitoring/bahaviour**
Management	☐ **Monthly energy consumption target compared to last year’s consumption**	☐ **Monthly energy consumption target compared to last year’s consumption**	☐ **Monthly energy consumption target compared to last year’s consumption**	☐ **Monthly energy consumption target compared to last year’s consumption**

Table 8.8: Recommendation of the case study buildings if the OLRLCI is used considering medium and high cost measures. A rating system has been used, using highlights: best practice with deep green, good practice with light green.

Long run budget measures (low, medium, high)	**Medium budget**	**High budget**	**High budget**	**Medium budget**
Buildings	**Potterrow building**	**Argyle House**	**Five Ways House**	**Elizabeth Courts II**
Location	**Edinburgh (northeast)**	**Edinburgh (northeast)**	**Birmingham (midlands)**	**Winchester (southeast)**
Building age in 2010	**2**	**60**	**50**	**2**
	New	**Existing**	**Existing with an upgrade in the heating system**	**Refurbished**
BREEAM score	**Excellent**	**-**	**-**	**Excellent**
Architectural	☐ **Consider changes in the interior layout of space** ☐ **Consider extensive building performance monitoring**	☐ **New passive solar envelope** ☐ **Recycled construction materials** ☐ **Add Insulation** ☐ **Reduce double glazing surface** ☐ **Increase window dimensions** ☐ **Double glazing or triple glazing where needed** ☐ **Consider low U-values** ☐ **Consider extensive building performance monitoring (heat losses and air leakages)**	☐ **New passive solar envelope** ☐ **Recycled construction materials** ☐ **Add Insulation** ☐ **Get rid of single-glazed windows and replace with double or triple where needed** ☐ **Increase window dimensions** ☐ **Double glazing or triple glazing where needed** ☐ **Consider low U-values** ☐ **Consider extensive building performance monitoring (heat losses and air leakages)**	☐ **Consider changes in the interior layout of space** ☐ **Consider extensive building performance monitoring** ☐ **Consider extensive building performance monitoring**

Heating consumption	Switch to biomass fuels for the CHP Consider back-up electric heating and 10% of renewable technology	Consider electric heating from renewable technology Consider CHP biomass Consider biomass condensing boilers	Consider switching to condensing type boilers with biomass fuel Consider electric heating and 10-30% of renewable technology	Use of electric heating through VRV Consider 10% of renewable technology
Cooling consumption	Mainly use of Consider back up electric cooling in the office space Consider 10% of renewable technology			Consider 10% of renewable technology
Control		Thermostat Sensors Zone control	Thermostat Sensors Zone control	
Occupancy awareness		Monitor/display of the KWh consumption Sensors for guiding the occupants when to close/open the windows	Monitor/display of the KWh consumption Sensors for guiding the occupants when to close/open the windows	
Embodied raw-material consumption	Consider up to 80% recycled heating or cooling equipments	Consider up to 80% recycled heating or cooling equipments	Consider up to 80% recycled heating or cooling equipments	Consider up to 80% recycled heating or cooling equipments

8.8.1 Application of the OLRLCII in Argyle House

This thesis has focused on developing a mechanism that can be used as reference for further applications. The case study buildings used are current examples; however, year by year, new buildings are built, building standards and policies change, and thus it is essential that the most current examples are considered. This tool is suggested for use mainly by environmental organisations, policy departments, energy services and departments and energy assessors responsible for auditing buildings and informing the building owners about the issues that need to be addressed and about what needs to happen. Through this indicator a baseline for potential development can be established. Also deeper understandings about the existing conditions of buildings can be revealed. The issues compared to current practices and benchmarks can be better positioned and it could also support planning application for potential changes.

Depending on the form that the indicator will take; assessment tool, eco-label, LCA indicator, BREEAM assessment category, rating system, the development of the indicator in this thesis intends to inform environmental decision making about:

1. Ways to conduct environmental performance evaluation. Which methods and approaches have been used to evaluate energy efficiency and raw-material efficiency.
2. Which type of data has to be collected.
3. The data limitations and the constraints and it provides assumptions that can be used to overcome limitations.
4. The significance of the environmental impacts caused, related to energy and raw-materials of both conventional and sustainable office buildings by looking at the results
5. Find a way to assess not only existing energy efficiency and raw-material efficiency but also long run efficiency.
6. Compare other buildings (conventional or sustainable) with the case study building characteristics used in this study to find out:
    a. Similarities and differences.
    b. What the existing issues on sustainable and conventional office building energy performance are.
    c. Influential parameters and factors of energy efficiency and raw-material efficiency.

d. Achievements and which features are important.
e. Considerations to ensure efficient performance.
f. Which measures have been suggested to improve efficiency now and in the long run.

For example, hypothetically the owner of Argyle House wants to renovate the building instead of demolishing it, to a BREEAM excellent office building. The architects, developers, investors and other stakeholders, or the owner, could use the sustainability indicator developed in this study in order to find out how the building could be renovated to BREEAM standard. Initially the practitioner must be able to describe the building characteristics of Argyle House (see chapter 6) and in order to get a better understanding of what needs to be achieved to look at the building characteristics of the BREEAM office buildings. The MATRIX table in appendix 8 summarises the building characteristics and it allows cross case comparison. The practitioner could then select (circle the characteristics, see how it is done in MATRIX) those BREEAM office characteristics that will better fit with what is needed to be achieved. Since Argyle House is going to be renovated it is assumed that renovation will concentrate on the EIIC refurbished BREEAM office building characteristics. According to the EIIC building design, Argyle House must go through significant refurbishment in order to maximize daylight, lower structural U-values and expose thermal mass. As the building is south oriented it is suggested to install a shading system in the south. The huge difference between the two buildings is that the long facades of the EIIC are in the west and east while for Argyle House they face north and south. Through the thermographic survey of Argyle House it is suggested to remove all the pre-cast concrete facade around the building and only the skeleton of the building retained. Each side of the building should be treated differently as with the EIIC to maximize passive solar heating and cooling. Figure 8.22 presents an idea of how the building could be first modelled to show the different building blocks (in a way to separate them). These recommendations are provided according to section 10.7 also.

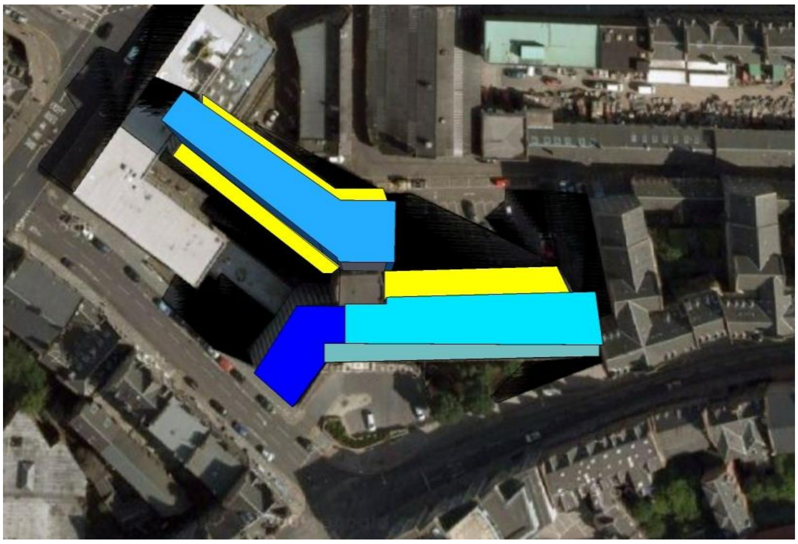

Figure 8.22: OLRCII Argyle House model using SketchUp. Model shows sections that could change to enhance energy efficiency.

What also needs to be considered are the building location and the surrounding shadows, as presented in section 6.1.3. Another highly important parameter is that the building will have to be fully insulated and double glazed. The infrared analysis conducted emphasises that the insulation must be installed very carefully and windows will have to be double checked in order to be as tightly sealed as possible. This will reduce heat losses. In terms of the indoor office space layout, the new indicator has unraveled that it is important to consider smaller volumes of working spaces. After the building design the practitioner will have to consider the operational parameter of the building. The MATRIX table can also be used at this point to select energy efficient heating technologies. The measures presented in the introduction highlight the use of local power generation and the use of mechanical heating and cooling. For this building a CHP technology could be a good choice if the perfomence criteria that have been developed from the online questionnaire survey are taken into consideration. In order to further maximise energy efficiency and to lower CO_2 emissions, the sensitivity analysis (section 9.8) shows that biomass fuel is a better option. In terms of the facility management the HDD evaluation of the BREEAM case studies unfold that it is important to take correct meter readings. Sub-metering control and zone control with thermostats and sensors will definitely improve the overall efficiency of the building's energy consumption, as recommended in tables 65 and 66. These recommendations have been unfolded by considering worst case hypothetical long run scenarios of the building (section 9.6, 10.6) developing the new sustainability indicator throughout this study. Hense it can be seen that the development of the OLRLCII can play a crucial role in environmental decision making for better long run energy and environmental performance of office buildings.

8.9 Summary

This chapter has discussed the significance of the development of a new sustainability indicator the ‘OLRLCII’ as derived from the exploration and the triangulation of the research findings of five key dimensions. This study suggests that the building design and the energy indicator need further exploration through additional POE methods. Most significantly this study has raised the importance of including the raw-material indicator ‘ERMEI’ in the existing sustainable assessment methods. Through this indicator an office building can be called sustainable when increasing the efficiency of one aspect does not reduce the efficiency of another, in this case where there is a long run sustained relationship between energy and raw-materials of heating and cooling systems. Through the application and further development of the new indicator, this problem shifting, known as environmental performance gap, can be resolved. This study has suggested ways that the new indicator and its components can be integrated within the existing SAMs.

CHAPTER 9: CONCLUSIONS

9.1 Key Conclusions

This PhD thesis has succeeded in addressing the aim and the objectives of the thesis, as well as providing answers to the research questions and testing the hypotheses. This has been achieved by exploring five key dimensions, as discussed in chapter 8. Through this exploration, a new sustainability indicator has been derived, the OLRLCII, which consists of two indicators: the energy indicator and the development of another indicator, the ERMEI, for inclusion of the embodied raw-material emissions. Methods of integrating the new indicator into existing SAMs have been explored and proposed. The key methods used to assess the environmental performance of heating and cooling systems of office buildings through the OLRLCII are POE methods and LCA. Further, a research framework has been developed (chapter 4) and a research flow diagram of the new indicator's components and methods used has been created and provided (chapter 8). The key component of the new indicator has been the development of hypothetical long run scenarios on the LCA results, in combination with a rating system and recommendations for potential improvements. The application of the new indicator has helped to come up with a list of conclusions, as follows:

1. Sustainable office buildings are better than conventional office buildings to a certain extent

It could be expected that sustainable office buildings perform better than conventional office buildings, since high energy reductions have been achieved. The BREEAM excellent assessment also makes this more credible. This thesis vitiates this opinion, showing that maintaining and enhancing energy efficiency depends on several internal and external parameters and influential factors. A passive solar designed building can have issues with its energy performance if the building envelope does not perform as expected. This happens if walls are not well insulated, if windows are not well sealed and single glazed, and if the construction materials used have high U-values. These are the most significant features to secure heating or cooling set temperatures inside the building. Current observation and monitoring tools such as the thermographic survey being used in the fieldwork can detect where heat losses occur from the building. Bearing in mind that the building has been well designed and sealed and properly insulated, issues can still occur in the energy efficiency of the systems if office buildings are not operated properly by the management team and the FM team. It is highly important to ensure that all the energy equipment within a system performs according to the thermostats and the set temperature parameters. It is also important that heating or cooling operates only when needed within the office hours - this will save energy and help to achieve energy efficiencies. Energy can be further reduced by increasing the set temperatures of the cooling system in the summer and by maximizing the use of natural ventilation. Equally, energy can be further reduced if the set heating temperature in the winter is slightly decreased. This will eventually improve energy efficiency and reduce energy consumption.

Other measures for reducing energy consumption and for bringing existing sustainable office buildings to new benchmark levels would be the installation of renewable technology in the buildings or the use of renewable fuels, as revealed by the LCA sensitivity analysis. Such an investment will be cost effective but it will help in achieving higher energy efficiencies and in reducing further greenhouse emissions.

The occupancy factor plays the most significant role in heat and cooling losses of a building and it can influence to a great extent the energy consumption. Indoor temperature comfort satisfaction depends on different occupants' perception. However, as the buildings in this case are offices, most of the control of the energy is the responsibility of the FM team. Occupants make the classic mistakes of leaving doors and windows open when heating or cooling must be on. This means that heat or cooling escapes and in order for the indoor set temperatures to be achieved the systems will have to perform longer and at higher speed (in the case of fans). This can greatly increase energy consumption. The issue can be resolved through frequent meetings with the occupants to inform them on the energy consumption of the buildings and on the targets that must be achieved. Occupants have to be aware of the consequences on the environment of their interaction with the building's products-technology. The LCA results can help in providing a better understanding about these consequences. Occupancy interaction could be enhanced only if the occupants are guided with ''what to do'' and when to ''do it''. This can happen by installing sensors in the buildings that will inform the occupant when to open or close the windows, for instance.

In order for sustainable office buildings to remain sustainable for longer it would also been helpful if the technologies used in office buildings were tested before installment. This would help to make comparisons between different equipment and systems and to find out which technology works better. The thesis suggests this area for further research. Apart from the building, the occupancy and the managing factors, all the systems within an office building must be checked for leakages as this influences more energy efficiency and energy consumption by more than 25%. If such measures are taken into consideration, this will help sustainable office buildings to remain sustainable in the long run. The idea is to avoid worst case scenarios of changing nothing, as demonstrated through the hypothetical scenarios were developed in the thesis.

2. Refurbished sustainable office buildings perform better than sustainable new office buildings

It is expected that sustainable new office buildings perform better than sustainable refurbished as the whole building is designed and constructed from scratch according to the passive solar design and energy efficiency standards and principles. Currently most of the sustainable office buildings with BREEAM excellent or outstanding are new office buildings. However the number of BREEAM excellent refurbished office buildings has increased. As yet, there are no BREEAM outstanding refurbished office buildings, although this could be achieved considering the recommendations provided.

This study has revealed that the cooling systems of sustainable refurbished office buildings is more energy efficient than sustainable new office buildings. The EIIC mechanical cooling system is the VRV/VRF type that operates with zone control and is switched on only in the office space-room whenever needed. Through this type, electricity for cooling is reduced. The CHP trigeneration type installed in the network of the Edinburgh University Campus is switched on in the summer period where cooling is not really needed. The un-used heat stored from the winter and not recovered from the system as new heat or power is used as cooling. However if cooling consumption is less than what is expected then the recovery loses its efficiency as the return fuel that passes the heat exchanger is below the accepted temperature of the system. Thus the waste heat is rejected into the environment. For CHP to be energy efficient in the summer it has been suggested that is is switched off in the summer period and backup mechanical cooling such as VRV technology is used if cooling is needed.

The natural gas condensing boilers used in the CHP is not the most efficient combination for the Potterrow building. Perhaps the use of biofuels such as biomass would have less environmental impact, although from the sensitivity analysis, it appears that heat pumps and VRV technology supplied with power from renewable is the most current state of the art combination for large office buildings. This kind of combination could actually upgrade the BREEAM scoring for the sustainable office buildings. This type of measure should also be considered as a potential measure for conventional office buildings. Ultimately, it all depends on plans.

From the existing POE survey and the POE additional survey of this thesis, it has been demonstrated that energy consumption of both types of office building needs further improvements, considering the existing office building benchmarks. At first it is suggested that all the heat losses detected must be treated and attention given to taking correct energy metering from the sub-meters. The control-facility management team should take further measures to reduce energy consumption, starting with the zone controls and the thermostat indoor set temperatures. Also it is important that no equipment is operated in off-office hours, evenings, weekends, and bank holidays. The management team and the FM team must put forward a plan for back up cooling and heating supply if needed during off-office hours and how this can be controlled so that heating consumption can decrease and not increase.

3. Conventional office buildings can potentially become BREEAM excellent or outstanding; better than existing current BREEAM excellent office buildings

Currently the UK green government has realised the potentials for energy savings by retrofitting existing building stock. However, there are still some barriers and gaps in the policy and targets for office buildings and most of the current energy programs that exist in the UK are for households. The UK government must look at developing further investment plans for the huge office building sector in the UK in order for existing stock to undergo the appropriate transformation to low and zero carbon office building (80% reduction in green house gasses by 2050).

Beyond this external parameter, the existing office buildings need in-depth retrofitting starting from constructing passive solar-thermal building envelope systems. In some building types built from the 1950s-60s onwards a ‘’face-off’’ procedure on the existing building envelopes can be deployed. Older buildings need facade retention-preservation of the existing facades of the buildings that are Listed or are in conservation areas. In-depth interior refurbishment will normally take place in these schemes and perhaps insulation and double glazing could be allowed in some cases.

The most important measure in old buildings is to maximise the insulation level, to reduce the glazing ratio, to replace single-glazed windows with double-glazed windows, to reduce the window surface and to lower u-values. Thereafter, depending on the budget, the most energy efficient systems must be used, considering the life span of the building and future scenarios for additional energy savings.

The energy recovery systems like CHP, reduces energy waste compared to power grid transmissions. This is highly important although its energy efficiency depends on various factors.

An important suggestion that this study raises is that in order to support decision making on the correct long run choices for heating or cooling system equipment, it would be helpful if the systems were tested and monitored prior to their installation in office buildings. This is an important area for consideration and for further research.

4. Conventional office buildings have lower embodied raw-material emissions than sustainable office buildings

Currently the UK policy has not considered the embodied raw-material emissions of heating and cooling systems, which is surprising considering the amount of new technologies needed annually to be installed in new office buildings and to replace existing old and low-energy efficient systems. It is sensible to expect that sustainable office buildings should have less heating and cooling systems as the building envelopes are made in such a way as to reduce heating and cooling consumption. However it was shown that the buildings themselves are not sufficient to enhance energy efficiency without the use of specific equipment types.

This study has revealed that energy efficiency overlaps material efficiency and causes significant raw-material emissions. The CHP for instance needs trench systems and underfloor heating with manifolds to enhance its performance. Additional equipment increases the embodied raw-material emissions. Also, some of the equipment used such as boilers and chillers are large in size and this also increases the raw-material emissions.

It is apparent that the office building sector takes the appropriate initiatives to contribute in the reduction of the embodied raw-material emissions. This can be further boosted by integrating this aspect into UK polices. The office building sector can contribute to this area either by maximizing the thermal performance of the building envelope to the maximum level or through innovation, which means that new technologies must be designed-produced so that the amount of heating and cooling systems will be reduced.

In the reduction of the embodied raw-material emissions manufacturing will play the most significant role. This thesis suggests that the use of eco-labels and ratings on the products will encourage developers and producers to produce low-embodied raw-material equipment. Maximising the recyclability content of the raw-materials will certainly help in reducing the embodied emissions. However whether recycled equipments will be preferred compared to completely new equipment, as this could have an impact in the life span of the product, needs further investigation.

The development of the ERMEI indicator can play a crucial role in the LCA assessment of raw-material emissions of products or systems and in bringing to the fore this particularly significant issue that threatens ecosystem quality, natural resources and human health.

5. The existing BREEAM excellent assessments prior to the building operation stage do not represent the actual energy and environmental performance of office buildings

The problem with the current sustainable office buildings that were assessed with BREEAM in the pre-construction stage in 2004 and 2006 is that the office buildings are not as energy efficient as expected. POE surveys were conducted only in the EIIC in 2010 and in 2012 in the Potterow building, but these are not yet available. The EIIC occupancy satisfaction survey showed what goes wrong in terms of indoor temperature heating and cooling comforts. The survey demonstrates that the building performs at benchmark levels. This study has shown that the thermal performance in the building envelope can be further improved and that a change in the indoor set temperatures and the operation of the systems only during office hours by even 10˚C can show substantial reductions in the energy consumption. Thus the POE evaluation is highly important to understand whether a sustainable office building performs as expected. Perhaps BREEAM should be re-assessed and the analogous credits should be provided, even if that means that e building from excellent goes to very good. This would more fair. However another solution would be to pre-monitor and pre-test systems before they are installed in the buildings to ensure that the most energy efficient solutions upon testing have been chosen.

6. The development of the new sustainability indicator OLRLCII that considers long run hypothetical scenarios can support decision making in maximizing energy efficiency and material efficiency in the long run.

The development of the new sustainability indicator and its proposed integration in the current energy and environmental assessments and consultancy is important in order to ensure high energy efficiencies and low embodied raw-material emissions in the long run before recommendations are provided.

9.2 Recommendations for Future Work

1. Integration of a new sustainability indicator into the existing SAMs

This study has revealed the significance of the development of the ERMEI and the OLRLCII and explored their application as a first attempt; methods of integration into the existing sustainable assessment methods and environmental labeling have been suggested. This integration needs further exploration, looking in more detail at all the components and contents of the SAMs.

2. Integration of the new indicators into the existing environmental policy

The integration of these new indicators can be enhanced through policy changes at EU and UK level. The embodied raw-material emissions of energy efficient heating and cooling systems must be further emphasized and implemented through environmental policy and standards. This will force the manufacturing and supply chain to reduce embodied emissions, to record and make available this kind of data.

3. Implementation of the development of long run scenarios through its integration into the existing LCA software packages (SimaPro).

The development of the hypothetical long run scenarios and their application and exploration through a new sustainability indicator research framework could also be applied and evaluated as an optional evaluation method though the existing LCA software packages.

4. UK office building energy and environmental performance registry: an e-database and an e-map could allow case study comparisons, classifications, benchmarking and energy behavior change.

This kind of system will help to keep under control the emission targets, it will provide an overview picture of the office building sector status and needs for change and it will also increase awareness.

5. Overcoming LCA data limitations and providing material specs: advanced digital technologies to help capture and analyse life cycle embodied raw-material emissions for building simulations

Advanced digital technology helps to measure and analyse different product components and material properties. It may be very helpful if that could be used to capture and analyse the eco-efficiency of building products and services through 3D digital modelling.

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Dimitrokali, E., & Hartungi, R., & Howe, J., Interdisciplinary Ph.D. Workshop in Sustainable Development, oral presentation on the paper, ‘Life Cycle Assessment To Evaluate The
Environmental Impacts Of Energy-Efficient Technology On Office Buildings’, Columbia University, New York 6-7 May 2011

Poster Presentations

Poster research presentation to an audience of MPs and Lords at the launch of a postgraduate strategy for Britain in the House of Commons, British Parliament, 2 March 2010

The environmental performance of heating and cooling between sustainable and conventional office buildings

by

Elisavet Dimitrokali
BA (Hons), MSc

VOLUME (II) -Appendices

A thesis submitted in partial fulfilment for the requirements for the degree of Doctor of Philosophy at the University of Central Lancashire

April 2014

PhD Thesis

Environmental Performance Evaluation of Heating and Cooling Between Sustainable and Conventional Office Buildings

Dr Elisavet Dimitrokali

CONTENTS

APPENDIX 1 PROJECT BRIEF

PURPOSE OF THE PROJECT BRIEF

The purpose of this project brief is to inform stakeholders taking part in the full life cycle phase of heating and cooling systems (see appendix 2) in office buildings, on the aims, objectives and broader contribution of this research on LCA. Further, information is included on the requirements needed to meet the objectives of this study. Please refer to the appendices while reading this document.

<table>
<tr><td colspan="2">**PROJECT TITLE:**
The impact of sustainable technology on office buildings, energy use, using Life Cycle Assessment (LCA)</td></tr>
<tr><td>**Institution:** University of Central Lancashire, Preston</td><td>**Department:** Centre for Sustainable Development,
School of Built and Natural Environment</td></tr>
<tr><td>**Author:** **Elisavet Dimitrokali**</td><td>**Date:**</td></tr>
</table>

AIM

The aim of using life cycle assessment (LCA) in this PhD is to investigate the environmental impacts of heating and cooling systems in office buildings in the UK. For this LCA study extensive research is needed on the inputs (raw materials, energy and waste) and on the outputs (which emissions are released into the air, water and landfills and which impacts occur) from the full life cycle phases/processes of the heating and cooling systems. This thesis will test the hypothesis that sustainable technologies can be more beneficial in the long run. To test this hypothesis, two case studies will be chosen; two conventional and two sustainable office buildings, which will be compared with LCA. When data is analysed, the results will be discussed and validated by an LCA panel of experts and final results will be written in a report which will be submitted to the stakeholders (see appendix 1 for the stages of the research).

OBJECTIVES

- ☐ Identify and measure the environmental impacts of heating and cooling systems in the environment
- ☐ Use a holistic approach (full life cycle-base and process-base approach) to identify issues and areas for improvement related to the existing technologies in new and refurbished sustainable and conventional office buildings in the UK (see appendix 2)
- ☐ Look at the environmental criteria-decisions taken by stakeholders in the full life cycle and support decision making (see appendix 2)
- ☐ Provide recommendations for improving environmental criteria for all the life cycle phases (existing and potential systems)
- ☐ Provide recommendations for potential development of the LCA application in the building sector
- ☐ Ensure objectivity of the results; assumptions will be considered during interpretation by the support of an LCA panel of experts

THE BROADER CONTRIBUTION OF THIS PHD ON LCA

- ☐ The overall interest of the thesis is on wide fields of research such as climate change, energy, waste and management, sustainability and sustainable development
- ☐ The main interest and contribution of the thesis is on reducing energy consumption and environmental impacts from the office building sector and on ensuring that sustainable technologies can be more beneficial in the long run
- ☐ The first international LCA study which will integrate scenarios for future changes in temperatures
- ☐ This study will be the first academic LCA in the UK to assess the environmental impacts of heating and cooling systems by making a comparison between conventional and sustainable office buildings
- ☐ This study is further significant because it will assess BREEAM certified buildings in the UK which will contribute to unravelling issues on the way certain buildings are certified
- ☐ By investigating the environmental impacts of heating and cooling systems there is also a contribution to reducing energy ratings and improving indoor environmental qualities
- ☐ This study will also look at issues of retrofitting on heating and cooling systems which have not been included in any LCA study on office buildings so far

CONSTRAINTS

Restrictions on time: Fieldwork research will start beginning of June 2010 and must finish by February 2011. Data collection must finish by the end of February.

Objectivity: Data collection is the most significant part of the research and realistic data from stakeholders needs to be collected.

Resources: Availability of data needed from case study research is highly important and it can influence the results of the LCA study.

REQUIREMENTS

For the case study research various data is needed. Different stakeholder groups will receive two parts of questionnaires. The first part will be on the criteria of decision making and the second part on the data that needs to be collected for the LCA.

RISK ASSESSMENT AND ETHICAL APPROVAL

Risk Assessment is covered by the University. There are no ethical issues

CONFIDENTIALITY

It is understood that some data might be commercially sensitive and I am happy to take steps to deal with that. Please let me know in advance if any of the information you provide to me is confidential or if there is some level of confidentiality.

METHODOLOGY

Stage 1: Data collections

Stage 2: Analysis of the environmental impacts of heating and cooling systems

Stage 3: Validation (LCA experts will provide information on the interpretation of the results)

Stage 4: Inform decision makers

APPENDIX 2 QUESTIONNAIRE FOR THE RAW-MATERIAL DATA COLLECTION

DETAILS OF MANUFACTURER AND PRODUCT:

Manufacturer Details:

Company Name:

ABN[15]:

Street Address:	Postal Address[16]: PO Box:	Phone:	Manufacturing Site Street Address[17]:
City/Town:	City/Town:	Fax:	City/Town
State:	State:	Email:	State:
Postcode:	Postcode:	Web:	Postcode:
Country:	Country:		Country:

Australian Distributor Details[18]:

Company Name:

ABN:

Street Address:	Postal Address[2]:	Phone:
City/Town:	City/Town:	Fax:
State:	State:	Email:
Postcode:	Postcode:	Web:
Country:	Country:	

Product Information:

Function(s)[19]:	Brand[20]:	Product[21]:

If you feel any additional information is necessary to describe your product, please provide it here:

---

[15] Australian companies only
[16] If applicable
[17] If different from main company address
[18] If different from manufacturer
[19] Eg, external cladding
[20] Eg, HardiPlank Cladding
[21] Eg, Woodgrain

Respondent’s Details:

Contact Name:	Position:	Phone:
Fax:	Email:	Submission Date:

ENVIRONMENTAL CHARACTERISTICS OF PRODUCT

Embodied Materials and Energy, and Associated Environmental Impacts

The embodied energy and materials are the total amount of energy and materials required to produce the particularproduct from raw materials and transport it to the building site. They include the energy and materials necessary for mining and harvesting basic inputs, transformation and manufacturing, and transport and packaging throughout the supply chain.

The environmental impact of such activities can be reduced through materials and energy efficiency, use of renewable energy and materials harvested sustainably, cleaner production and the use of low-toxicity materials, the use of recycled materials and so on.

1 INPUTS INTO THE MANUFACTURING PROCESS

This section aims to define the environmental impacts of:

- mining and harvesting raw materials;
- collection and possible reprocessing of reused/recycled materials;
- production of components; and
- transport of inputs to the manufacturer's premises.

This is often referred to as the cradle-to-gate segment of the life cycle.

Many manufacturers will not yet have a detailed and accurate knowledge of the environmental impacts of activities one or more steps up their supply chain. It is assumed that all manufacturers, however, will have a keen interest in the physical characteristics of the material inputs into their processes for quality assurance reasons, at least.

Information relating directly to physical characteristics of your material inputs is sought immediately below.

Other questions relating to the environmental impacts of the inputs into your manufacturing process that you may find more difficult to answer have been placed in Appendix A. To answer these questions you will need to obtain information from your suppliers, perhaps by getting them to fill in a questionnaire like this one.

Materials

1A1 Please identify the following for the materials in your manufactured product:

(a) Name of material
(b) Percentage by weight of whole
(c) Original geographic location
(d) Process of acquisition and/or extraction

Input Material 1	Input Material 2
(a)	(a)
(b)	(b)
(c)	(c)
(d)	(d)
Input Material 3	Input Material 4
(a)	(a)
(b)	(b)
(c)	(c)
(d)	(d)
Input Material 5	Input Material 6
(a)	(a)
(b)	(b)
(c)	(c)
(d)	(d)

Minor materials do not need be included, unless they are likely to be of particular environmental significance. You may define a cut off criterion for including materials in Section 1A1,– eg , 2% by weight of final product]. Have you applied a cutoff criterion and if so what is it?:

Cutoff criterion:

If the product is not supplied in bulk, what is its weight per item?

Kg

1A2 Does the product contain post-consumer[22] waste material? Yes/No/Don't Know

If yes, please identify the material(s) and the percentage of the total product weight each post-consumer material component represents.

Post-Consumer Material	Percentage of Total Product Weight

1A3 Does the product contain post-industrial[23] waste? Yes/No/Don't Know

If yes, please identify the material(s) and the percentage of total product weight each post-industrial material represents.

---

[22] Post-consumer waste material is material from *products* and/or associated packaging that have been used by domestic or commercial /industrial consumers.

[23] Post-industrial waste material is industrial scrap from other manufacturing plants. The use of in-plant scrap is considered in Section 1B, rather than here.

Post-Industrial Material	Percentage of Total Product Weight

1A4 Does the product contain renewable materials such as agricultural products, by-products or wastes?
Yes/No/Don't Know

If yes, please identify the material(s), its source and the percentage of the total product weight it represents:

Material	Description of Source	Percentage of Total Product Weight

Are these renewable materials sustainably harvested or extracted? Yes/No/Don't Know

If yes, please identify which one(s) and describe the processes involved:

Material	Description of Sustainable Harvesting or Extraction

1A5: If timber is used in the product, is it re-used/recycled, from a plantation source or certified by the Forest Stewardship Council or another recognised reputable agency? Yes/No/Don't Know/Not Applicable

If yes, please provide details:

Supplementary information on inputs into your manufacturing process is sought in Appendix A. T o answer these additional questions, where relevant, will require the provision of information from your suppliers.

2 YOUR MANUFACTURING PROCESS

This section aims to define the environmental impacts of the manufacture of your product.

Materials

2A1 Is scrap material from your manufacturing process re-used, or recycled? Yes/No

If yes, please identify the material(s), whether it is re-used/recycled in your process or recycled by another user, and what percentage of the material in your product this represents:

Material	Used by you (%)	Used by Others (%)

2A2 Are any non-hazardous solid materials disposed of to landfill from your process? Yes/No

If yes, please indicate the total amount (in kg/kg of product or kg/item of product – specify which):
______________ kg/_____ of product

Please provide as much detail as you can on the composition of this solid waste stream:

Material	% by weight of landfilled waste stream
TOTAL	100

2A2 Is water used in the manufacturing process? Yes/No

If yes, how much water is required in manufacturing (in L/kg of product, or L/item of product – specify which): _________L/ _____ of product

2A3 Is non-potable, recycled or waste water *from an external source of supply* used? Yes/No

If yes, please describe and indicate what percentage of total water consumption this represents:

2A4 Have specific *in-plant* water efficiency or water re-use/recycling measures been implemented? Yes/No

If yes, please describe the measures indicating when they were introduced and the savings in water consumption (in L/kg of product or L/item of product – specify which) that have resulted.

Measure	When Implemented	Savings

Energy

2B1 Please specifiy the energy use per kg or per item of product from each of the following energy sources:

Electricity	kWh/
Natural Gas	MJ/
Diesel	Litres/
LPG	Litres/
Biomass (specify- wood/straw etc)	kg/
Other (specify)	/

If electricity is used what is its source?

The Grid %

Certified Green Power % Supplier

Own geneneration % %

If you generate your own electricity, please indicate the fuel(s) used and the estimated generation efficiency:

Fuel	**Generation Efficiency**

2B2 Have specific in-plant energy efficiency measures been implemented? Yes/No

If yes, please describe the measures indicating when they were introduced and savings in energy consumption (in MJ/kg or MJ/item of product) that have resulted.

Measure	When Implemented	Savings

Greenhouse Gases

2C1 Have you calculated the embodied greenhouse gas emissions associated with the manufacture of your product? Yes/No

If yes, what is it (in kg CO_2-e/kg of material or kg CO_2-e/item of product)?
__________kg CO_2-e/____ of product

2C2 In addition to energy efficiency measures, has switching from more to less carbon-intensive fossil fuels or to renewable energy taken place to reduce emissions of carbon dioxide? Yes/No

If yes, please describe the measures indicating when they were introduced and the reductions in carbon dioxide emissions (in MJ/kg or MJ/item of product) that have resulted.

Measure	Reduction in CO_2 emissions achieved

2C3 Do emissions of any of the following direct greenhouse gases :(methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HCFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6)) and indirect greenhouse gases (carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane volatile organic compounds (NMVOCs)) occur in the manufacturing process? Yes/No

If yes, if possible please identify the gases, and the nature, source and scale (in kg of the gas concerned/kg or item of product – specify which) of the emissions:

Greenhouse Gas	Nature, Source and Scale of Emissions

Are any steps planned to reduce such emissions?: Yes/No

If yes, please describe the emission being addressed, the planned measure(s) and its timing, and the anticipated impact (quantified if possible):

Greenhouse Gas	Measure and Timing	Anticipated Impact

Ozone Depletion

2D1 Are the following ozone-depleting gases (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, methyl chloroform (1,1,1-trichloroethane – $C_2H_3Cl_3$), methyl bromide (CH_3Br) carbon tetrachloride (CCl_4) used in the manufacturing process? Yes/No

If yes, are there any associated emissions of these gases? Yes/No/Don’t Know

If yes, please identify the gases and the nature, source and scale of any emissions (in kg of the gas concerned/kg of product or item of product – specify which)

Ozone-Depleting Gas	Nature, Source and Scale of Emissions

Hazardous Substances Inputs and Releases to the Environment

Appendix B contains the 90 substances (or classes of substances) listed on Australia's National Pollutant Inventory whose release into the environment must be reported on from 2001/2002 onward.

This section is seeking to gain information on the use of hazardous substances in the manufacturer's supply chain (the avoidance of which is an aspect of cleaner production) and their release into the environment following their use or creation in the supply chain.

2E1 Are any of the substances in Appendix B used in your manufacturing process? Yes/No/Don't Know

If yes, please indicate which substances and how they are used in your process:

Hazardous Substance	Manner of Use

2E2 During manufacture are any of the substances in Appendix B released to or deposited in:

(i) air
(ii) surface water bodies
(iii) aquifers
(iv) sewer
(v) landfill
(vi) storage facilities Yes/No

If yes, please indicate which substances, the manner of their release or deposition, and the quantity involved (in kg/kg of product or kg/item of product – specify which):

Substance	Manner of Release or Deposition	Quantity

2E3 Do you have specific plans in place to strive towards zero pollution from the manufacturing process?

Yes/No

If yes, please provide details:

Substance(s)	Measure and Timing	Anticipated Impact

Other

2F1 In addition to the above, have any other actions been taken to lessen the environmental impact of the manufacturing process? Yes/No

If yes, please describe and quantify the benefit if possible:

Action	Benefit

3 BUILDING OPERATION

Materials

5A1 Does your product have an effective lifetime of less than the anticipated lifetime of most buildings? Yes/No

If yes, please indicate the expected lifetime of your product: __________ years

5A2 Does your product consume or deliver water as an essential part of its operation? Yes/No

If yes, please provide indicate the water efficiency of your product in standard operating mode (in standard units, eg L/minute or L/cycle):

Details of Standard Operating Mode	Water Efficiency

If the product is able to operate in any additional modes, please describe those modes and provide the water efficiency of each:

Details of Operating Mode	Water Efficiency

Energy

5B1 Is your product[24] likely to be incorporated into the building fabric? Yes/No

If yes, please provide the following data: Thermal Resistance (R):
________$m^2W^{-1}K^{-1}$
Density (D):
________$kg.m^{-3}$
Heat Capacity (Cp):
________$kJ.kg^{-1}K^{-1}$

For transparent/translucent products, please provide: % Light transmission
________%
Solar Heat Gain Coefficient:
____

5B2 Does your product consume energy while functioning? Yes/No

If no , go to 5B5

If yes, is there a recognised energy rating or benchmarking system, or standard unit of output efficiency (eg, star rating, lumens/watt etc)? Yes/No

If yes, please describe the rating system/efficiency measure and your product's performance relative to it:

If no, please provide whatever information you can on your product's energy efficiency.

5B3 Is your product designed to operate in a range of different energy-consuming modes (eg full power, standby, sleep, off)? Yes/No

If yes, please list the operating modes and the power demand in each:

Operating Mode	Power Demand (W)

---

[24] For products made up of composite elements, eg a framed window unit, please provide data for the unit as a whole

5B4 If properly serviced/maintained over its lifetime should your product continue to operate at the same efficiency as when installed or commissioned? Yes/No

If yes, please provide information on the assurances you provide in this regard:

If no, please provide information on the expected diminution of performance over time (eg, hours of operation) and any assurances that you provide regarding minimum levels of performance over time.

5B5 Do the conditions in the operating environment (eg temperature, humidity) impose any restrictions on the performance of your product? Yes/No

If yes, please provide information on the limiting conditions and their impact on performance:

Limiting Conditions	Impact Upon Performance

Indoor Air Quality

5C1 Does your product have the potential to impact negatively on indoor air quality[25]? Yes/No/Don't Know

If yes, have emission rates been tested for using recognised procedures? Yes/No

If yes, please specify the pollutants tested for and attach copies of test reports:

Pollutants

---

[25] Products with potential to impact negatively on indoor air quality may include (but should not be assumed to be restricted to): Adhesives, Biocides (which may be incorporated in products to resist pest attack), Carpet (including backing and underlay), Ceiling Panels and Tiles, Chalks, Cleaning Products, Composite Wood Products (including furniture and shelving), Control Joint fillers, Floor Coverings, Flexible Fabrics, Fuel (fossil or biomass)-burning equipment, Gaskets, Glazing Compounds, HVAC Systems, Insulation (acoustic, fire and thermal),Linings, Paints, Partitions, Plasterboard, PVC (Vinyl) Products, Sealants, Toners and Toner-Fusing Equipment (eg photocopiers and laser printers),Wall Coverings, Wood Finishes and Preservatives, Work Surfaces

APPENDIX 3 LIST OF BASELINE DATA COLLECTION ON THE CASE STUDY SITE VISIT

CONVENTIONAL BUILDING GENERAL DATA

Discussion	Responder	Me
1. Size of the building		
2. Location		
3. Orientation		
4. Date		
5. Years of operation		
6. Construction type		
7. Refurbishment/re-arrangements		
8. Number of occupants		
9. Occupancy hours		
10. Which sections are occupied, which are not?		
11. Energy certification		
12. Performance certification		
13. Ventilation		
14. Heating system		
15. Cooling system		
16. Control systems		
17. Occupancy control		
18. Energy type		

19. Source of energy		
20. U-values		
21. Air-permeability		
22. Energy consumption		
23. Insulation materials		
24. Air tightness test		
25. Annual reports on the efficiency of heating and cooling systems		
26. Report on the construction materials		

PLANT ROOM

Systems	heating	cooling
1. Description of the systems		
2. Equipments of the heating/cooling		
3. Description of the heating/cooling process		
4. Control system		
5. Parameters		
6. Indoor temperature		
7. Date of installation/years of operation		
8. Maintenance service		
9. Hours of operation		
10. Heat flows		

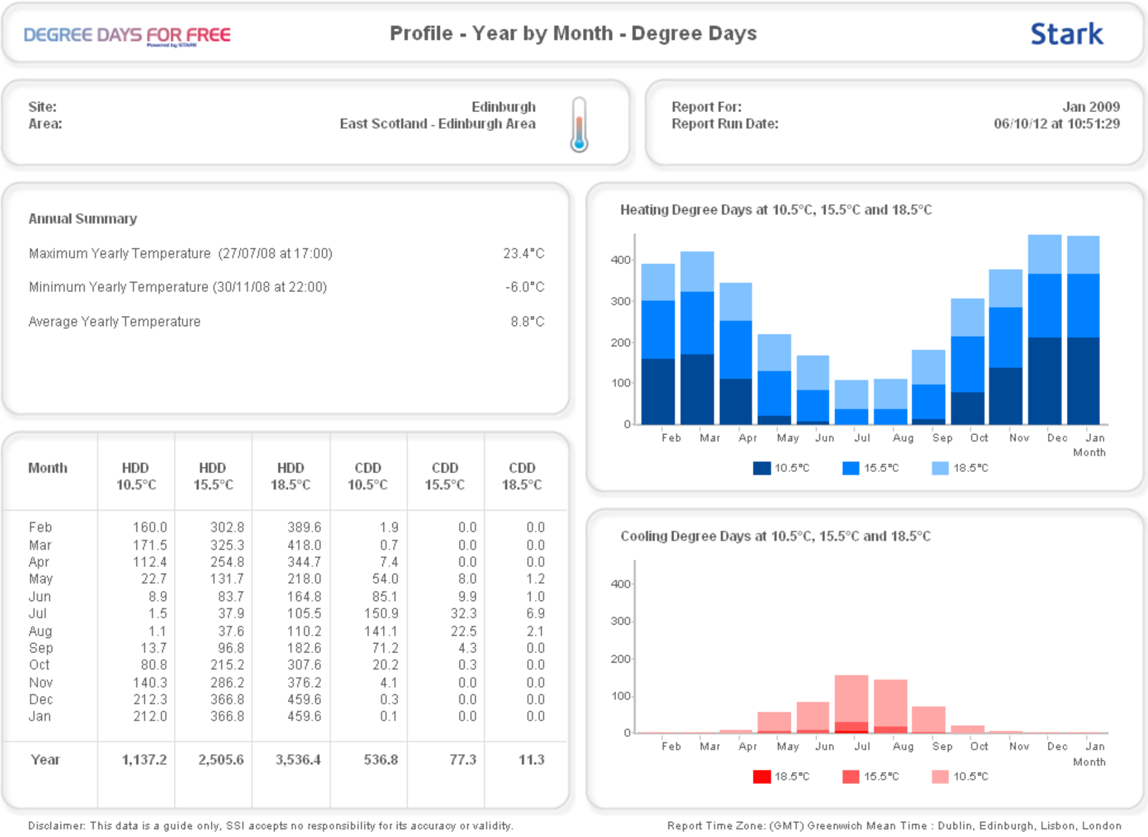
11. Heat losses		
12. Performance certificate		
13. Energy consumption		
14. Manufacturer		
15. Model		

OTHER DATA

Data request	Responder	Interviewer
1. Performance certificates		
2. Energy certificates		
3. Reports on construction of the building		
4. Schedule drawings: reports		
5. Drawings/CAD drawings: plans, sections, building services and plant room		
6. Energy metering		
7. Maintenance reports		
8. Manufacturer’s details		
9. Performance report		
10. Specifications on the systems		

APPENDIX 4 HEATING DEGREE DATA OF THE CASE STUDY BUILDINGS

Monthly DD data has been collected from the ‘DEGREE DAYS FOR FREE’ by STARK, available at (http://www.degreedaysforfree.co.uk/index.aspx) and in the following figures.



DEGREE DAYS FOR FREE

Profile - Year by Month - Degree Days

Stark

Site: Edinburgh
Area: East Scotland - Edinburgh Area

Report For: Jan 2009
Report Run Date: 06/10/12 at 10:51:29

Annual Summary

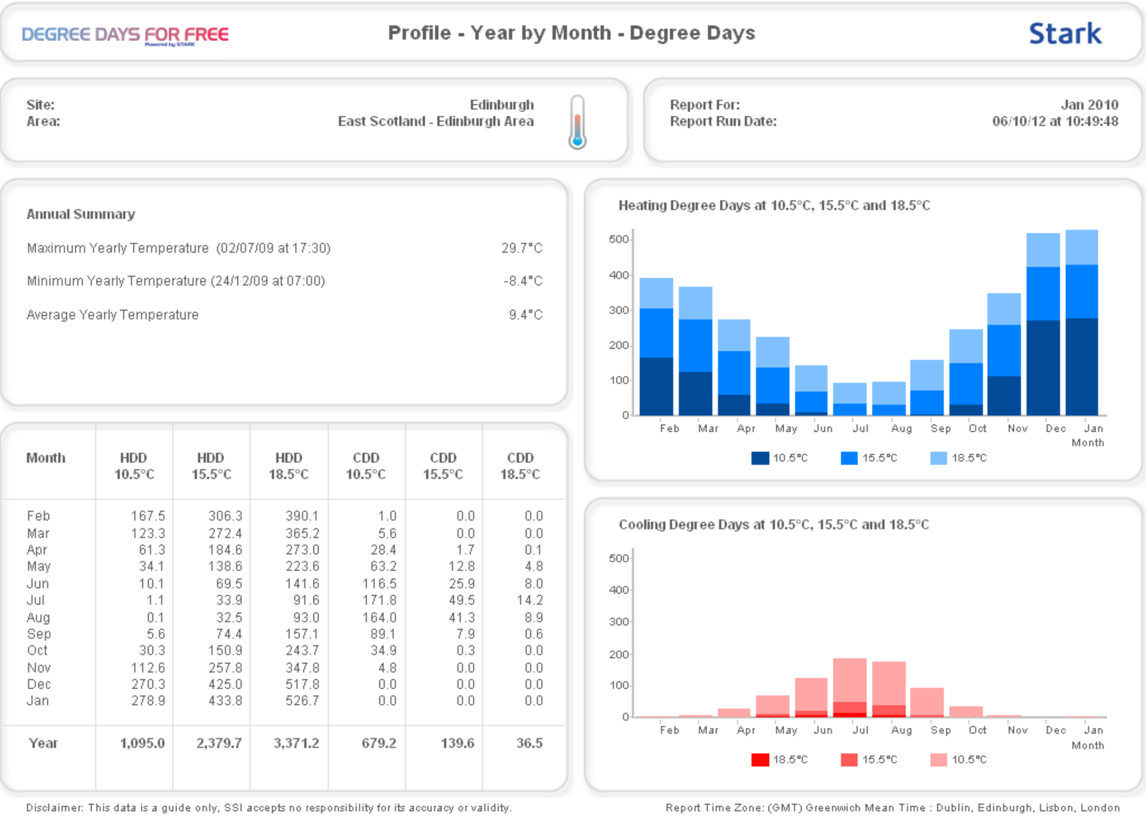
Maximum Yearly Temperature (27/07/08 at 17:00)	23.4°C
Minimum Yearly Temperature (30/11/08 at 22:00)	-6.0°C
Average Yearly Temperature	8.8°C

Month	HDD 10.5°C	HDD 15.5°C	HDD 18.5°C	CDD 10.5°C	CDD 15.5°C	CDD 18.5°C
Feb	160.0	302.8	389.6	1.9	0.0	0.0
Mar	171.5	325.3	418.0	0.7	0.0	0.0
Apr	112.4	254.8	344.7	7.4	0.0	0.0
May	22.7	131.7	218.0	54.0	8.0	1.2
Jun	8.9	83.7	164.8	85.1	9.9	1.0
Jul	1.5	37.9	105.5	150.9	32.3	6.9
Aug	1.1	37.6	110.2	141.1	22.5	2.1
Sep	13.7	96.8	182.6	71.2	4.3	0.0
Oct	80.8	215.2	307.6	20.2	0.3	0.0
Nov	140.3	286.2	376.2	4.1	0.0	0.0
Dec	212.3	366.8	459.6	0.3	0.0	0.0
Jan	212.0	366.8	459.6	0.1	0.0	0.0
Year	**1,137.2**	**2,505.6**	**3,536.4**	**536.8**	**77.3**	**11.3**

Heating Degree Days at 10.5°C, 15.5°C and 18.5°C

Cooling Degree Days at 10.5°C, 15.5°C and 18.5°C

Report Time Zone: (GMT) Greenwich Mean Time : Dublin, Edinburgh, Lisbon, London



DEGREE DAYS FOR FREE

Profile - Year by Month - Degree Days

Stark

Site: Edinburgh
Area: East Scotland - Edinburgh Area

Report For: Jan 2010
Report Run Date: 06/10/12 at 10:49:48

Annual Summary

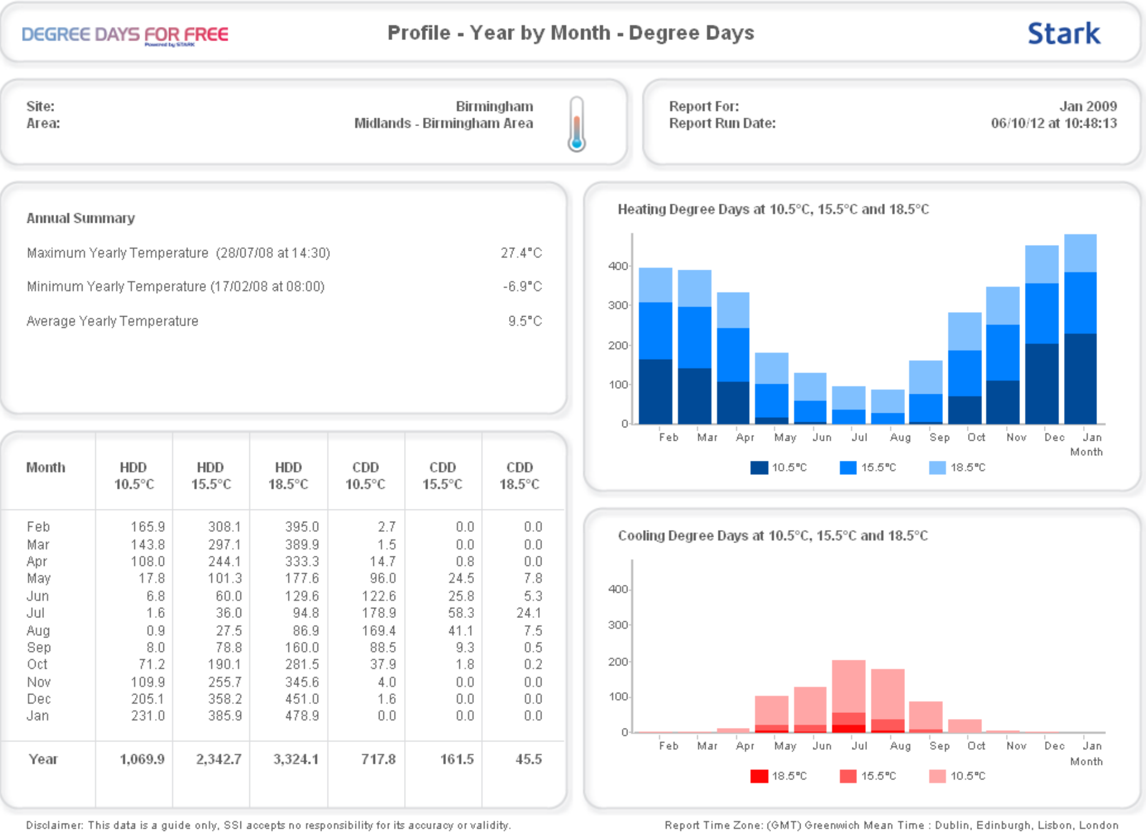
Maximum Yearly Temperature (02/07/09 at 17:30)	29.7°C
Minimum Yearly Temperature (24/12/09 at 07:00)	-8.4°C
Average Yearly Temperature	9.4°C

Month	HDD 10.5°C	HDD 15.5°C	HDD 18.5°C	CDD 10.5°C	CDD 15.5°C	CDD 18.5°C
Feb	167.5	306.3	390.1	1.0	0.0	0.0
Mar	123.3	272.4	365.2	5.6	0.0	0.0
Apr	61.3	184.6	273.0	28.4	1.7	0.1
May	34.1	138.6	223.6	63.2	12.8	4.8
Jun	10.1	69.5	141.6	116.5	25.9	8.0
Jul	1.1	33.9	91.6	171.8	49.5	14.2
Aug	0.1	32.5	93.0	164.0	41.3	8.9
Sep	5.6	74.4	157.1	89.1	7.9	0.6
Oct	30.3	150.9	243.7	34.9	0.3	0.0
Nov	112.6	257.8	347.8	4.8	0.0	0.0
Dec	270.3	425.0	517.8	0.0	0.0	0.0
Jan	278.9	433.8	526.7	0.0	0.0	0.0
Year	**1,095.0**	**2,379.7**	**3,371.2**	**679.2**	**139.6**	**36.5**

Heating Degree Days at 10.5°C, 15.5°C and 18.5°C

Cooling Degree Days at 10.5°C, 15.5°C and 18.5°C

Report Time Zone: (GMT) Greenwich Mean Time : Dublin, Edinburgh, Lisbon, London



DEGREE DAYS FOR FREE

Profile - Year by Month - Degree Days

Stark

Site: Birmingham
Area: Midlands - Birmingham Area

Report For: Jan 2009
Report Run Date: 06/10/12 at 10:48:13

Annual Summary

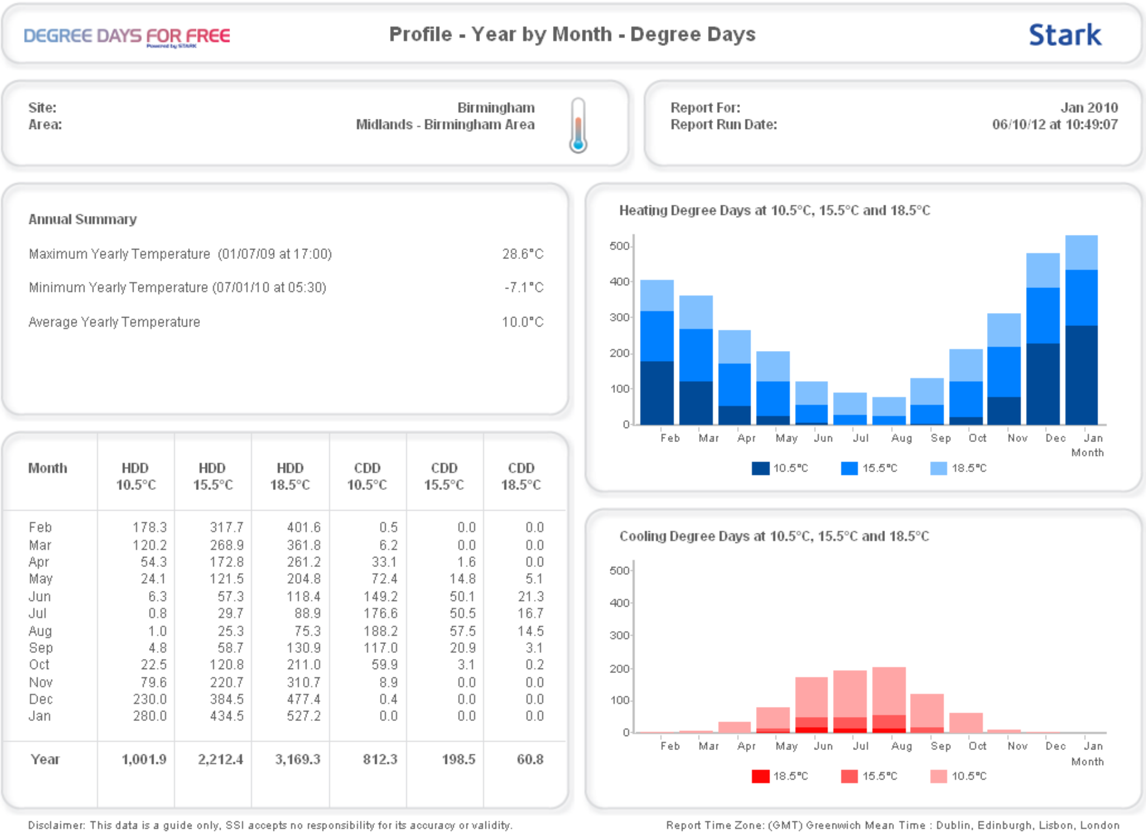
Maximum Yearly Temperature (28/07/08 at 14:30)	27.4°C
Minimum Yearly Temperature (17/02/08 at 08:00)	-6.9°C
Average Yearly Temperature	9.5°C

Month	HDD 10.5°C	HDD 15.5°C	HDD 18.5°C	CDD 10.5°C	CDD 15.5°C	CDD 18.5°C
Feb	165.9	308.1	395.0	2.7	0.0	0.0
Mar	143.8	297.1	389.9	1.5	0.0	0.0
Apr	108.0	244.1	333.3	14.7	0.8	0.0
May	17.8	101.3	177.6	96.0	24.5	7.8
Jun	6.8	60.0	129.6	122.6	25.8	5.3
Jul	1.6	36.0	94.8	178.9	58.3	24.1
Aug	0.9	27.5	86.9	169.4	41.1	7.5
Sep	8.0	78.8	160.0	88.5	9.3	0.5
Oct	71.2	190.1	281.5	37.9	1.8	0.2
Nov	109.9	255.7	345.6	4.0	0.0	0.0
Dec	205.1	358.2	451.0	1.6	0.0	0.0
Jan	231.0	385.9	478.9	0.0	0.0	0.0
Year	**1,069.9**	**2,342.7**	**3,324.1**	**717.8**	**161.5**	**45.5**

Heating Degree Days at 10.5°C, 15.5°C and 18.5°C

Cooling Degree Days at 10.5°C, 15.5°C and 18.5°C

Report Time Zone: (GMT) Greenwich Mean Time : Dublin, Edinburgh, Lisbon, London



Profile - Year by Month - Degree Days

Site: Birmingham
Area: Midlands - Birmingham Area

Report For: Jan 2010
Report Run Date: 06/10/12 at 10:49:07

Annual Summary

Maximum Yearly Temperature (01/07/09 at 17:00)	28.6°C
Minimum Yearly Temperature (07/01/10 at 05:30)	-7.1°C
Average Yearly Temperature	10.0°C

Month	HDD 10.5°C	HDD 15.5°C	HDD 18.5°C	CDD 10.5°C	CDD 15.5°C	CDD 18.5°C
Feb	178.3	317.7	401.6	0.5	0.0	0.0
Mar	120.2	268.9	361.8	6.2	0.0	0.0
Apr	54.3	172.8	261.2	33.1	1.6	0.0
May	24.1	121.5	204.8	72.4	14.8	5.1
Jun	6.3	57.3	118.4	149.2	50.1	21.3
Jul	0.8	29.7	88.9	176.6	50.5	16.7
Aug	1.0	25.3	75.3	188.2	57.5	14.5
Sep	4.8	58.7	130.9	117.0	20.9	3.1
Oct	22.5	120.8	211.0	59.9	3.1	0.2
Nov	79.6	220.7	310.7	8.9	0.0	0.0
Dec	230.0	384.5	477.4	0.4	0.0	0.0
Jan	280.0	434.5	527.2	0.0	0.0	0.0
Year	**1,001.9**	**2,212.4**	**3,169.3**	**812.3**	**198.5**	**60.8**

Heating Degree Days at 10.5°C, 15.5°C and 18.5°C

Cooling Degree Days at 10.5°C, 15.5°C and 18.5°C

Disclaimer: This data is a guide only, SSI accepts no responsibility for its accuracy or validity.

Report Time Zone: (GMT) Greenwich Mean Time : Dublin, Edinburgh, Lisbon, London

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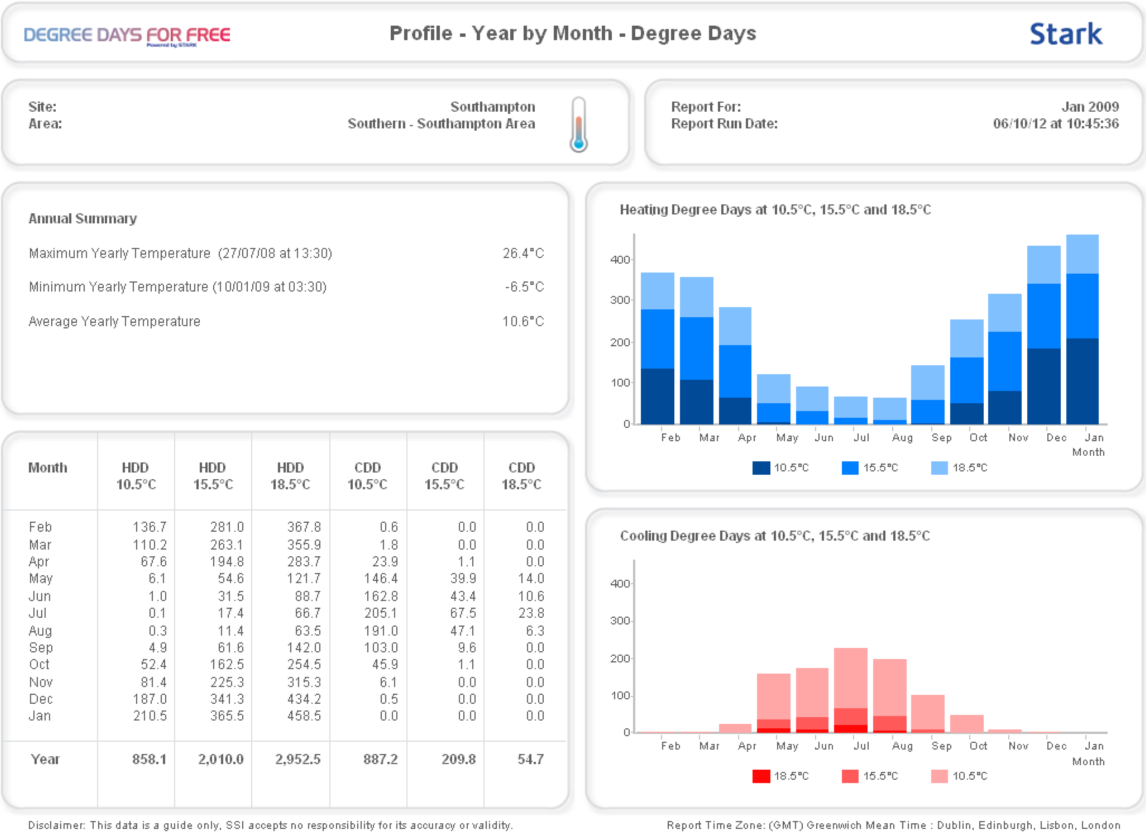


Profile - Year by Month - Degree Days

Site: Southampton
Area: Southern - Southampton Area

Report For: Jan 2009
Report Run Date: 06/10/12 at 10:45:36

Annual Summary

Maximum Yearly Temperature (27/07/08 at 13:30)	26.4°C
Minimum Yearly Temperature (10/01/09 at 03:30)	-6.5°C
Average Yearly Temperature	10.6°C

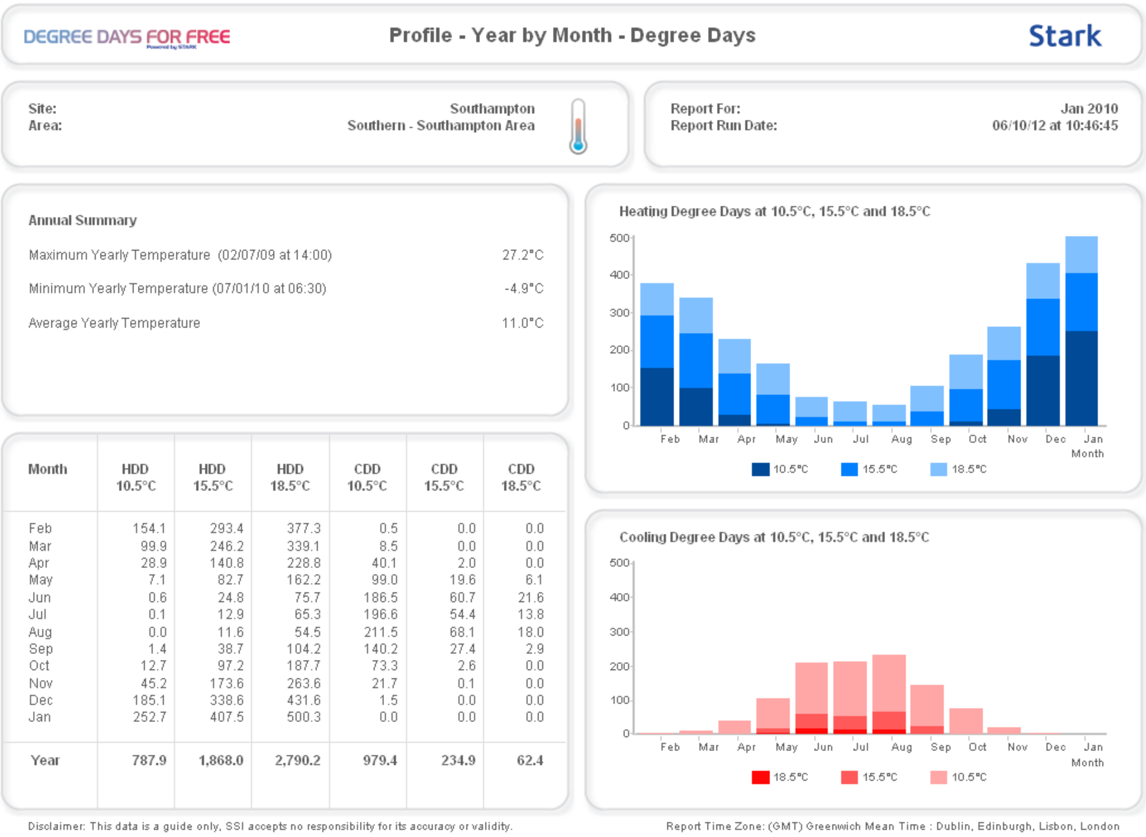
Month	HDD 10.5°C	HDD 15.5°C	HDD 18.5°C	CDD 10.5°C	CDD 15.5°C	CDD 18.5°C
Feb	136.7	281.0	367.8	0.6	0.0	0.0
Mar	110.2	263.1	355.9	1.8	0.0	0.0
Apr	67.6	194.8	283.7	23.9	1.1	0.0
May	6.1	54.6	121.7	146.4	39.9	14.0
Jun	1.0	31.5	88.7	162.8	43.4	10.6
Jul	0.1	17.4	66.7	205.1	67.5	23.8
Aug	0.3	11.4	63.5	191.0	47.1	6.3
Sep	4.9	61.6	142.0	103.0	9.6	0.0
Oct	52.4	162.5	254.5	45.9	1.1	0.0
Nov	81.4	225.3	315.3	6.1	0.0	0.0
Dec	187.0	341.3	434.2	0.5	0.0	0.0
Jan	210.5	365.5	458.5	0.0	0.0	0.0
Year	**858.1**	**2,010.0**	**2,952.5**	**887.2**	**209.8**	**54.7**

Heating Degree Days at 10.5°C, 15.5°C and 18.5°C

Cooling Degree Days at 10.5°C, 15.5°C and 18.5°C

Disclaimer: This data is a guide only, SSI accepts no responsibility for its accuracy or validity.

Report Time Zone: (GMT) Greenwich Mean Time : Dublin, Edinburgh, Lisbon, London



DEGREE DAYS FOR FREE

Profile - Year by Month - Degree Days

Stark

Site: Southampton
Area: Southern - Southampton Area

Report For: Jan 2010
Report Run Date: 06/10/12 at 10:46:45

Annual Summary

Maximum Yearly Temperature (02/07/09 at 14:00)	27.2°C
Minimum Yearly Temperature (07/01/10 at 06:30)	-4.9°C
Average Yearly Temperature	11.0°C

Month	HDD 10.5°C	HDD 15.5°C	HDD 18.5°C	CDD 10.5°C	CDD 15.5°C	CDD 18.5°C
Feb	154.1	293.4	377.3	0.5	0.0	0.0
Mar	99.9	246.2	339.1	8.5	0.0	0.0
Apr	28.9	140.8	228.8	40.1	2.0	0.0
May	7.1	82.7	162.2	99.0	19.6	6.1
Jun	0.6	24.8	75.7	186.5	60.7	21.6
Jul	0.1	12.9	65.3	196.6	54.4	13.8
Aug	0.0	11.6	54.5	211.5	68.1	18.0
Sep	1.4	38.7	104.2	140.2	27.4	2.9
Oct	12.7	97.2	187.7	73.3	2.6	0.0
Nov	45.2	173.6	263.6	21.7	0.1	0.0
Dec	185.1	338.6	431.6	1.5	0.0	0.0
Jan	252.7	407.5	500.3	0.0	0.0	0.0
Year	**787.9**	**1,868.0**	**2,790.2**	**979.4**	**234.9**	**62.4**

Heating Degree Days at 10.5°C, 15.5°C and 18.5°C

Cooling Degree Days at 10.5°C, 15.5°C and 18.5°C

Report Time Zone: (GMT) Greenwich Mean Time : Dublin, Edinburgh, Lisbon, London

APPENDIX 5 HEATING DEGREE DAY BASE TEMPERATURES

MAP BY REGION

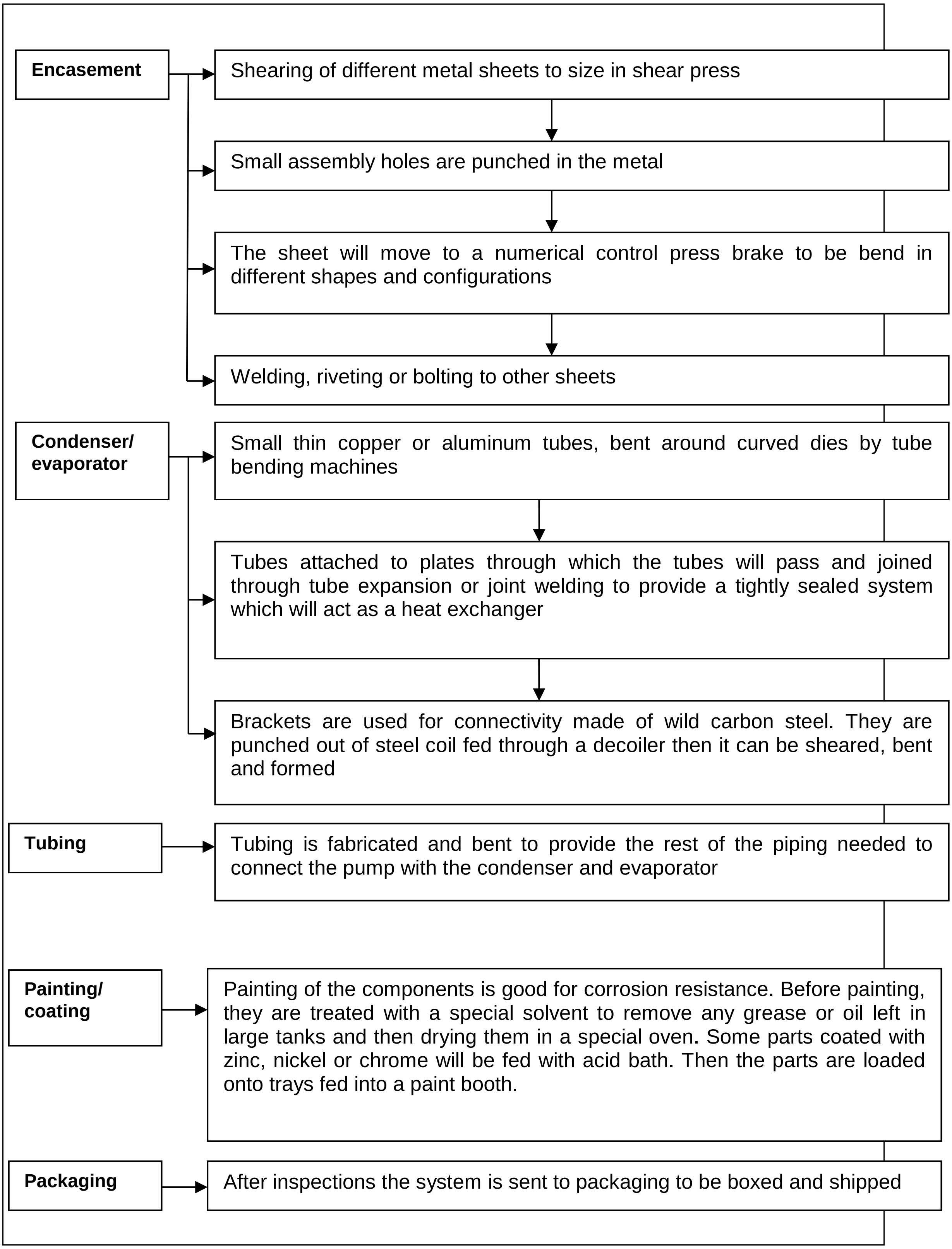
APPENDIX 6 HEATING DEGREE DATA ASSUMPTIONS FOR THE CASE STUDY BUILDINGS

2009	Conventional				BREEAM			
	Argyle House	HDD	Five Ways House	HDD	Potterrow Building	HDD	Elizabeth Courst II	HDD
Base temperature	15,5		15,5		10,5		10,5	
Jan	129,207	366,8	596,377	385,9	2.121,08	212		210,5
Feb	117,314	302,8	531,817	308,1	2.429,30	160		136,7
Mar	119,687	325,3	435,452	297,1	2.690,47	171,5		110,2
Apr	104,225	254,8	256,025	244,1	2.868,44	112,4		67,6
May	95,085	131,7	118,12	101,3	2.987,50	22,7		6,1
June	87,491	83,7	9,585	60	0	8,9		1
July	88,753	37,9	8,661	36	0	1,5		0,1
Aug	87,222	37,6	9,317	27,5	1303,911429	1,1		0,3
Sep	88,189	96,8	40,459	78,8	1.338,58	13,7		4,9
Oct	94,762	215,2	293,214	190,1	1.399,25	80,8		52,4
Nov	96,65	286,2	285,253	255,7	1.618,44	140,3		81,4
Dec	105,238	366,8	600,558	358,2	1.744,38	212,3		187
Sum	**1213,823**	**2505,6**		**2342,8**	**20.501,35**	**1137,2**		**858,2**

2010	Conventional				BREEAM			
	Argyle House	HDD	Five Ways House	HDD	Potterrow Building	HDD	Elizabeth Courst II	HDD
Base temperature	15,5		15,5		10,5		10,5	
Jan	104,023	433,8	596,377	434,5	2.121,08	278,9		252,7
Feb	98,121	306,3	531,817	317,7	2.429,30	167,5		154,1
Mar	103,456	272,4	435,452	268,9	2.690,47	123,3		99,9
Apr	91,253	184,6	256,025	172,8	2.868,44	61,3		28,9
May	87,494	138,6	118,12	121,5	2.987,50	34,1		7,1
June	85,198	69,5	9,585	57,3		10,1		0,6
July	84,113	33,9	8,661	29,7		1,1		0,1
Aug	82,338	32,5	9,317	25,3	1303,911429	0,1		0
Sep	84,179	74,4	40,459	58,7	366,3	5,6		1,4
Oct	91,017	150,9	293,214	120,8	408,5	30,3		12,7
Nov	94,47	257,8	437,183	220,7	477,0	112,6		45,2
Dec	95,925	425	587,172	384,5	1.744,38	270,3		185,1
Sum	**1101,587**	**2379,7**	**3323,382**	2212,4	**17.396,90**	**1095,2**		**787,8**

APPENDIX 7 MANUFACTURING PROCESSES DURING THE PRODUCTION OF HEATING-COOLING SYSTEMS

Manufacturing processes of heat pumps



Encasement

Shearing of different metal sheets to size in shear press

Small assembly holes are punched in the metal

The sheet will move to a numerical control press brake to be bend in different shapes and configurations

Welding, riveting or bolting to other sheets

Condenser/ evaporator

Small thin copper or aluminum tubes, bent around curved dies by tube bending machines

Tubes attached to plates through which the tubes will pass and joined through tube expansion or joint welding to provide a tightly sealed system which will act as a heat exchanger

Brackets are used for connectivity made of wild carbon steel. They are punched out of steel coil fed through a decoiler then it can be sheared, bent and formed

Tubing

Tubing is fabricated and bent to provide the rest of the piping needed to connect the pump with the condenser and evaporator

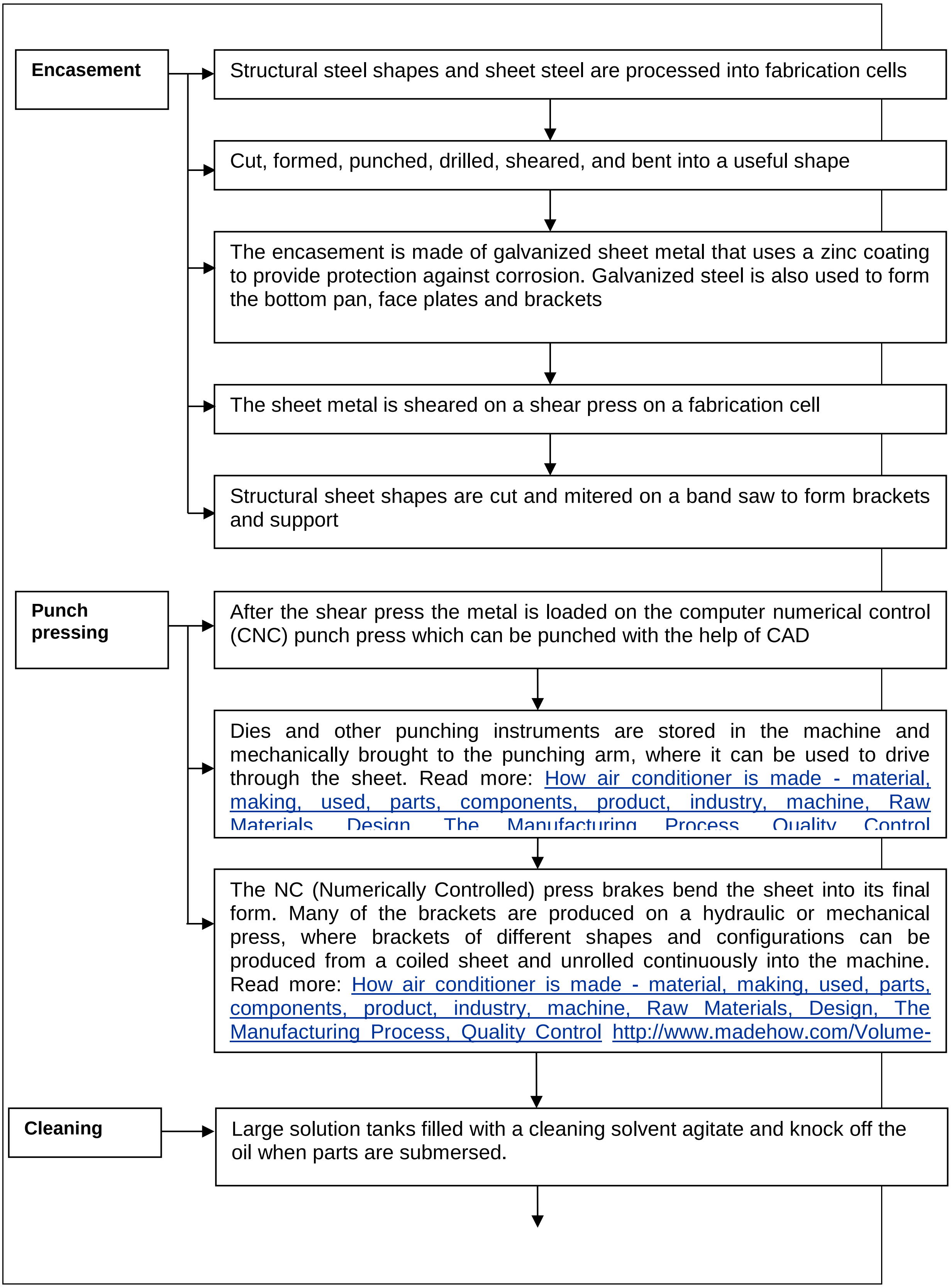
Painting/ coating

Painting of the components is good for corrosion resistance. Before painting, they are treated with a special solvent to remove any grease or oil left in large tanks and then drying them in a special oven. Some parts coated with zinc, nickel or chrome will be fed with acid bath. Then the parts are loaded onto trays fed into a paint booth.

Packaging

After inspections the system is sent to packaging to be boxed and shipped

Manufacturing processes of air-conditioners



Encasement

Structural steel shapes and sheet steel are processed into fabrication cells

Cut, formed, punched, drilled, sheared, and bent into a useful shape

The encasement is made of galvanized sheet metal that uses a zinc coating to provide protection against corrosion. Galvanized steel is also used to form the bottom pan, face plates and brackets

The sheet metal is sheared on a shear press on a fabrication cell

Structural sheet shapes are cut and mitered on a band saw to form brackets and support

Punch pressing

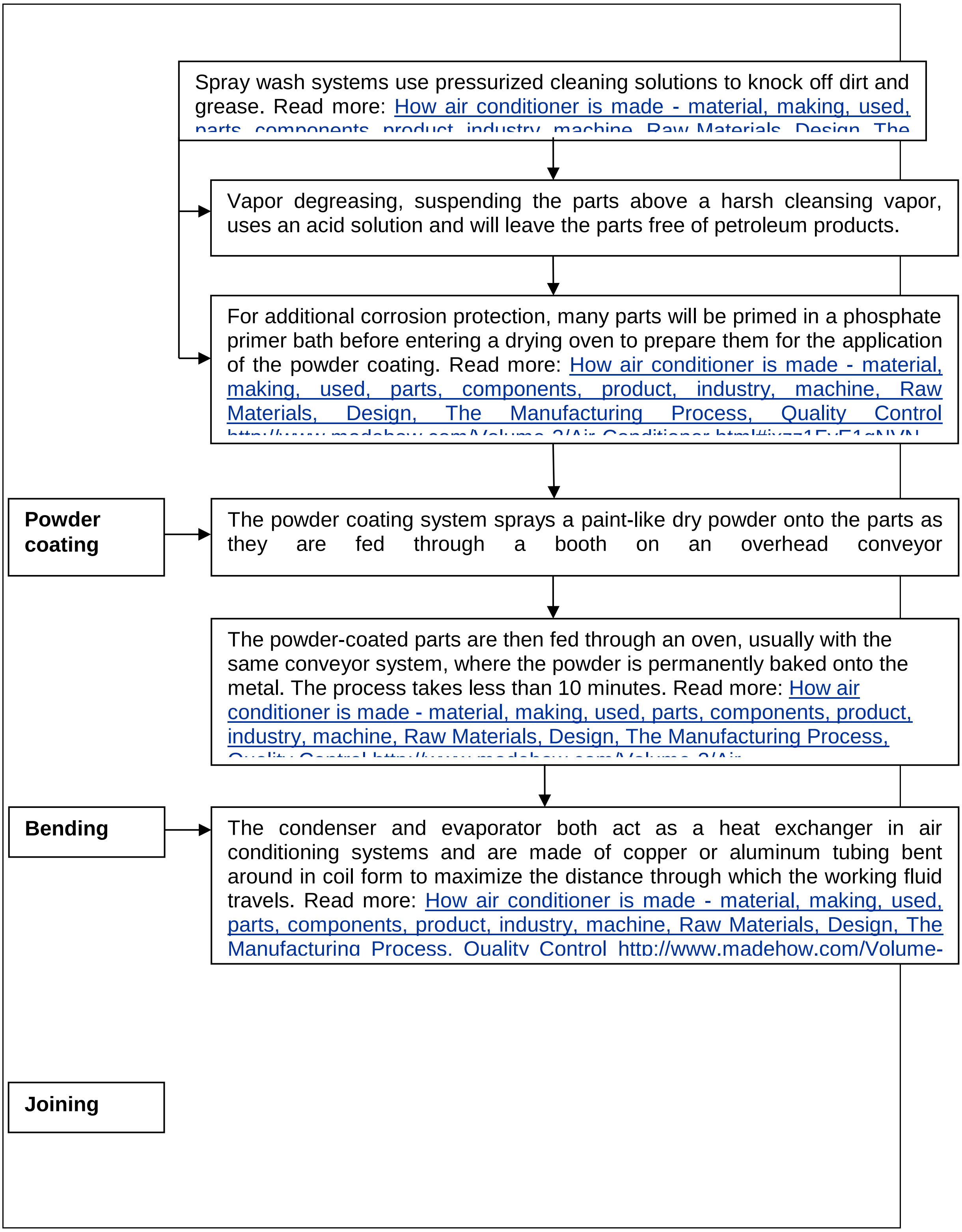
After the shear press the metal is loaded on the computer numerical control (CNC) punch press which can be punched with the help of CAD

Dies and other punching instruments are stored in the machine and mechanically brought to the punching arm, where it can be used to drive through the sheet. Read more: How air conditioner is made - material, making, used, parts, components, product, industry, machine, Raw Materials, Design, The Manufacturing Process, Quality Control

The NC (Numerically Controlled) press brakes bend the sheet into its final form. Many of the brackets are produced on a hydraulic or mechanical press, where brackets of different shapes and configurations can be produced from a coiled sheet and unrolled continuously into the machine. Read more: How air conditioner is made - material, making, used, parts, components, product, industry, machine, Raw Materials, Design, The Manufacturing Process, Quality Control http://www.madehow.com/Volume-

Cleaning

Large solution tanks filled with a cleaning solvent agitate and knock off the oil when parts are submersed.



Spray wash systems use pressurized cleaning solutions to knock off dirt and grease. Read more: How air conditioner is made - material, making, used, parts, components, product, industry, machine, Raw Materials, Design, The

Vapor degreasing, suspending the parts above a harsh cleansing vapor, uses an acid solution and will leave the parts free of petroleum products.

For additional corrosion protection, many parts will be primed in a phosphate primer bath before entering a drying oven to prepare them for the application of the powder coating. Read more: How air conditioner is made - material, making, used, parts, components, product, industry, machine, Raw Materials, Design, The Manufacturing Process, Quality Control http://www.madehow.com/Volume-3/Air-Conditioner.html#ixzz1FyE1gNVN

Powder coating

The powder coating system sprays a paint-like dry powder onto the parts as they are fed through a booth on an overhead conveyor

The powder-coated parts are then fed through an oven, usually with the same conveyor system, where the powder is permanently baked onto the metal. The process takes less than 10 minutes. Read more: How air conditioner is made - material, making, used, parts, components, product, industry, machine, Raw Materials, Design, The Manufacturing Process, Quality Control http://www.madehow.com/Volume-3/Air-

Bending

The condenser and evaporator both act as a heat exchanger in air conditioning systems and are made of copper or aluminum tubing bent around in coil form to maximize the distance through which the working fluid travels. Read more: How air conditioner is made - material, making, used, parts, components, product, industry, machine, Raw Materials, Design, The Manufacturing Process, Quality Control http://www.madehow.com/Volume-

Joining

APPENDIX 8 MATRIX

Baseline Data MATRIX-Building Characteristics

Key notes	
🟩	benchmark
🟩	energy efficient
🟧	medium energy efficient
🟥	low energy-efficient

Office buildings	Potterrow Building	Elizabeth Courts II (former Asburton Court)	Argyle House	Five Ways House
Case study category	**BREEAM new**	**BREEAM refurbished**	**Existing/conventional/future retrofit or demolition**	**Existing/heating plant refurbishment**
Location				
Region	**South East of Scotland**	**South East England**	**South East of Scotland**	**Midlands**
County	**Midlothian**	**Hampshire**	**Midlothian**	**West Midlands**
City/Town	**Edinburgh**	**Winchester**	**Edinburgh**	**Birmingham**
Address	10 Crichton Street/S Charles Street,	High Street, Sussex Street, Tower Street and Tower Road	Laydylawson street and Lauriston place	George Street, Five Ways

	EH8 9AB/EH8 9AD			
Orientation				
building orientation	west	west	south	north
longer facades orientation	west, east and south	west and east	north and south, southwest	north and south
Latitude coordinates	N51 3	N 55.56	N55 56	N52 28
Longitude coordinates	W1 19	W3 11	W3 11	W1 54
Building area/heights				
Total gross floor area	**16,100m2**	**12,600m2**	**20,472**	**15.000m2**
Floors	**6**	**4**	**11**	**6**
Floor heights	2875	2700	n/a	n/a
Floor to floor	3600	n/a	n/a	n/a
Planning grid	1500	1300	n/a	n/a
Raised floor void	450 medium grade	340mm	n/a	n/a
Blocks	n/a	west, east and north blocks	blocks A (zone 3,4),B (zone 1,2) block,C	n/a
Phases	Phase 1 11,900m2 and	n/a	n/a	n/a

	Phase 2A 4,200m2, Phase 2B not built			
Construction				
Year of construction	2008	1960	1960	1950
Listed building (grade a,b,c)	n/a	Grade B', in 1998	n/a	n/a
Conservation area	n/a	n/a	n/a	n/a
Year of refurbishment	n/a	2007-2009	n/a	2001 heating system replacement
Years old	3	52	52	62
Years of life span extension (see online questionnaire survey)	n/a	40	n/a	only for the heating system about 25-35 years?
Extend of refurbishment	n/a	concrete frame retention and foundation + new interiors + new building services	n/a	extend boiler capacity, pipework change, radiators replacement, life cycle replacement
Objectives for refurbishment/new building development	minimisation of energy-water consumption, reduction of harmful emissions, promotion of waste reduction-reuse-	1. High sustainable in any regard possible 2. New flexible working methods 3. Efficient use of assets 4. Meet tight budjet	proposal by HM Revenue for staff relocation, cost effective	cost reduction, energy saving

	recovery, implementation of environmental friendly transport plans			
Walling structure, solid/void	a vertical emphasis with a high percentage of solid to void. Thus the Potterrow fenestration pattern also tends to have windows with a vertical emphasis and a percentage of solid to void in the order of 60:40 to provide a relationship to the surrounding buildings and to reduce solar	The in situ soffits were repaired, the thermal mass was left exposed, brick and metallic facades with ventilation chimneys. Composite timber windows, composite metal clad insulated panels supported by retained in situ concrete. Roof retained in-situ concrete slab and precast concrete planks on steel structure. Floor retained existing in-situ waffle slab.	precast loadbearing panels each panel measured 15 ft. long by 9ft. 6in.The external faces of the loadbearing mullions are of Eglinton white limestone aggregate on white cement.	concrete walls, slabs, no insulation

	heat gain and achieve good daylighting to the interior			
Construction materials	Concrete-in situ slabs and cores and precast columns. The facade is formed from precast concrete panels. Standard units are used in a number of patterns. Stone facade precast panels face the	re-clad in timber/aluminium composite cladding with brick on the outer facades	Pre-cast Concrete	Concrete

	streets and polished white precast panels face the courtyard.			
Window structure	aluminium uPVC windows and curtain wall	timber based window	double glazed PVc	double glazed
Window glazing	glazing ration 40%	n/a	n/a	n/a
Insulation	thermal insulation	thermal insulation	no	no
Floor	solid and void, carpeted	concrete slab, carpeted	concrete slab, carpeted	concrete slab, carpeted
ceiling	solid and void, carpeted	concere slab, plasterboard	concere slab, plasterboard	concere slab, plasterboard
Roof structure	3 layer polymer modified mastic asphalt roof	n/a		n/a
Green building characteristics				
U-Values				
floors	0,2	assumed 0,2	n/a	n/a
walls	0,24	assumed 0,24	n/a	n/a
glazing	2,08	assumed 2,08	approx.3,3 and 3,7	approx.3,3 and 3,8
roof	0,22	assumed 0,22	n/a	n/a

Passive Technology	40%:60% solid: void, limit solar gain, maximise natural light, solar control coating on south and west facing glazing, opening windows, exposed concrete soffits, slab in floor void.	solar shading (sun control device), exposing soffits for thermal mass, exposed concrete slab of the original building to absorb night air, energy efficient envelope	n/a	n/a
Airtightness	Great care was taken with the design of the cladding interfaces to create an air tight construction. A mock-up was tested prior to installation. BRSIA carried out on-site thermal imaging and air-tightness testing which		n/a	n/a

	resulted in an air-tightness value of 6.7m3/m2@50 Pa which is a third less than the English Technical Standards which require 10m3/m2@50 Pa	6 m3/m2@50Pa (using VELFAC windows)		

Embodied CO2	n/a	Retention of the concrete frame saved 50% of the embodied energy normally required to construct a building. A large proportion of demolition material has been recycled through the contractor's supply chain, included precast concrete cladding panels. Waste heat from cooling plant of the Council's Data Centre will be recycled to heat area of the building in winter	n.a	n.a

Baseline Data MATRIX-Parameters

Office buildings	**Potterrow Building**	**Elizabeth Courts II (former Asburton Court)**	**Argyle House**	**Five Ways House**
Case study category	**BREEAM new**	**BREEAM refurbished**	**Existing/conventional/future retrofit or demolition**	**Existing/heating plant refurbishment**
Temperatures (in degree celcious)				
Set indoor temperatures	21	22 -24	21	28
Set temperatures (degree celcious)				
external air temperatures summer	24°Cdb , 19°C wb	n/a	24°Cdb , 19°C wb	n/a
external air temperatures winter	-1°C db, -1°C wb	n/a	-1°C db, -1°C wb	n/a
Set temperatures (degree celcious)	21°C	22°C -24°C	21°C	28°C
winter	25°C less than 5%/year	21	25°C less than 5%/year	n/a
summer	28 less than 1%/year	max.25 degrees	28 less than 1%/year	n/a
Desing parameters				
LTHW flow temperature	80°C			

LTHW return temperature	60°C			
Pressure	80kPa			
Heating operational hours/day				
January	CHP operated 24h/d although building operates from 9:00 to 17:00	7:00 am-18:00	6:00 am - 16:00 pm	6:00 am-19:15pm
February	CHP operated 24h/d although building operates from 9:00 to 17:01	7:00 am-18:00	6:00 am - 15:30 pm (1 hour off at lunch)	6:00 am-19:15pm
March	CHP operated 24h/d although building operates from 9:00 to 17:02	7:00 am-18:00	6:00 am - 15:30 pm (1 hou off at lunch)	6:00 am-19:15pm
April	CHP operated 24h/d although building operates from 9:00 to 17:03	7:00 am-18:01	6:00 am - 15:30 pm (1 hour off at lunch)	6:00 am-19:15pm
May	CHP operated 24h/d although building operates from 9:00 to 17:04	off	off	off
June	CHP operated 24h/d although building operates from 9:00 to 17:05	off	off	off
July	CHP operated 24h/d although building operates from 9:00 to 17:06	off	off	off

August	CHP operated 24h/d although building operates from 9:00 to 17:07	off	off	off
September	CHP operated 24h/d although building operates from 9:00 to 17:08	off	off	off
October	CHP operated 24h/d although building operates from 9:00 to 17:09	7:00 am-18:00	6:00 am - 16:00 pm	6:00 am-19:15pm
November	CHP operated 24h/d although building operates from 9:00 to 17:10	7:00 am-18:00	6:00 am - 16:00 pm	6:00 am-19:15pm
December	CHP operated 24h/d although building operates from 9:00 to 17:11	7:00 am-18:00	6:00 am - 16:00 pm	6:00 am-19:15pm
Weekends	CHP operated 24h/d	20% of the electricity consumption	off	off

Baseline Data MATRIX-Heating system

Office buildings	**Potterrow Building**	**Elizabeth Courts II (former Asburton Court)**	**Argyle House**	**Five Ways House**
Case study category	**BREEAM new**	**BREEAM refurbished**	**Existing/conventional/future retrofit or demolition**	**Existing/heating plant refurbishment**
Heating				
Technology Type	district CHP providing heat, power and small amount of cooling. No boilers in the building. Perimeter radiators, heat recovery.	VRF heat pumps (rare for heating), LPHW feeding radiators from high-efficient condensing natural gas fired boilers augmented with heat recovery from data centre	central heating, oil fired low energy efficient boilers feeding radiators with LTHW	A two pipe floor, central and returning system. 3 boilers are directly used for the central heating of the site. They are rotated on a weekly basis for optimum use and asset longevity. When the 3 boilers installed with BMS controls, usage and temperature controls revised and set to achieve optimum performance and a reduction in energy consumed. Every room has a radiator and

				heating pipe work. Gas type boilers.
Heating equipment capacity in the building				
boilers	3	3	2	3
radiators	522	434	1892	1185
underfloor heating	4	1	0	0
trench heaters	69	0	0	0
unit heater	0	1	0	0
overdoor heating	3	1	3	0
thermal store	1	0	0	0
tanks	0	0	2 oil tanks	0
calorifier	0	0	0	0
feed and expansion tank	0	0	1	1

turbines	3	0	0	0
CHP engine	1X JMS 612 GS-N.L (19,800kg)	0	0	0
CHP cylinders	12	0	0	0
pumps	22	16	4	15
heat exchanger	4	2	0	0
pressuration unit	0	1	0	0
unit heater	0	1	0	0
pipes (LTHW and transmission to the radiators systems)	total number not provided due to the variety of sizes and forms	considered measuring distances and lengths of pipes to reach radiators in each floor	total number not provided due to the variety of sizes and forms	considered measuring distances and lengths of pipes to reach radiators in each floor
Sizes (minimum/maximum) (mm) (see schedules in appendices)				
boilers	8330x5475x5050	2110X1290X1890 (1328kg)	2800x1500x1600	1260x2440x1070 (2750kg)
radiators	600-1517x190-700x68-198	220-320x57-166x400-1800	150x1100x600	1200x620x720(average)
underfloor heating	625X210X86	625X210X87	n/a	n/a
trench heaters	2500-12400x165x190	n/a	n/a	n/a
overdoor heating	1500-1800X380-565X270	2000x480x250	120x900x200	n/a
thermal store	$75m^3$	n/a	n/a	n/a
tanks	n/a	n/a	29850x35850x23850	n/a
calorifier	n/a		3100x1600x1600	

feed and expansion tank	n/a	n/a	1900x1300x1200	n/a
CHP engine	7600x2200x2800	n/a	n/a	n/a
pumps (by weight)	n/a	n/a	n/a	n/a
heat exchanger	n/a	1100x470x1100	n/a	n/a
pressuration unit		325x430x180	n/a	n/a
unit heater	n/a	650x650x315	n/a	n/a
pipes (LTHW and transmission to the radiators systems)		not considered	total lenght:78.0320m	not considered
Heating output (minimum/maximum) (watt)				
boilers	11373kw	529-650kW(heat loss rate at 70^{0}C) (90^{0}C flow and 81^{0}C return)	1500kW	800kW(flow temperature 90^{0}C and return 35^{0}C)
radiators	350-1779 (from 16-21^{0}C)(system flow and return temperature 80/60^{0}C)	584-2440		3222btu/h or 944watts(average 2086 W0
underfloor heating	7500-10000 (t 21 ^{0}C)	it varies from zone to zone:zone 1: 3.0, zone 2: 2.4, zone 3:1.2 , zone 4,5:3.0, zone 6:3.5, zone 7:4.5, zone 8: 6.75	n/a	n/a
trench heaters	250-3200 (system flow and return temperature 80/60^{0}C)	n/a	n/a	n/a

overdoor heating (heating capacity)	12-14 Kw	9kW	n/a	n/a
thermal store	n/a	n/a	n/a	n/a
tanks	n/a	n/a	n/a	n/a
calorifier	n/a	n/a	n/a	n/a
feed and expansion tank	n/a	n/a	n/a	n/a
CHP engine	1,704kW	n/a	n/a	n/a
pumps	n/a	n/a	n/a	n/a
heat exchanger	n/a	550kW(50^{0}c entering flow and 40^{0}C leaving)	n/a	n/a
Emission rate mg/kWh				
Nitrogen oxides (NOx)	n/a	38,5	n/a	n/a
Carbon monoxide	n/a	3,4,11	n/a	n/a
Efficiencies				
boilers	89% gas firing	net 107,0% and calorific 96,5%	40%	net 92% and calorific 83%
radiators	n/a	n/a	n/a	n/a
underfloor heating	n/a	n/a	n/a	n/a
trench heaters	n/a	n/a	n/a	n/a
overdoor heating	n/a	n/a	n/a	n/a

thermal store	n/a	n/a	n/a	n/a
tanks	n/a	n/a	n/a	n/a
calorifier	n/a	n/a	n/a	n/a
feed and expansion tank	n/a	n/a	n/a	n/a
pumps	n/a	n/a	n/a	n/a
heat exchanger	n/a	n/a	n/a	n/a
pressuration unit	n/a	n/a	n/a	n/a
pipes (LTHW and transmission to the radiators systems)	n/a	n/a	n/a	n/a
Control system				
BMS	yes	yes	no	yes

Baseline Data MATRIX-Cooling system

Office buildings	Potterrow Building	Elizabeth Courts II (former Asburton Court)	Argyle House	Five Ways House
Case study category	**BREEAM new**	**BREEAM refurbished**	**Existing/conventional/future retrofit or demolition**	**Existing/heating plant refurbishment**
Cooling				
Technology Type	natural ventilation + CHP + mechanical in comms rooms	natural ventilated. Mechanical cooling in meeting rooms, printing hubs, auditorium, restaurants, least efficient areas by VRF heat pump system. Exposed concrete slab of the original building to absorb night air for cooling.	natural ventilation & air conditioners in comms rooms, server rooms	natural ventilation & air-conditions in comms rooms, server rooms
Cooling system capacity/type				
Number of air-conditioners (indoor)	5	40	25	17
Outdoor heat-pumps	0	0	29	7

buffer vessel (tank storage for chilled water and extra heat)	0	1	0	0
dry air coller	0	3	0	0
pressuration unit	0	1(chilled water)	0	0
pumps	0	8	0	0
chillers	2 inside the building, 1 in CHP (2 circuits)	3	0	0
Chiller refrigerant type (efficiency)	R407c claimed as zero ozone	R134a(non-toxic, without chlorine)	n/a	n/a
Sizes (minimum/maximum) (mm)				
air-conditioners (indoor)	2950x815x1995	290x79x238 (see attached specs)	(see recording survey)	
Outdoor heat-pumps	n/a	n/a	(see recording survey)	1240X1020X330
buffer vessel	n/a	2500litres	n/a	n/a
dry air coller	n/a	4785x2250x2150	n/a	n/a
pressuration unit	n/a	8000 litres/15 meters	n/a	n/a
pumps	n/a	n/a	n/a	n/a
chillers (L,W,H)	2 chillers: 2000-3603x800-1158x1545-1225	2557x980x1800	n/a	n/a
Efficiencies				
air-conditioners (indoor)		2.8-4.36 (R-410A)	EER-cooling: 1.54 and COP: heating: 1.34(estimated by using inputs and outputs from the labels)	

Outdoor heat-pumps		n/a	4.34(R410A)EER-cooling: 3.61 and COP:heating: 4.63 (a similar example is taken of a toshiba RAV as this info is not provided on the labels)	EER-cooling:3.46 and COP-heating:4.67
buffer vessel	n/a	n/a	n/a	n/a
dry air coller	n/a	n/a	n/a	n/a
pressuration unit	n/a	n/a	n/a	n/a
pumps	n/a	n/a	n/a	n/a
chillers (COP)	03-0,8(high efficiency heat economiser that enhances energy savings by recovering thermal energy from exhaust gas)	R134a(non-toxic,without chlorine)	n/a	n/a
Cooling output				
air-conditioners (indoor) (cooling load)	35kW (flow and return t: 6/12^{0}C summer, 14/17 in winter)	2.2 -2.8kW(flow 48^{0}C, return 43^{0}C		8.02kW
Outdoor heat-pumps	n/a	n/a		5.3kW
buffer vessel	n/a	n/a	n/a	n/a
dry air coller	n/a	340kW	n/a	n/a
pressuration unit	n/a	n/a	n/a	n/a
pumps	n/a	n/a	n/a	n/a
chillers- Refrigerant	2 chillers:110kW(flow 6^{0}C, return 12^{0}C)	255kW(6^{0}C flow, return 11^{0}C)	n/a	n/a
Ventilation				

Ventilation type	mixed mode displacement ventilation, peak lopping cooling, night purge, underflooring ventilation through atrium	natural ventilated openable windows and duct 'wind throughs' on top floors controlled by BMS. Over winter localised air-handling units provide fresh air via swirl diffusers in the floor	natural ventilation	natural ventilation
Energy from renewables	0%	plan for the future	0%	0%

Baseline Data MATRIX-Energy and Environmental Evaluations

Office buildings	**Potterrow Building**	**Elizabeth Courts II (former Asburton Court)**	**Argyle House**	**Five Ways House**
Case study category	**BREEAM new**	**BREEAM refurbished**	**Existing/conventional/future retrofit or demolition**	**Existing/heating plant refurbishment**
Evaluation Methods				
BREEAM score (full document appendices)	2004 version, excellent 74%	2006 version, excellent 72,89%	n/a	n/a
Energy Performance Certificate (EPC) (typical rating is D 76-100) (appendices)	B' rated by Envest	n/a	no EPC	C rating 57
Post Ocuupancy Evaluation (POE)	The University will be conducting Post Occupancy Evaluation. It is hoped to take this further than human comfort criteria and energy consumption but also focus on research by an architectural psychologist on the performance of the interactive spaces. This would involve surveys of occupants and observation over a two	yes (see appendices the TEAM Detailed monitoring report).	no	no

	year period. It will be available in 2013.			
Monitoring Survey (see appendices and case study research chapter, case study 2)	not completed	yes (see appendices)	no	no
Thermography survey (see appendices and the case study research chapter)	yes (BSRIA) and fieldwork	fielwork	fielwork	fielwork
Environmental claims (credits achieved)				
BREEAM	**71,99%**	**72,89%**	**n/a**	**n/a**
Version	**2005**	**2006**	**n/a**	**n/a**
Credit allocations for energy	**76% (13 from 17)**	**66,67% (12 from 18)**	**n/a**	**n/a**
Credit allocations for material	**50% (7 from 15)**	**50% (6 from 12)**	**n/a**	**n/a**
Credit allocations for pollution	**58% (7 from 12)**	**40% (6 from 15)**	**n/a**	**n/a**
Management	**70% (7 from 10)**	**100,00% (9 from 9)**	**n/a**	**n/a**

Land use and ecology	**50% land use (1 from 2) and 78% ecology (7 from 9)**	**80,00% (8 from 10)**	**n/a**	**n/a**
Monitoring		**Carbon trust**		
Energy and CO2 Claims	The predicted CO2 emissions are 16kgCO2/sqm/yr (asset) and 42kgCO2/sqm/yr (operational).	the design solution has reduced the carbon emission from 90kgCO2/sqm/yr to a targeted level of 39kgCO2/sqm/yr . It has been claimed by the project team that it could achieve 30kgCO2/sqm/yr .	cost effective, high heat-oil consumption, about 70% vacant in 2012.	costs and energy efficiency have improved but not to the current standard.
ECON19 office building benchmarks (2003 latest version) (see literature review)	The asset achieves a 70% reduction when compared to ECON 19 Type 3 Good Practice asset emissions.	This represents an annual reduction of around 70% equivalent to 200 average UK households compared to ECON 19 Type 3 Good Practice asset emissions.	3 times the electricity of a typical type 3 benchmark office building.	n/a
Environmental performance indicators (energy and CO2)	29 $KgCO_2/m^2/a$ asset 70% reduction	from 90kg CO2/m2/annum to 30-39.	n/a	n/a
Asset CO2 Predicted	16 $KgCO_2/m^2/a$ asset including CHP supply side savings (39%)	n/a	n/a	n/a
Asset CO^2 actual		n/a	n/a	n/a

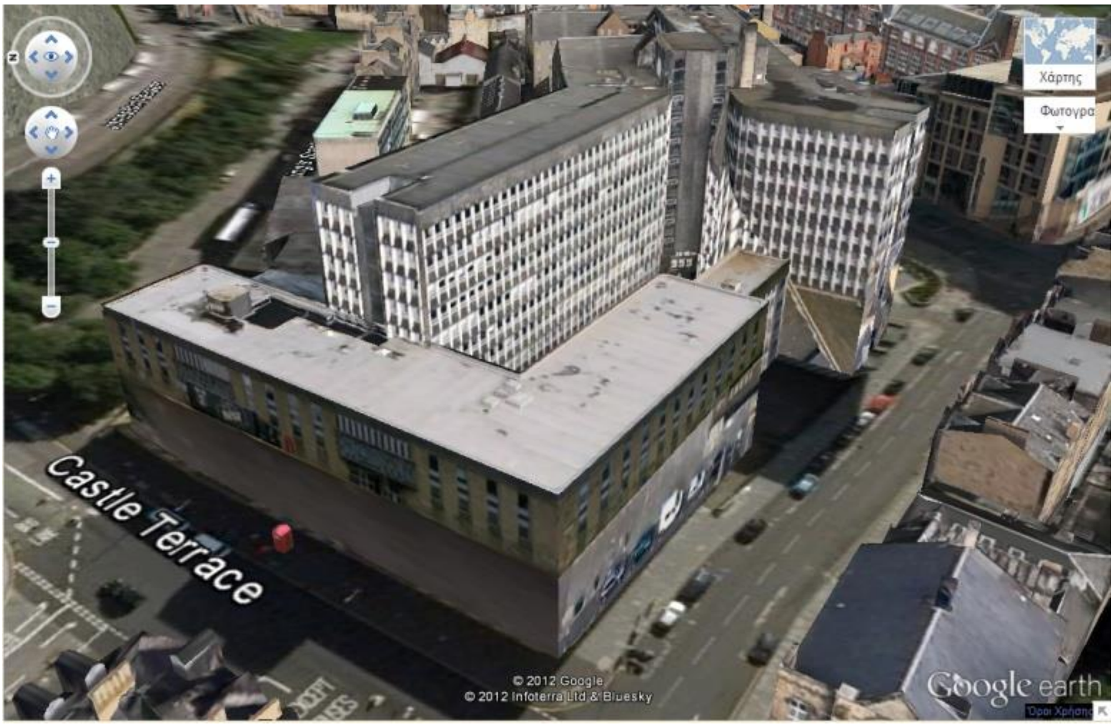
	55 $KgCO_2/m^2/a$ operational			
Operational CO^2 predicted	42 $KgCO_2/m^2/a$ operational including CHP supply side savings (39%)	70% reduction in energy consumption	n/a	n/a
Operational CO^2 actual	465 $KgCO_2/m^2$ (598 kg/CO2/m2 including 60 year life cycle replacements) from Envest analysis	n/a	n/a	n/a
Embodied CO2	n/a	BRE's Envest II software showed that 50 % reduction due to the re-use of the structural frame and of the foundations	n/a	n/a
Awards	RIAS Andrew Doolan Prize for the 'Best Building in Scotland' in 2008.Building/UKGBC Sustainability Award 2009, 'Sustainable Project of the Year' BCO Award 2010, 'Refurbished/RecycledWorkplace above 2000sqm' (Regional) Constructing Excellence, London & South East 2010	Building/UKGBC Sustainability Award 2009, 'Sustainable Project of the Year' BCO Award 2010, 'Refurbished/RecycledWorkplace above 2000sqm' (Regional) Constructing Excellence, London & South East 2010 Award, 'Legacy (Sustainability)' Retrofit Award 2010,	n/a	n/a

	Award, 'Legacy (Sustainability)' Retrofit Award 2010, 'Commercial Building' RICS Award 2010, 'Sustainability' (Regional - South East) CIBSE Award 2011, 'Refurbishment Project of the Year' Highly commended, SCALA Civic Building of the Year 2010 Shortlisted, 'Public Building of the Year ', Building Awards 2010	'Commercial Building' RICS Award 2010, 'Sustainability' (Regional - South East) CIBSE Award 2011, 'Refurbishment Project of the Year' Highly commended, SCALA Civic Building of the Year 2010 Shortlisted, 'Public Building of the Year ', Building Awards 2010		

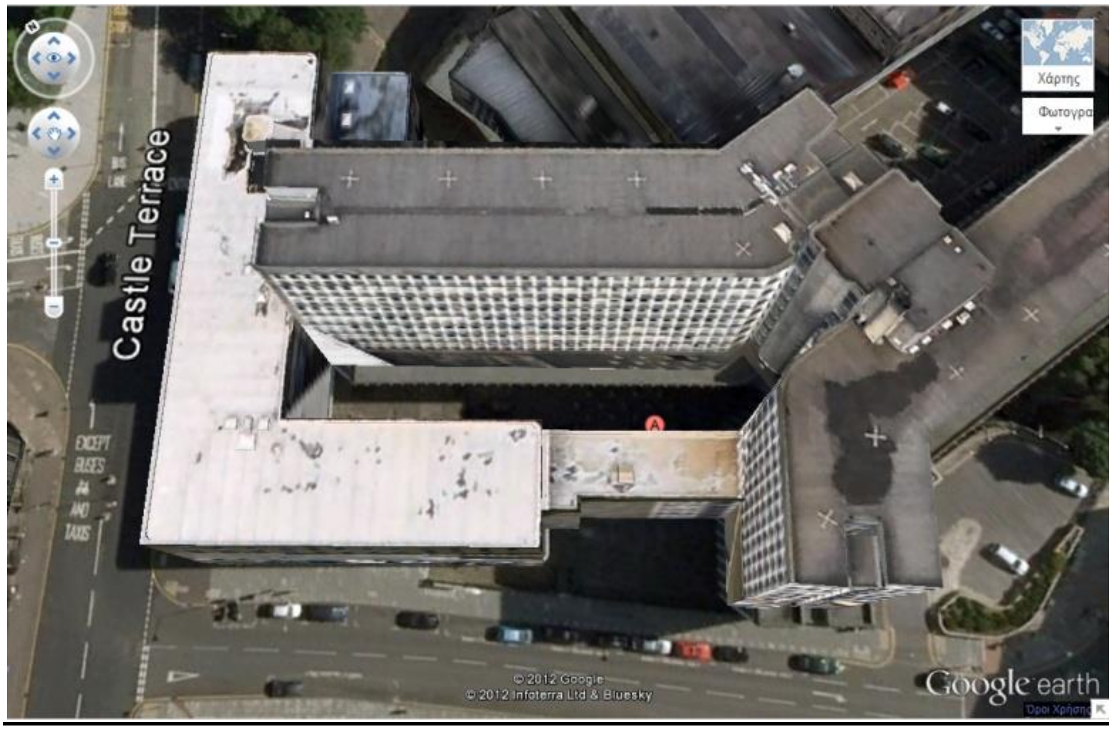
APPENDIX 9 PERSPECTIVE VIEWS OF THE OFFICE BUILDINGS

Argyle House

Perspective View of the building facing North



Perspective View of the building facing West/South



Perspective View of the building facing West

Perspective View of the building facing South


W Port
© 2012 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2012 TerraMetrics
© 2012 Infoterra Ltd & Bluesky
Google earth
Ημερομηνία εικόνων: 7/21/2008
1945
55°56'47.04" Β 3°12'00.36" Δ ανύψ 77 μ
Eye alt 126 μ


© 2012 Google
Image © 2012 Getmapping plc
Image © 2012 TerraMetrics
© 2012 Infoterra Ltd & Bluesky
Google earth
Ημερομηνία εικόνων: 5/11/2009
1945
55°56'47.50" Β 3°12'04.88" Δ ανύψ 100 μ
Eye alt 115 μ


Castle Terrace
© 2012 Google
Image © 2012 Getmapping plc
Image © 2012 TerraMetrics
© 2012 Infoterra Ltd & Bluesky
Google earth
Ημερομηνία εικόνων: 5/11/2009
1945
55°56'49.04" Β 3°11'58.62" Δ ανύψ 85 μ
Eye alt 140 μ


A700
© 2012 Google

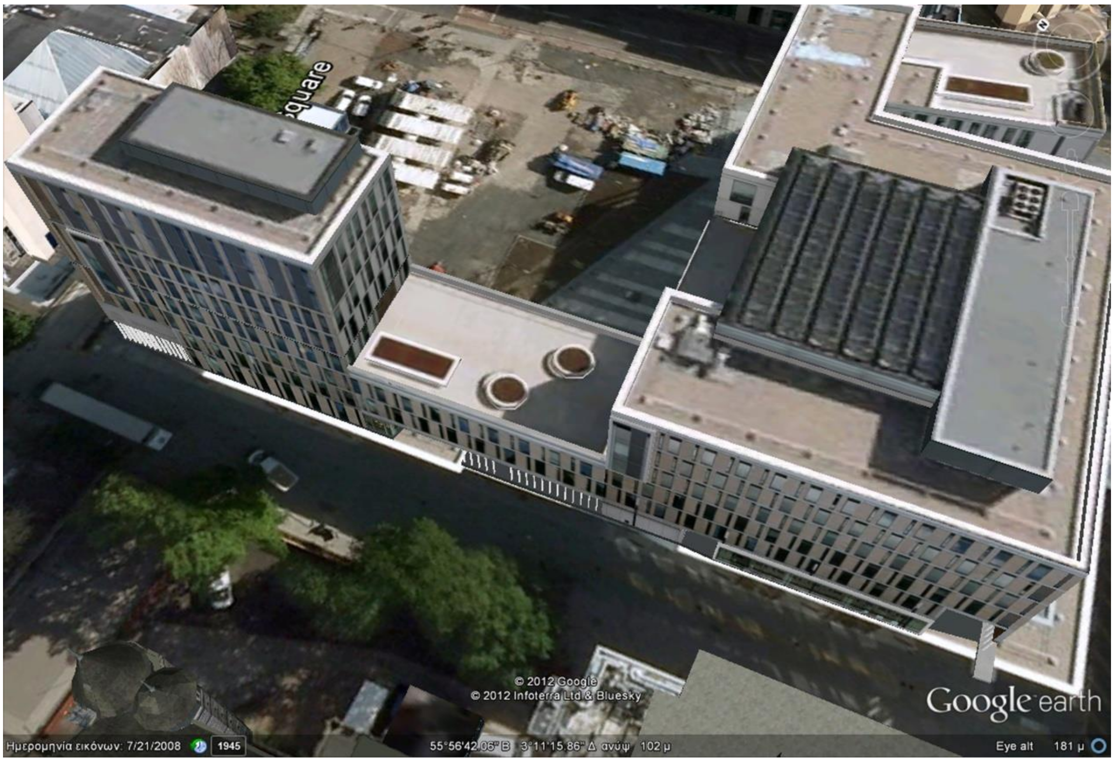
Potterrow Building

Perspective View of the building facing the West

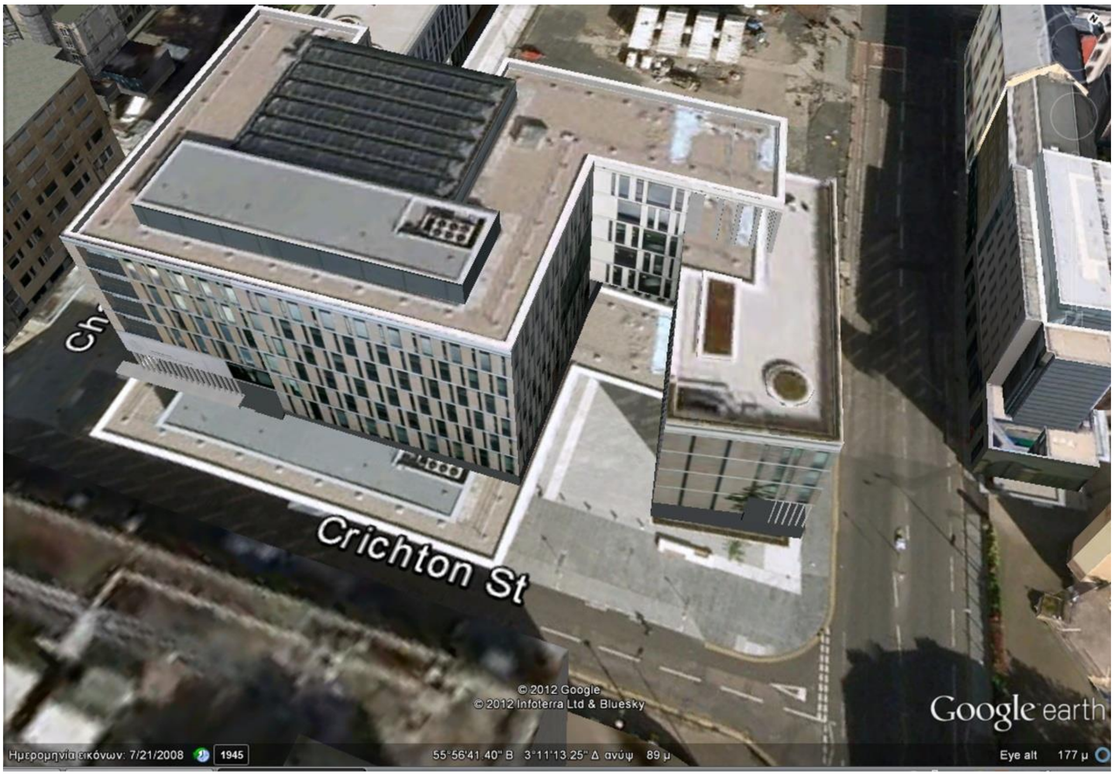
Perspective View of the building facing the South

Perspective View of the building facing the East North

Perspective View of the building facing the North West



View from the West



View from South

Five Ways House

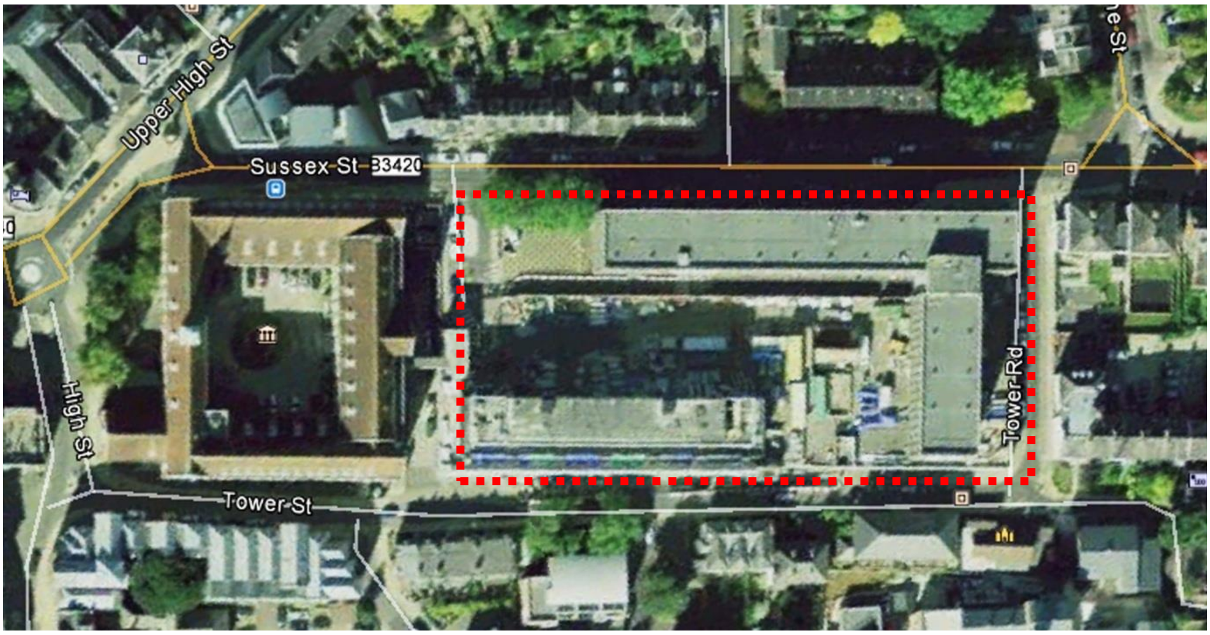
View from the south

View from the north and the east

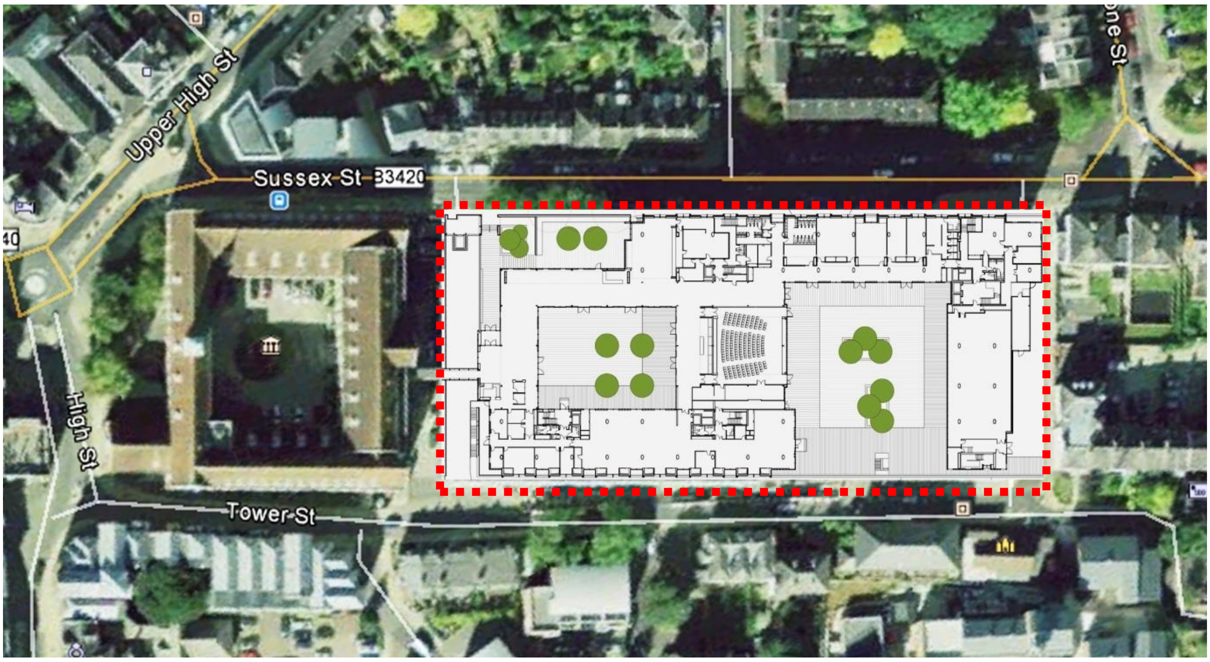
View from the north

View from the west

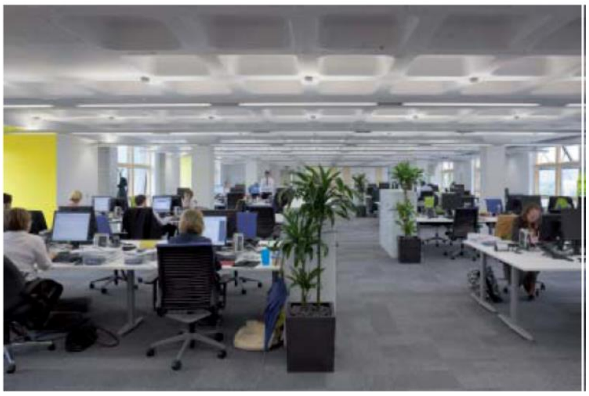
Elizabeth Courts II

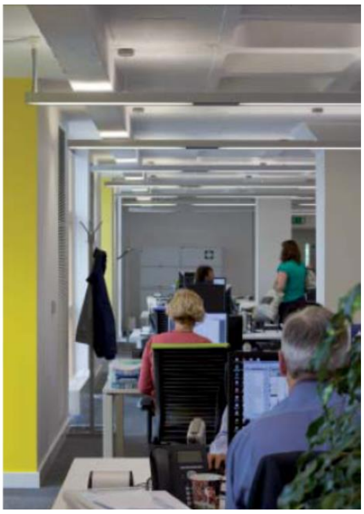


Former Ashburton Court, Winchester



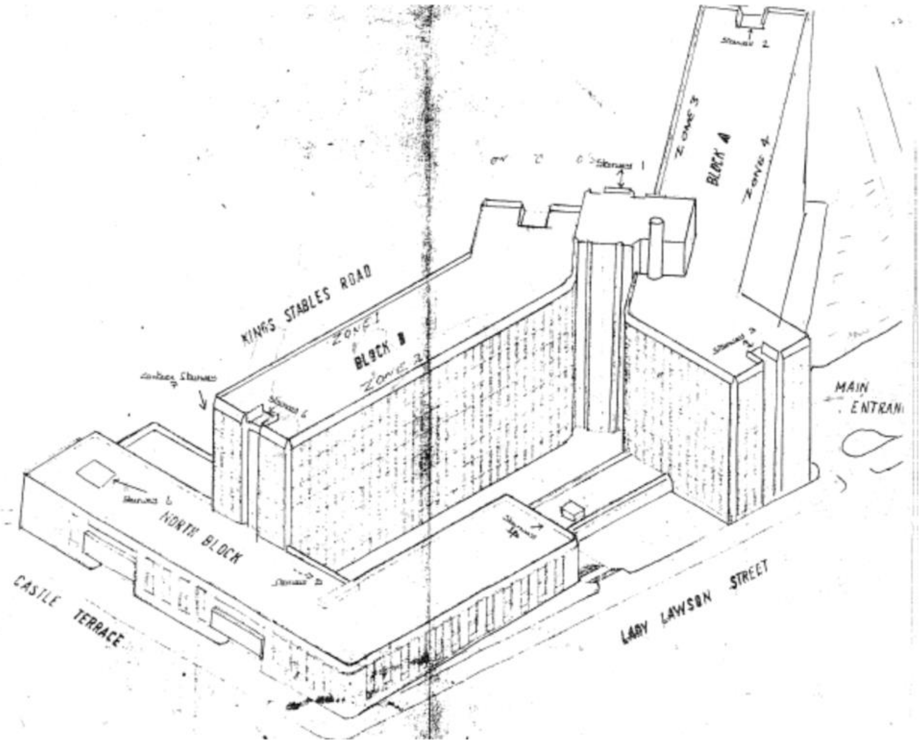
Refurbishment of the Elizabeth Courts, Winchester



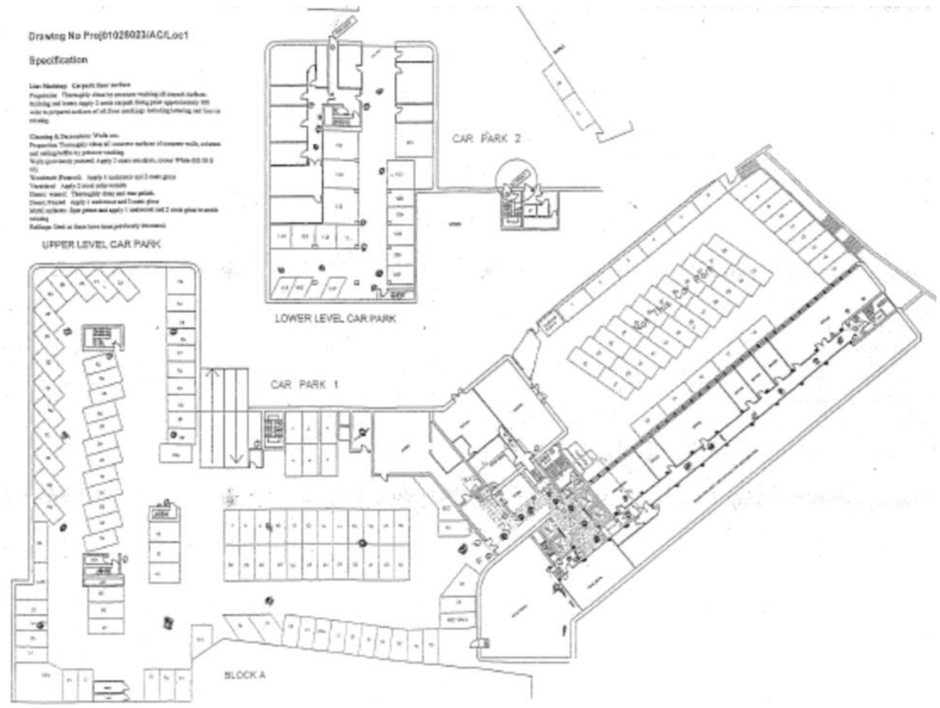


APPENDIX 10 ARCHITECTURAL DRAWINGS

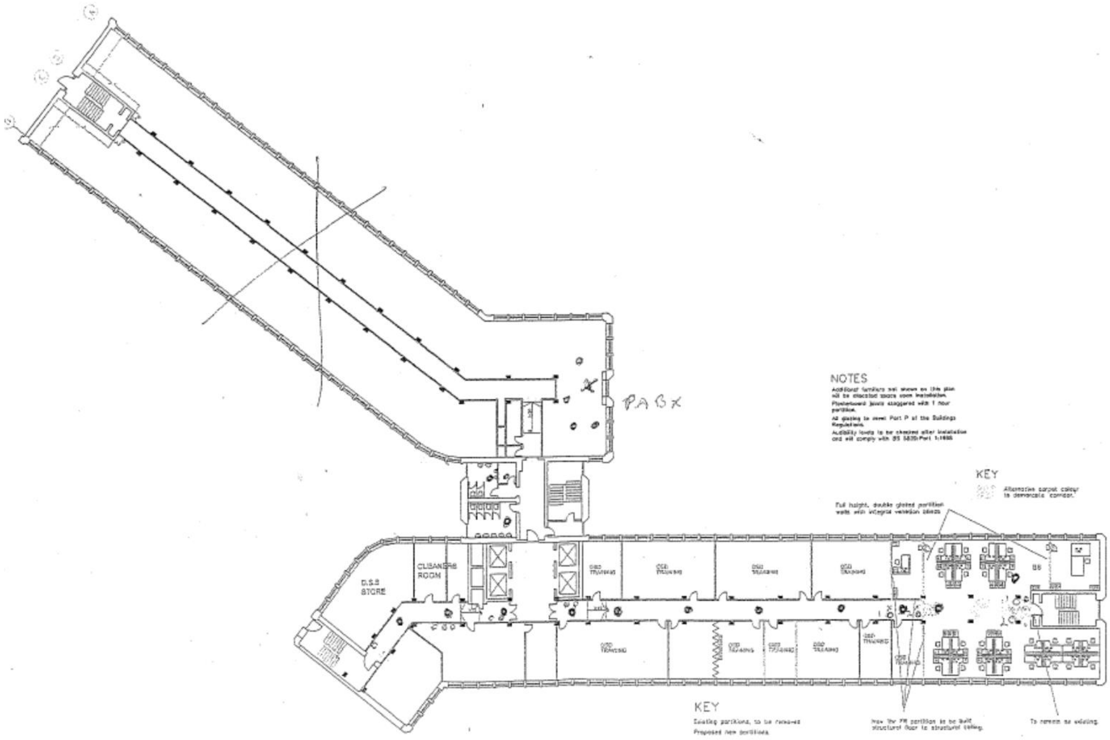
Argyle House



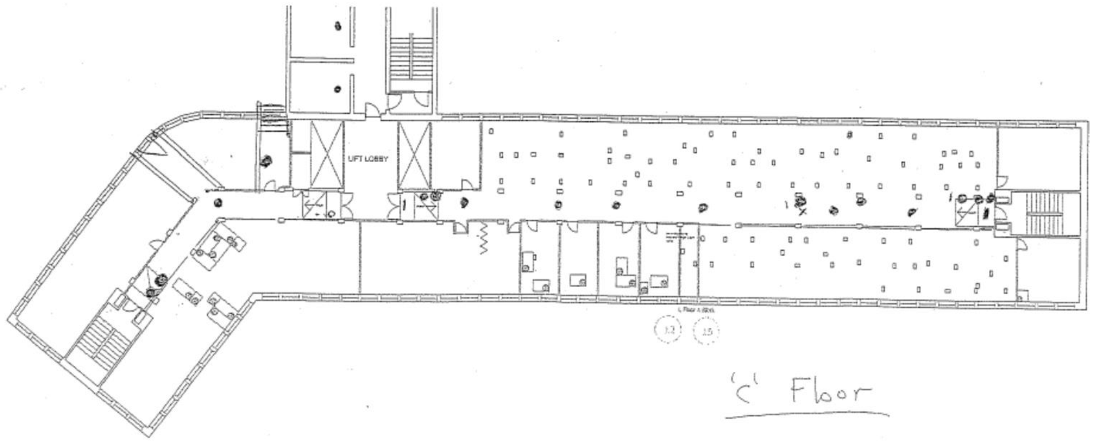
3D perspective from the west



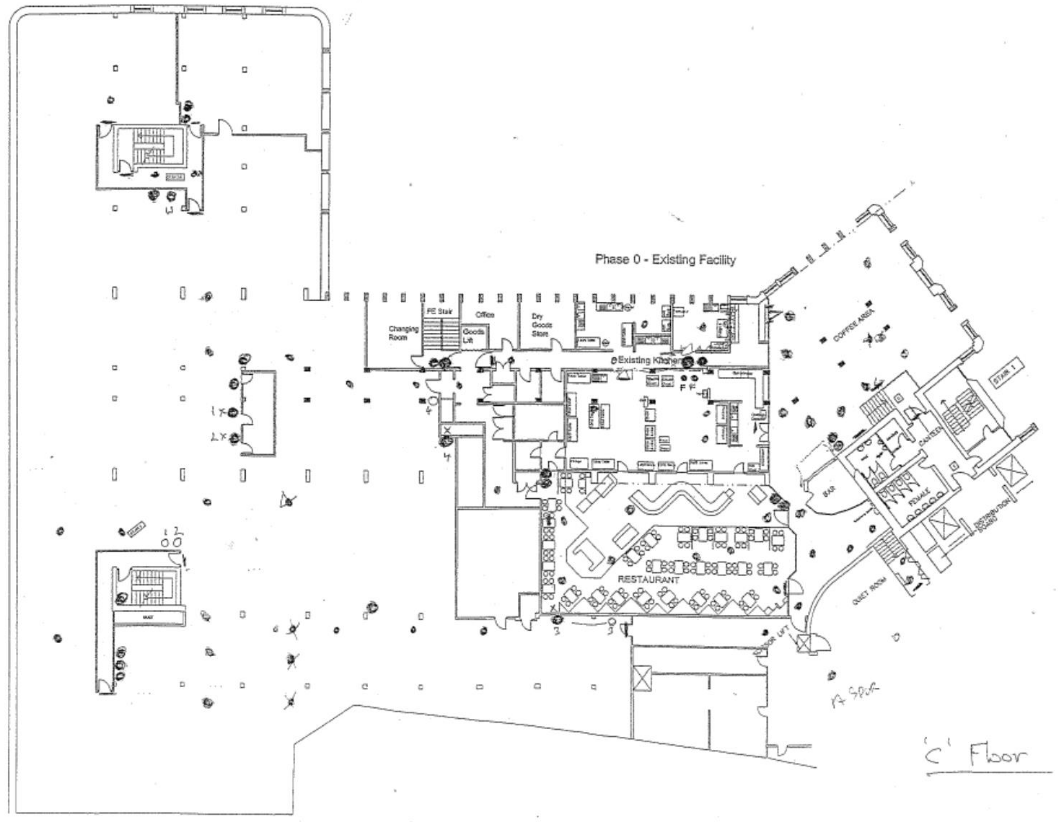
Basement floor from the car parking on the left and on the right from the plantrooms.



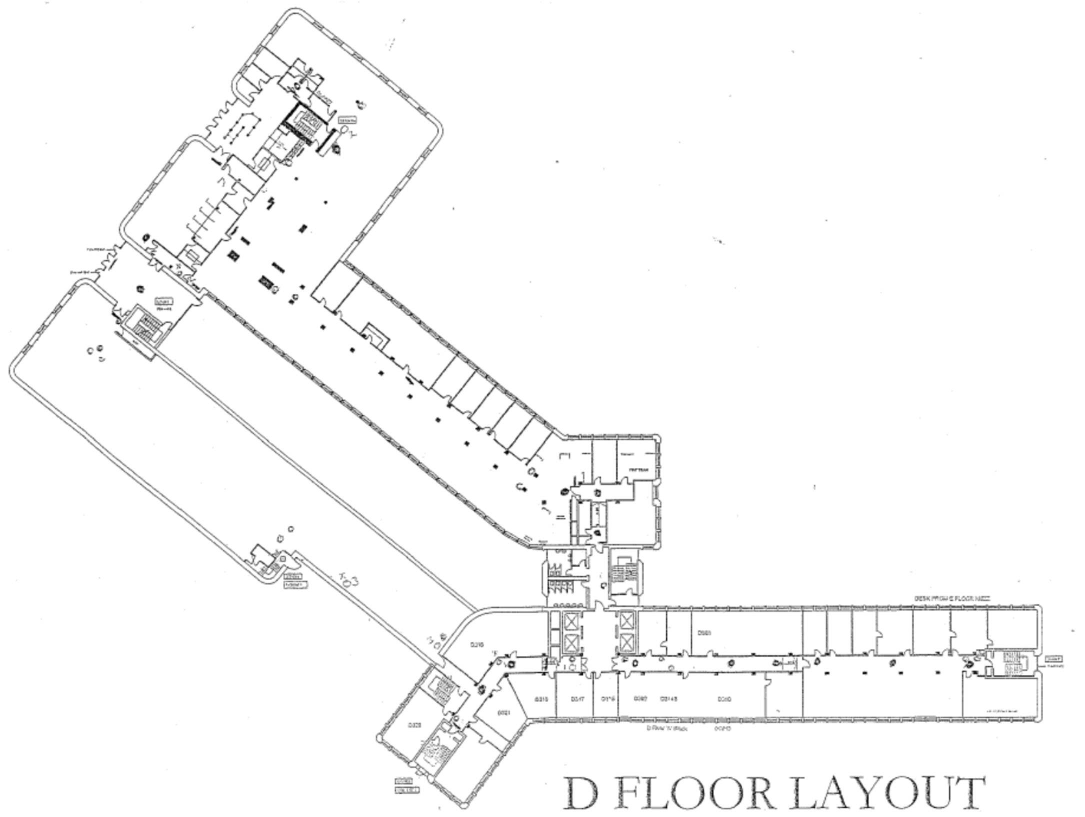
Level B



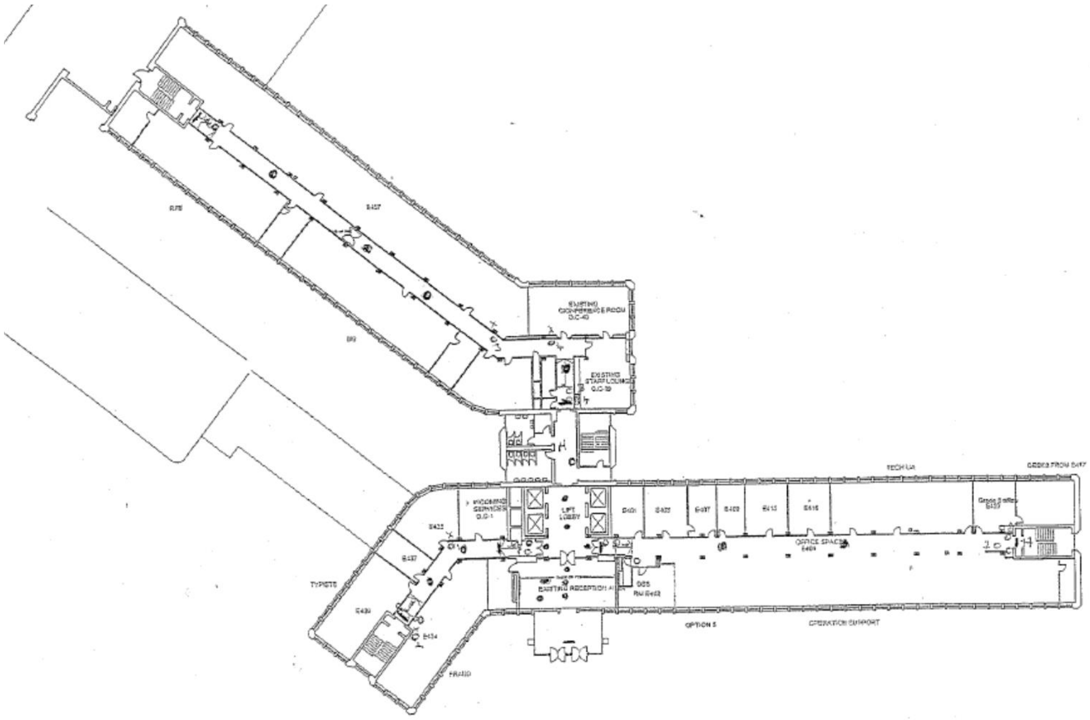
Level C, Block A



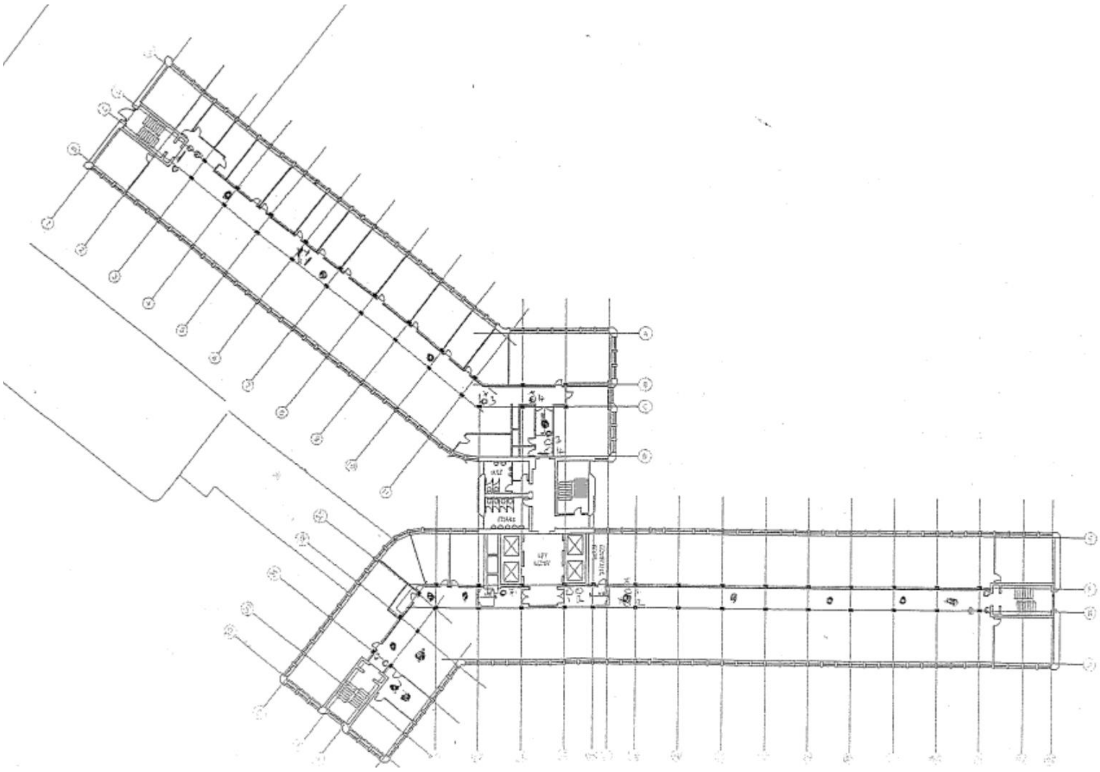
Level C, Block B



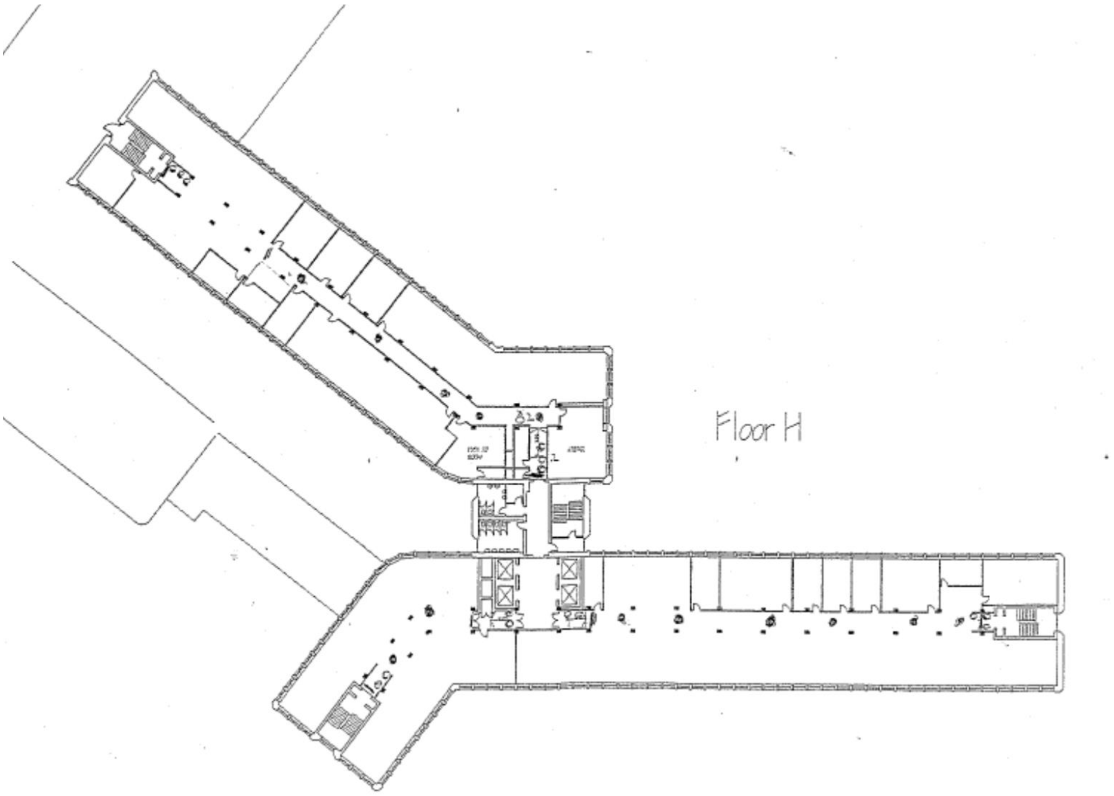
Floor D



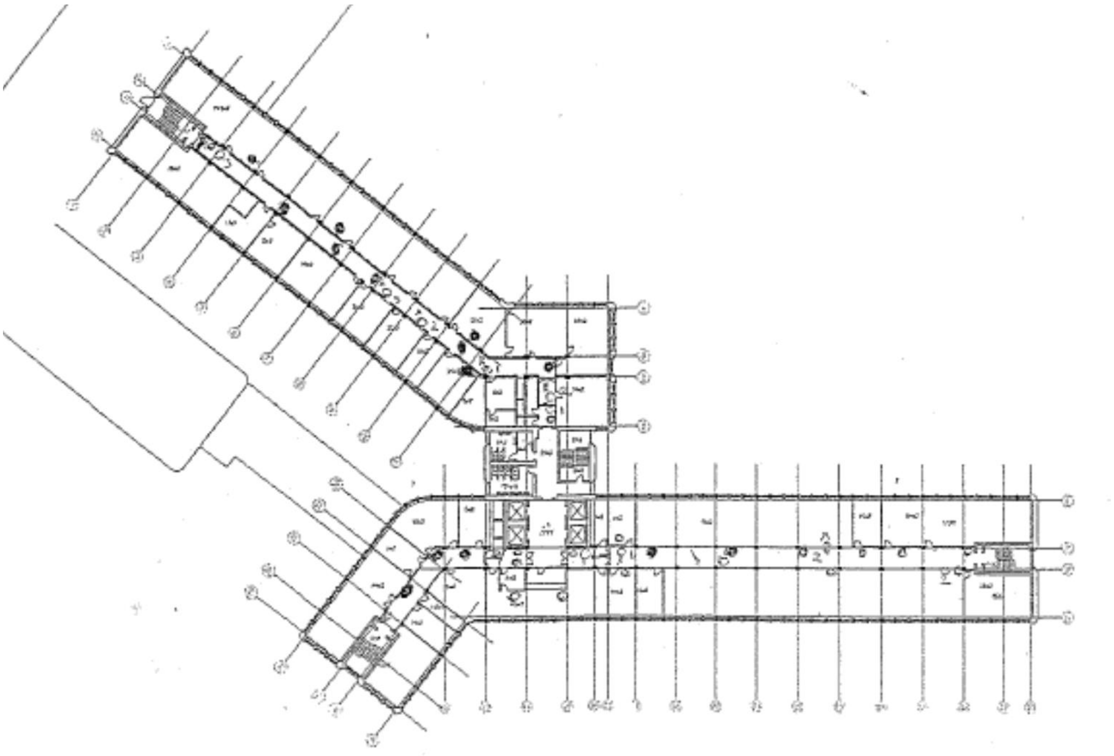
Floor E



Level F



Floor H



Floor J

Figure 51: Floor K, Block B

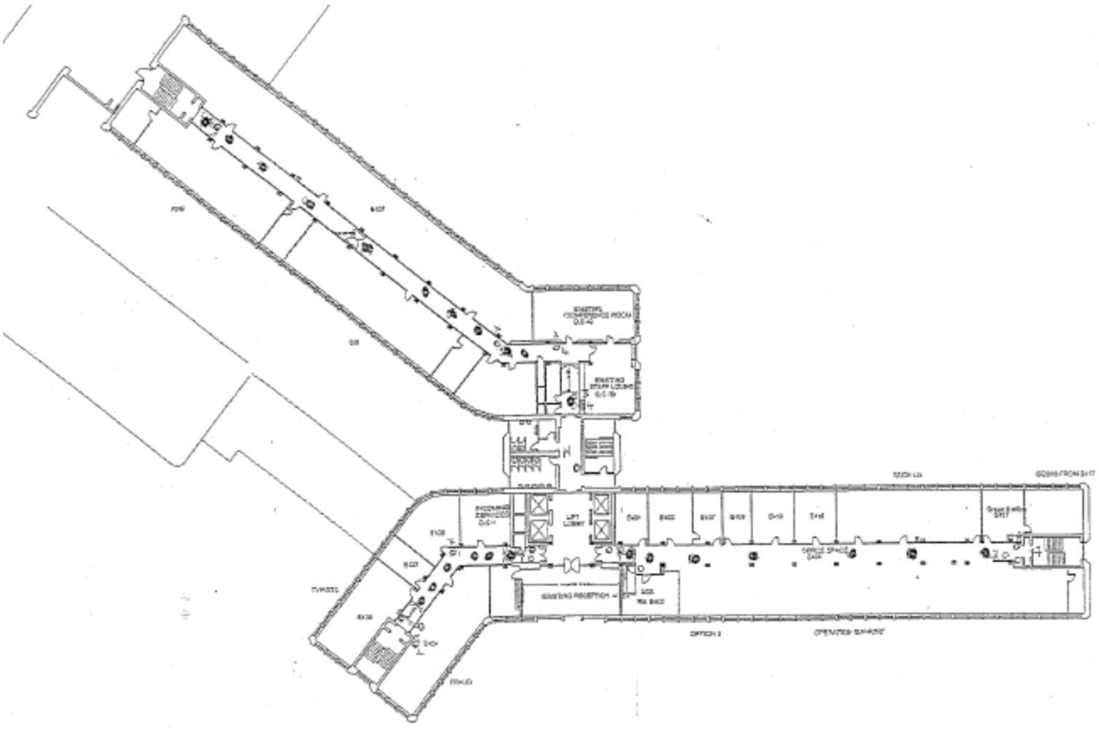


Figure 52: Floor L

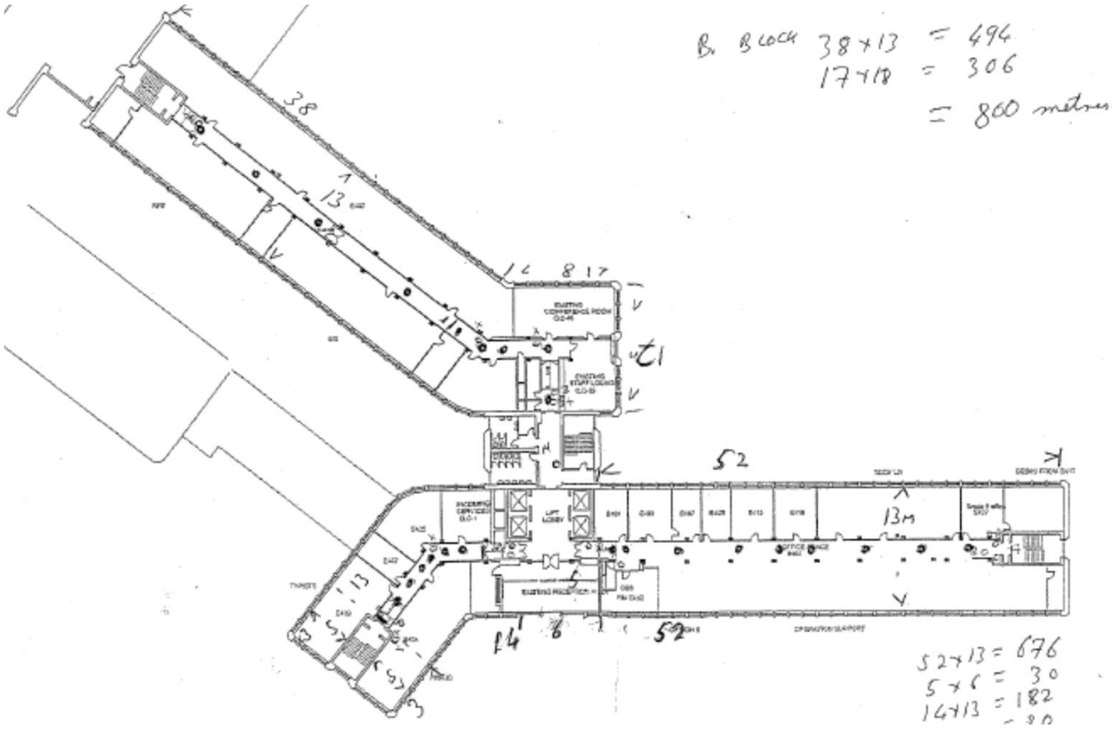


Figure 53: Floor M

Potterrow Building

Figure 54: Basement, Potterrow Building, phase 1 and 2

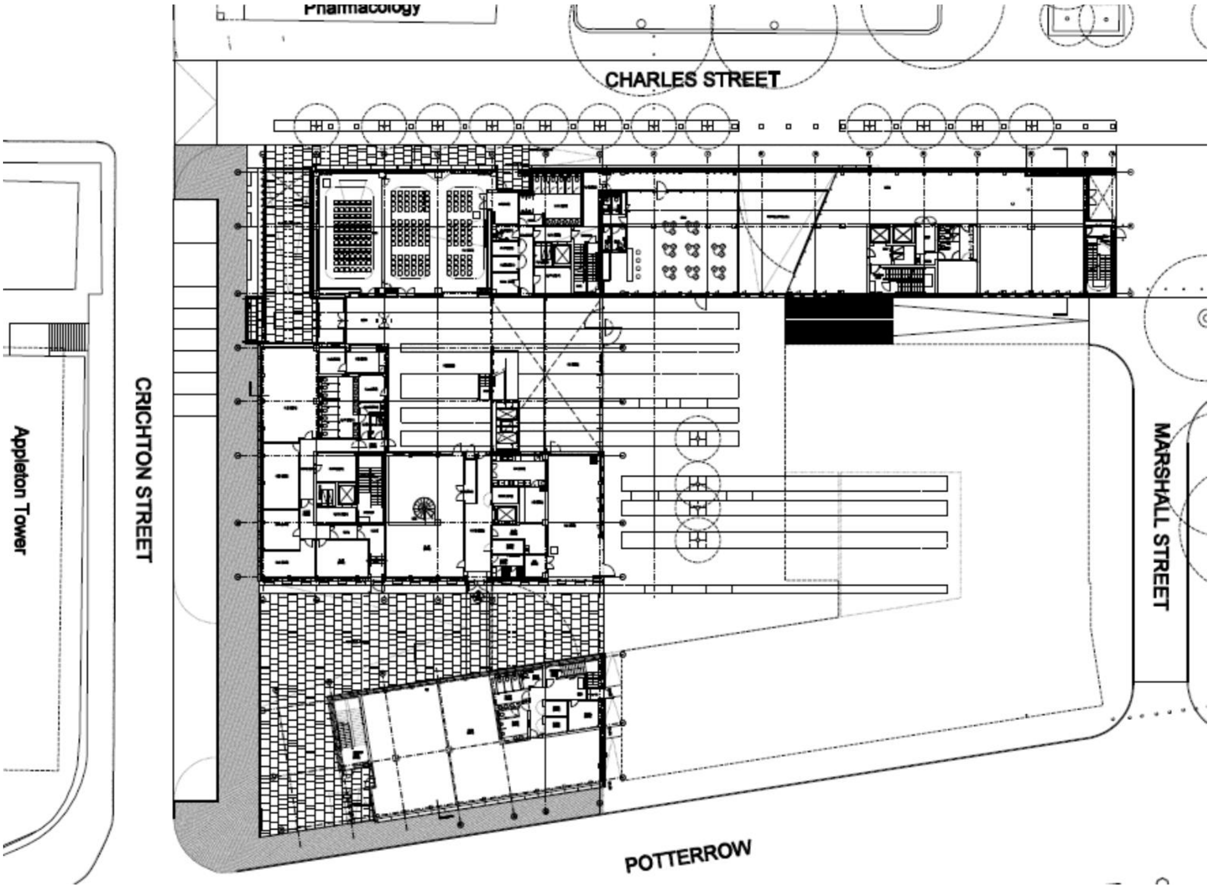
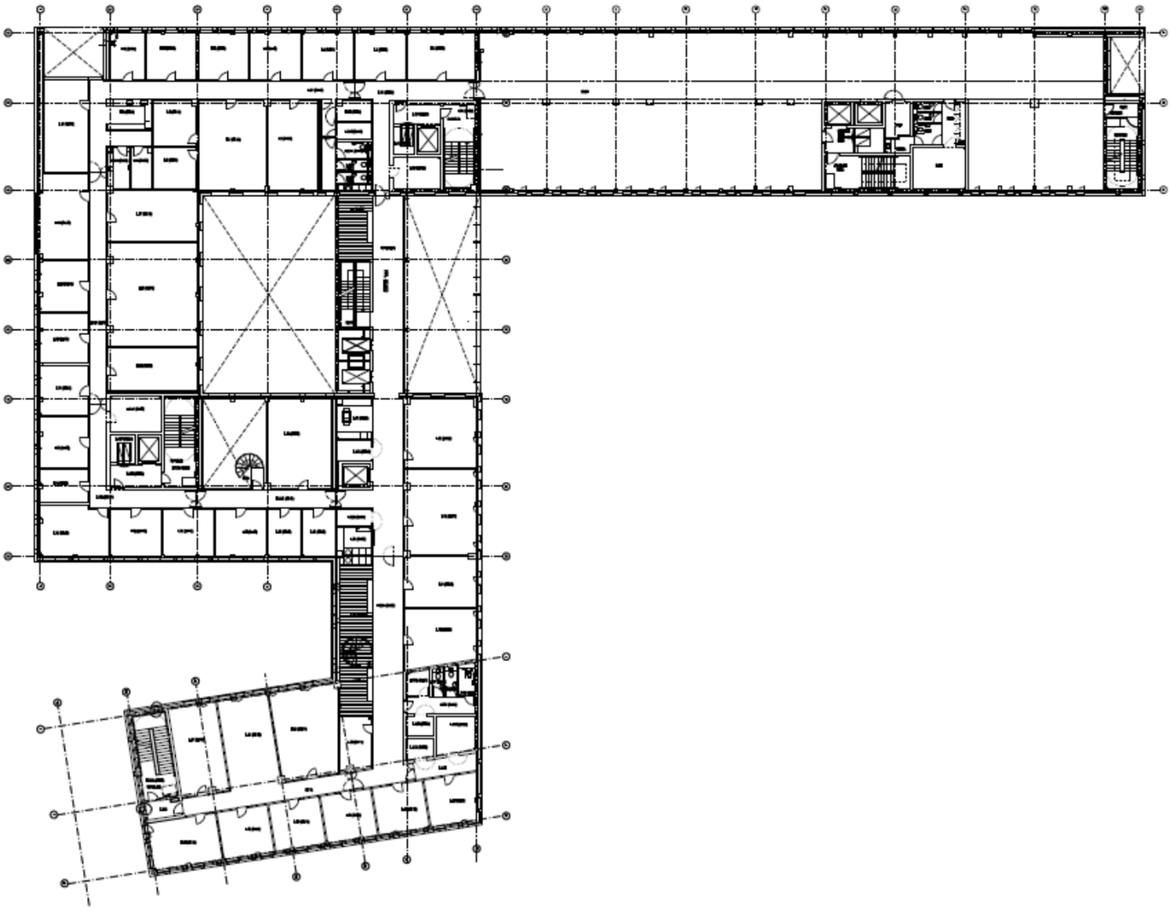
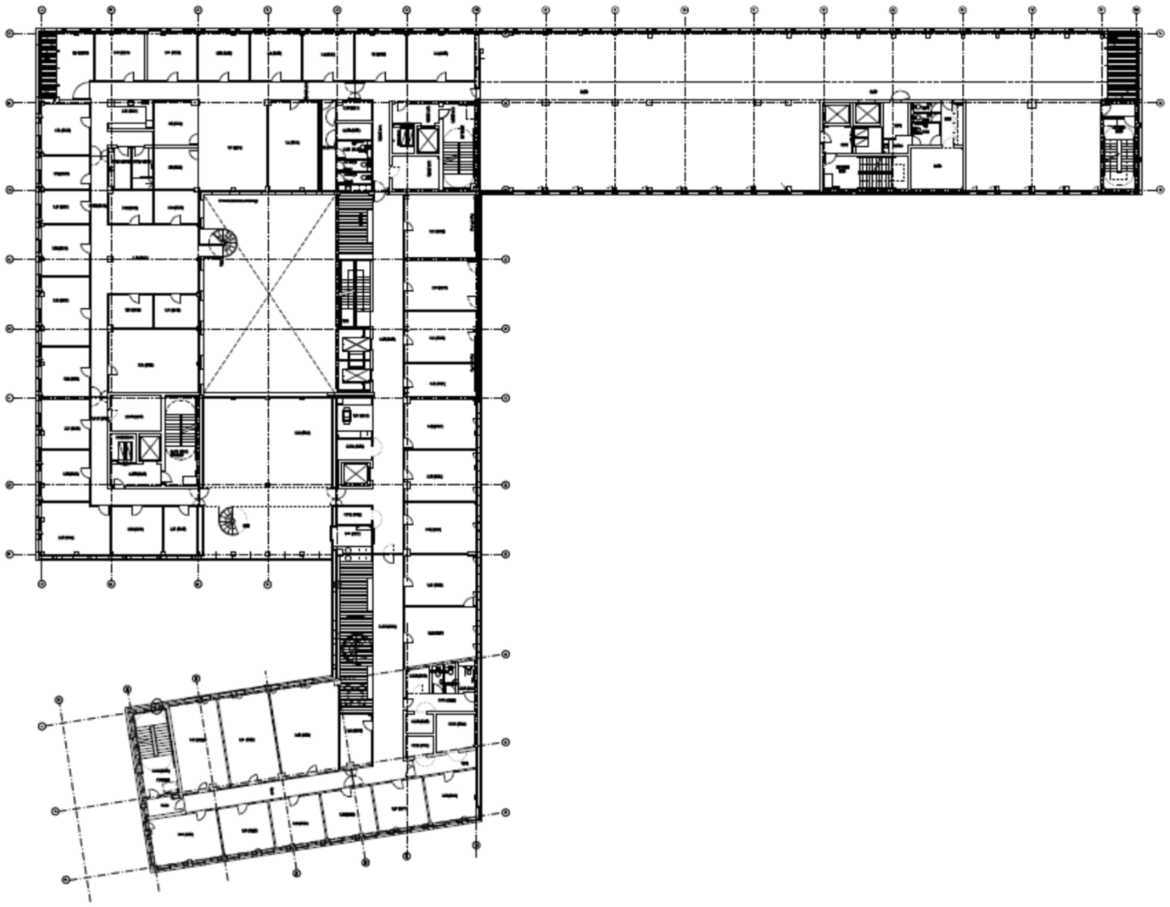


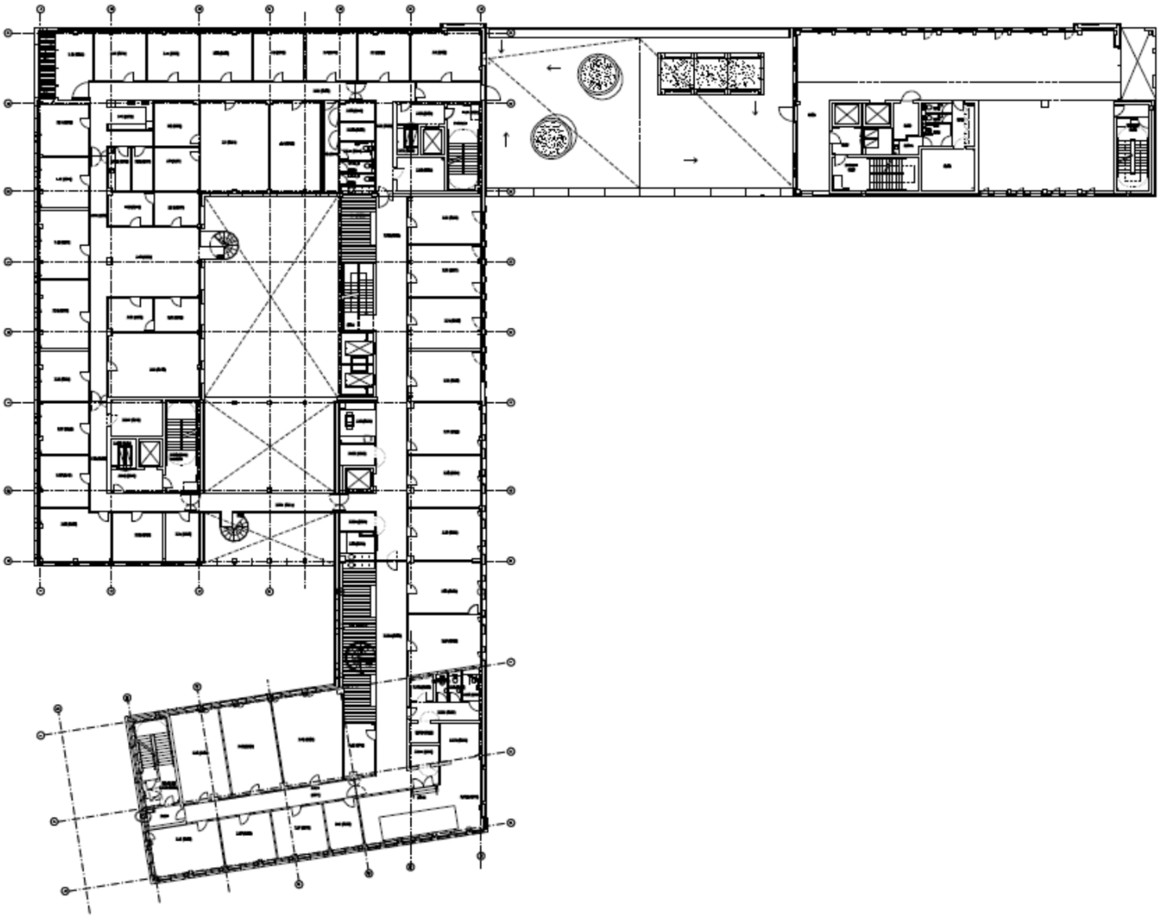
Figure 55: Ground floor, Potterrow Building, phase1 and 2



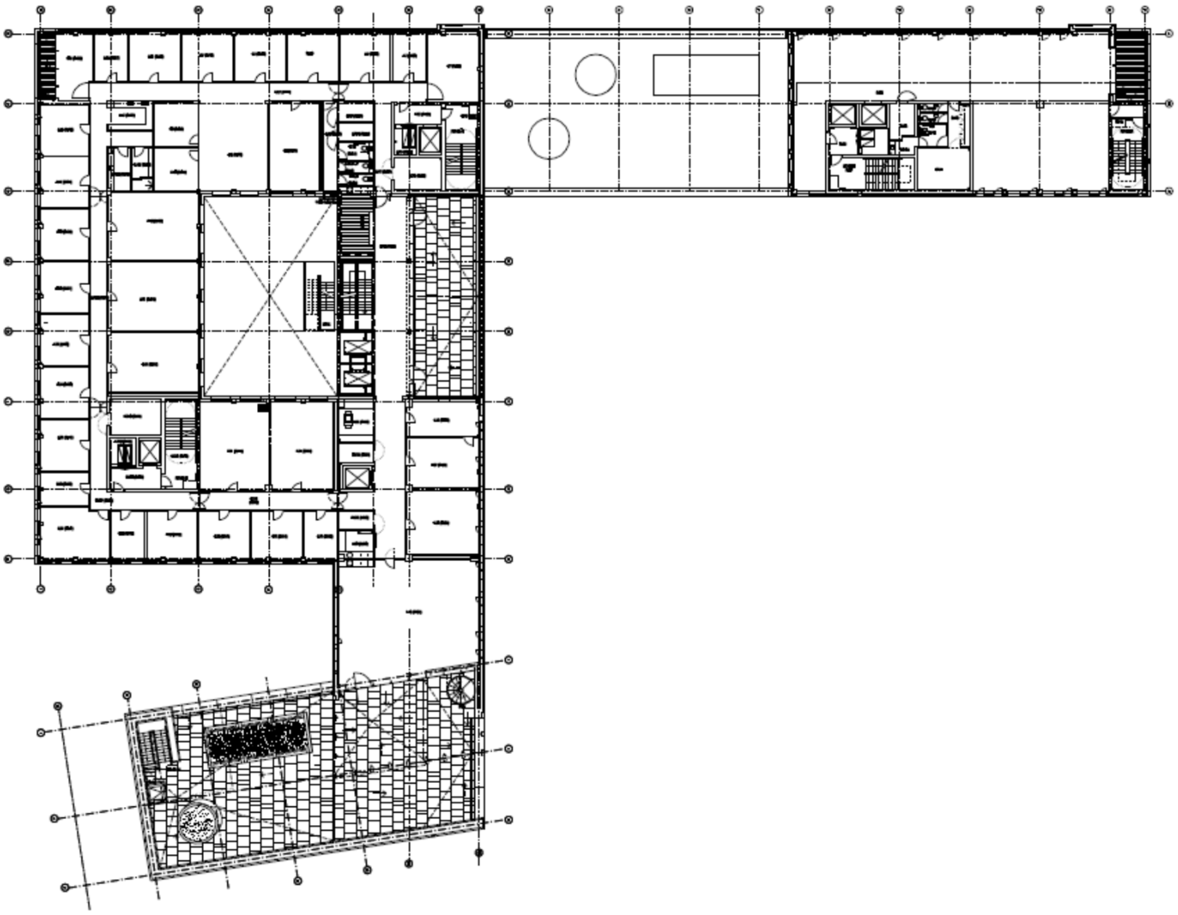
First floor, Potterrow Building, phase 1 and 2



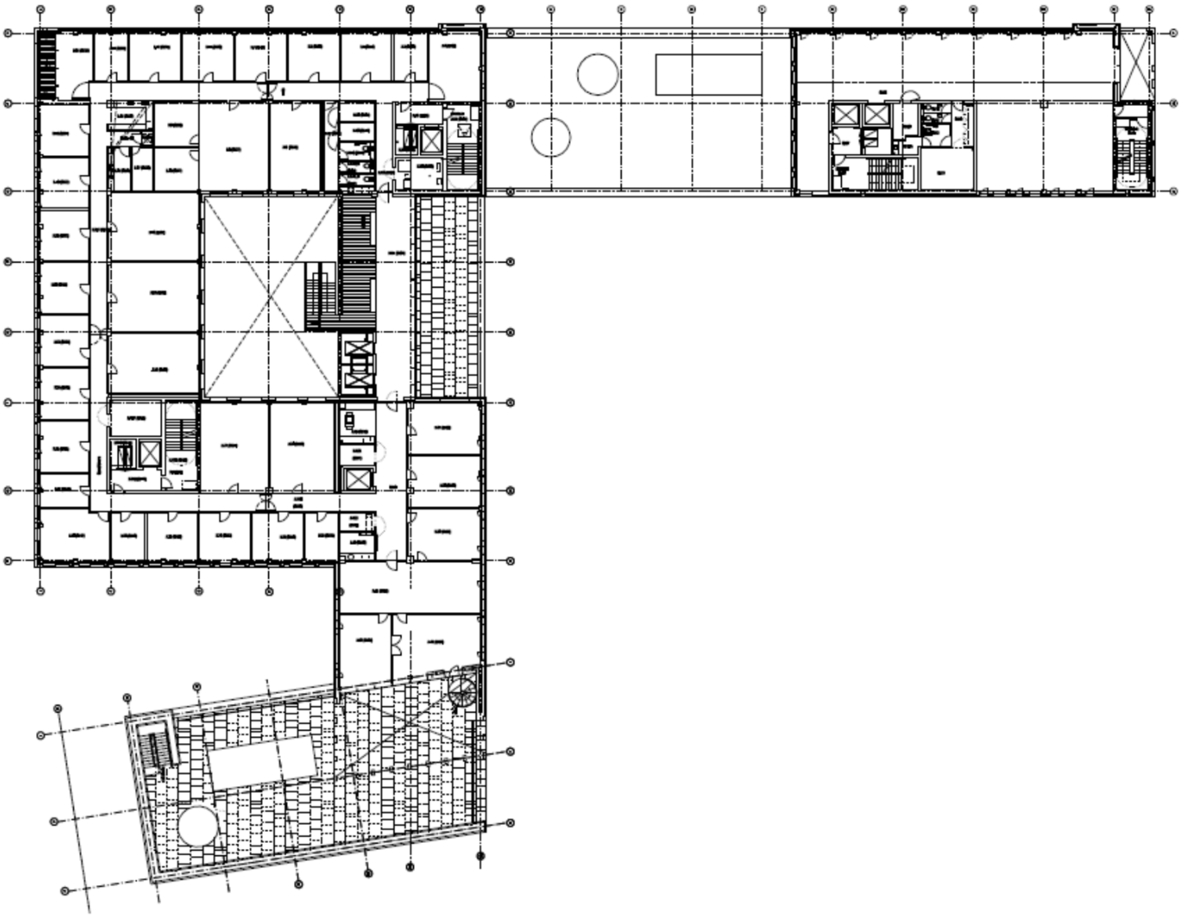
Second floor, Potterrow Building, phase 1 and 2



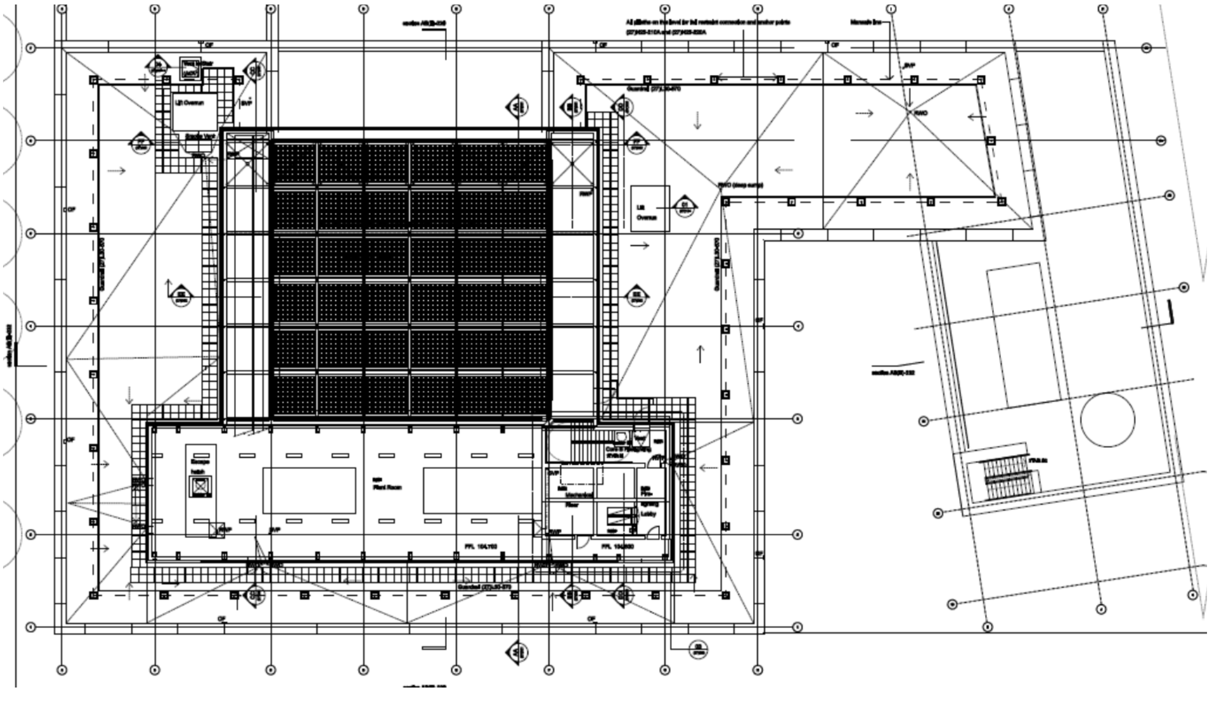
Third floor, Potterrow Building, phase 1 and 2



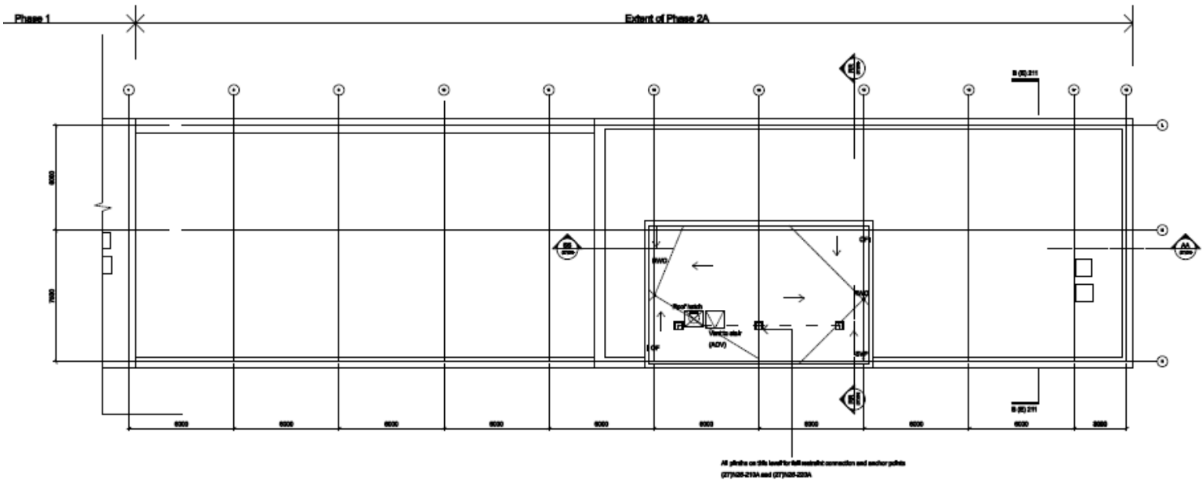
Fourth floor, Potterrow Building, phase 1 and 2



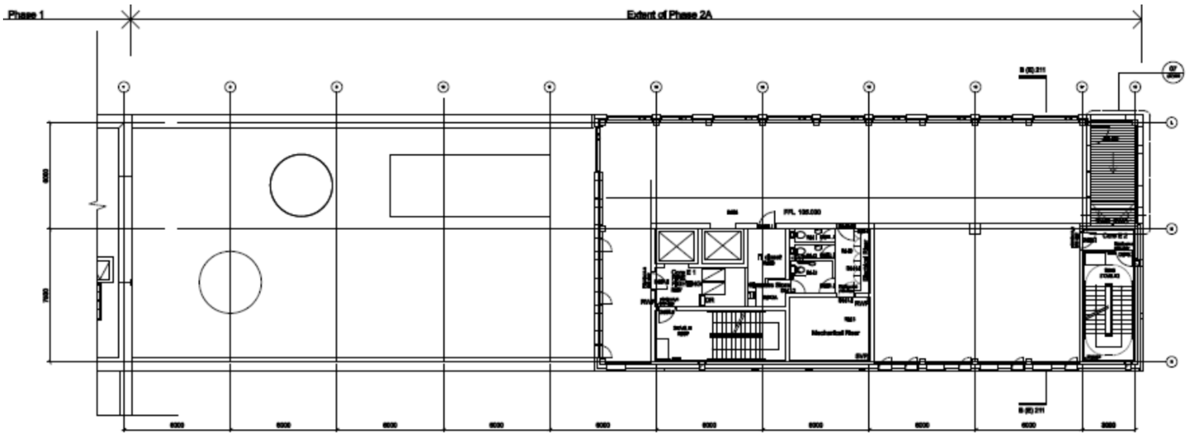
Fifth floor, Potterrow building, phase 1 and 2



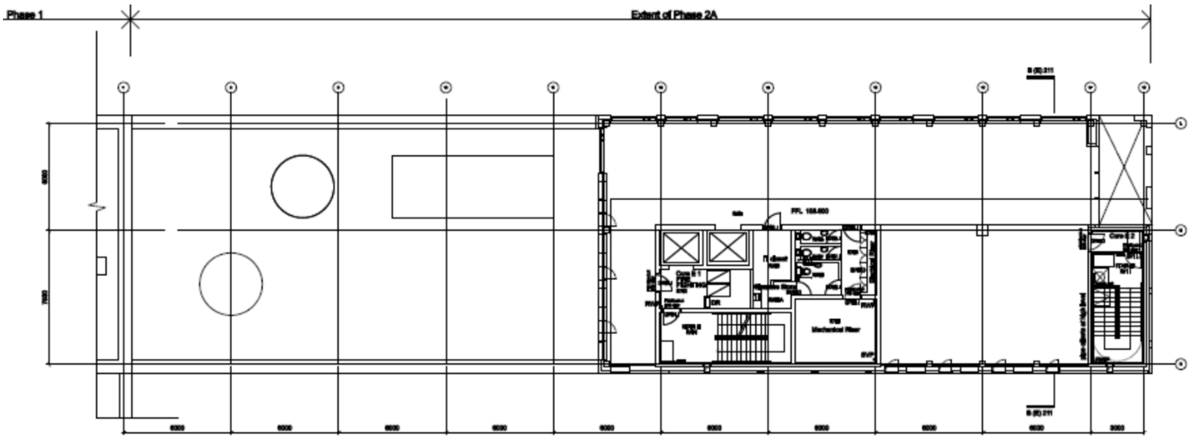
Roof, Potterrow Building, phase 1



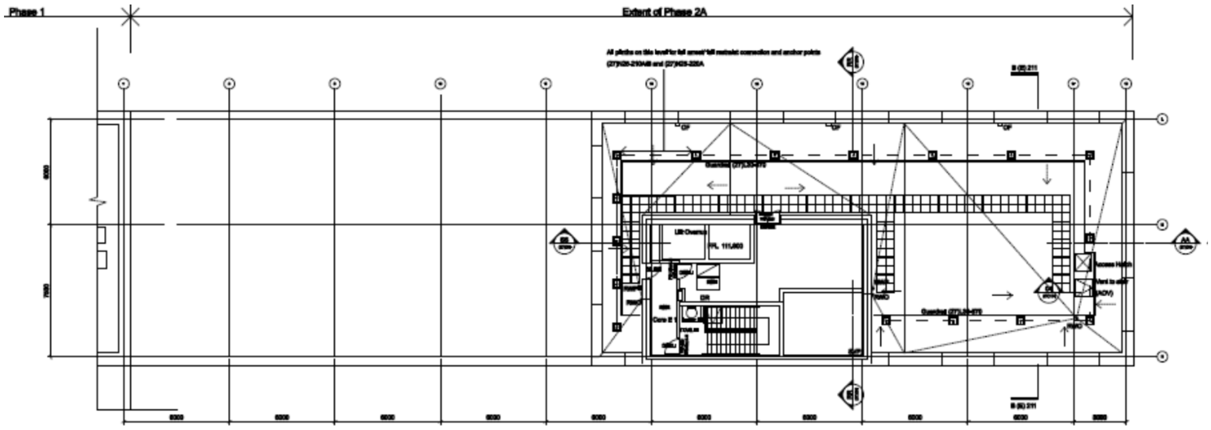
Roof, Potterrow Building, phase 2



Sixth floor, Potterrow Building, phase 2



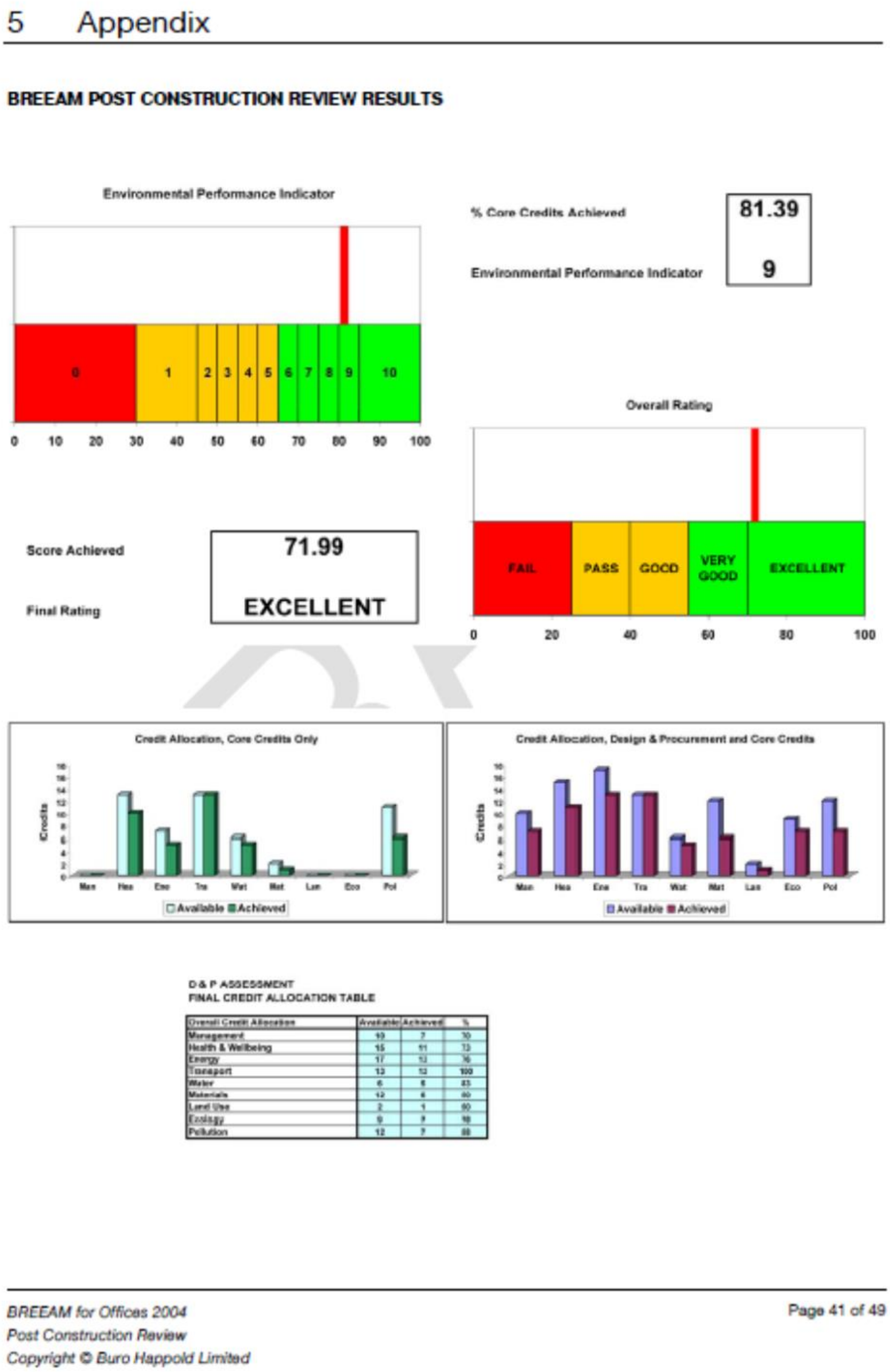
Seventh floor, Potterrow Building, phase 2



Eighth floor, Potterrow Building, phase 2

APPENDIX 11 BREEAM SCORE

Potterrow



5 Appendix

BREEAM POST CONSTRUCTION REVIEW RESULTS

% Core Credits Achieved 81.39

Environmental Performance Indicator 9

Score Achieved 71.99

Final Rating EXCELLENT

D & P ASSESSMENT
FINAL CREDIT ALLOCATION TABLE

Overall Credit Allocation	Available	Achieved	%
Management	10	7	70
Health & Wellbeing	15	11	73
Energy	17	13	76
Transport	13	13	100
Water	6	5	83
Materials	12	6	50
Land Use	2	1	50
Ecology	9	7	78
Pollution	12	7	58

BREEAM for Offices 2004
Post Construction Review
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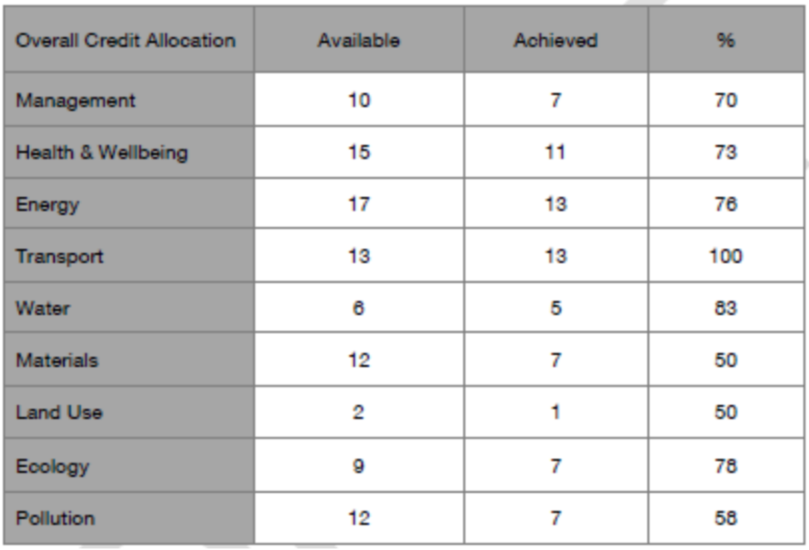
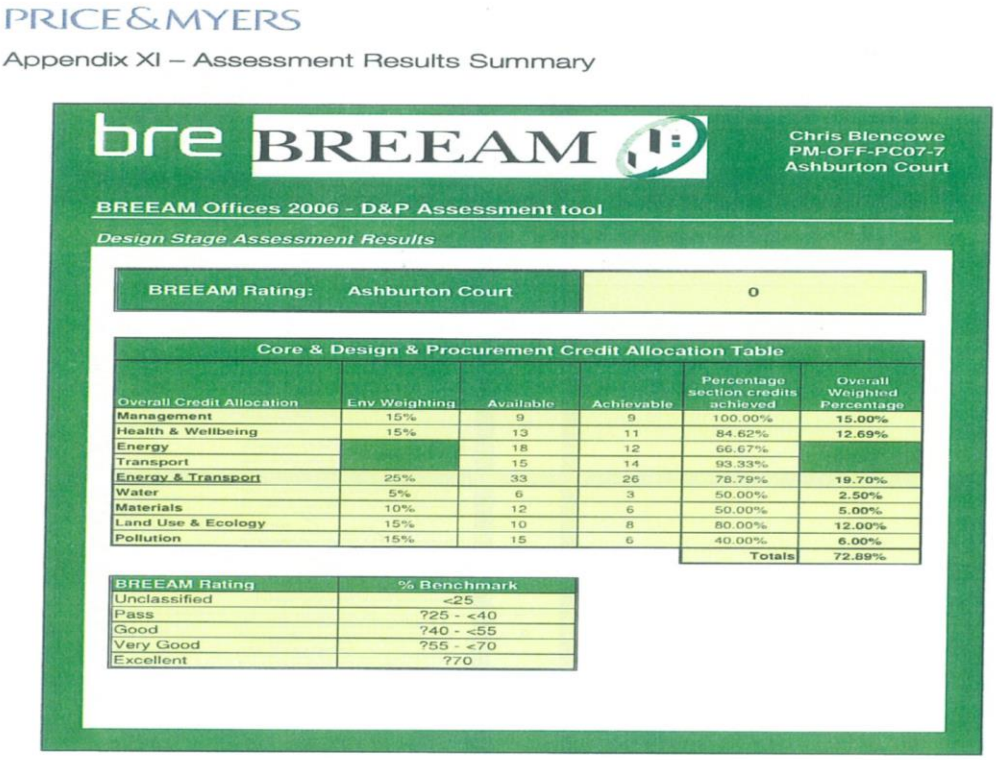
Page 41 of 49



Overall Credit Allocation	Available	Achieved	%
Management	10	7	70
Health & Wellbeing	15	11	73
Energy	17	13	76
Transport	13	13	100
Water	6	5	83
Materials	12	7	50
Land Use	2	1	50
Ecology	9	7	78
Pollution	12	7	58

Elizabeth Courts II



PRICE & MYERS

Appendix XI – Assessment Results Summary

bre BREEAM

Chris Blencowe
PM-OFF-PC07-7
Ashburton Court

BREEAM Offices 2006 - D&P Assessment tool

Design Stage Assessment Results

BREEAM Rating:	Ashburton Court	0

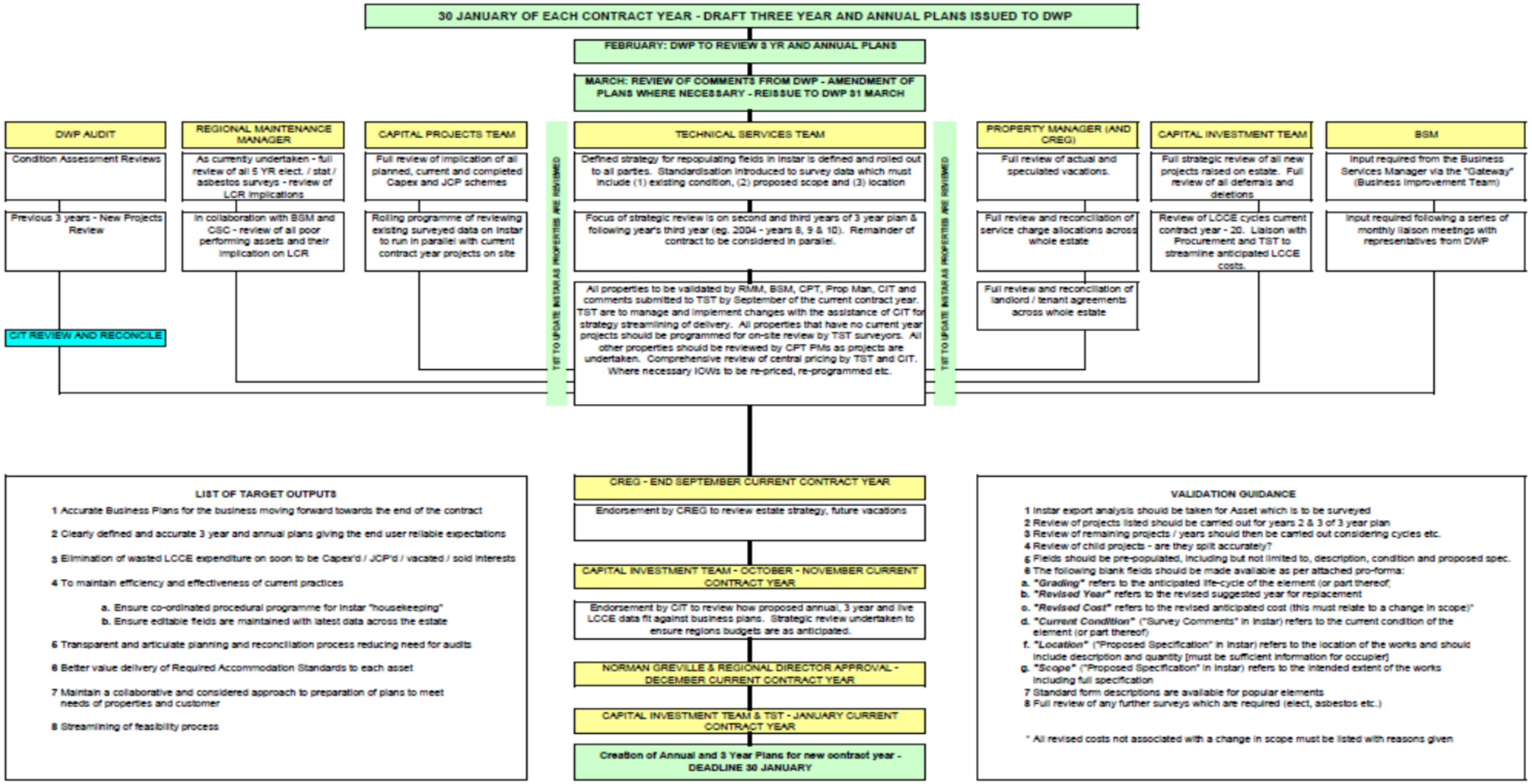
Core & Design & Procurement Credit Allocation Table

Overall Credit Allocation	Env Weighting	Available	Achievable	Percentage section credits achieved	Overall Weighted Percentage
Management	15%	9	9	100.00%	15.00%
Health & Wellbeing	15%	13	11	84.62%	12.69%
Energy		18	12	66.67%	
Transport		15	14	93.33%	
Energy & Transport	25%	33	26	78.79%	19.70%
Water	5%	6	3	50.00%	2.50%
Materials	10%	12	6	50.00%	5.00%
Land Use & Ecology	15%	10	8	80.00%	12.00%
Pollution	15%	15	6	40.00%	6.00%
				Totals	72.89%

BREEAM Rating	% Benchmark
Unclassified	<25
Pass	?25 - <40
Good	?40 - <55
Very Good	?55 - <70
Excellent	?70

APPENDIX 12 LIFE CYCLE MANAGEMENT

FLOW CHART OF INSTAR REVIEW PROCESS



30 JANUARY OF EACH CONTRACT YEAR - DRAFT THREE YEAR AND ANNUAL PLANS ISSUED TO DWP

FEBRUARY: DWP TO REVIEW 3 YR AND ANNUAL PLANS

MARCH: REVIEW OF COMMENTS FROM DWP - AMENDMENT OF PLANS WHERE NECESSARY - REISSUE TO DWP 31 MARCH

DWP AUDIT

Condition Assessment Reviews

Previous 3 years - New Projects Review

CIT REVIEW AND RECONCILE

REGIONAL MAINTENANCE MANAGER

As currently undertaken - full review of all 5 YR elect. / stat / asbestos surveys - review of LCR implications

In collaboration with BSM and CSC - review of all poor performing assets and their implication on LCR

CAPITAL PROJECTS TEAM

Full review of implication of all planned, current and completed Capex and JCP schemes

Rolling programme of reviewing existing surveyed data on Instar to run in parallel with current contract year projects on site

TECHNICAL SERVICES TEAM

Defined strategy for repopulating fields in Instar is defined and rolled out to all parties. Standardisation introduced to survey data which must include (1) existing condition, (2) proposed scope and (3) location

Focus of strategic review is on second and third years of 3 year plan & following year's third year (eg. 2004 - years 8, 9 & 10). Remainder of contract to be considered in parallel.

All properties to be validated by RMM, BSM, CPT, Prop Man, CIT and comments submitted to TST by September of the current contract year. TST are to manage and implement changes with the assistance of CIT for strategy streamlining of delivery. All properties that have no current year projects should be programmed for on-site review by TST surveyors. All other properties should be reviewed by CPT PMs as projects are undertaken. Comprehensive review of central pricing by TST and CIT. Where necessary IOWs to be re-priced, re-programmed etc.

PROPERTY MANAGER (AND CREG)

Full review of actual and speculated vacations.

Full review and reconciliation of service charge allocations across whole estate

Full review and reconciliation of landlord / tenant agreements across whole estate

CAPITAL INVESTMENT TEAM

Full strategic review of all new projects raised on estate. Full review of all deferrals and deletions

Review of LCCE cycles current contract year - 20. Liaison with Procurement and TST to streamline anticipated LCCE costs.

BSM

Input required from the Business Services Manager via the "Gateway" (Business Improvement Team)

Input required following a series of monthly liaison meetings with representatives from DWP

LIST OF TARGET OUTPUTS

1 Accurate Business Plans for the business moving forward towards the end of the contract

2 Clearly defined and accurate 3 year and annual plans giving the end user reliable expectations

3 Elimination of wasted LCCE expenditure on soon to be Capex'd / JCP'd / vacated / sold interests

4 To maintain efficiency and effectiveness of current practices

  a. Ensure co-ordinated procedural programme for Instar "housekeeping"
  b. Ensure editable fields are maintained with latest data across the estate

5 Transparent and articulate planning and reconciliation process reducing need for audits

6 Better value delivery of Required Accommodation Standards to each asset

7 Maintain a collaborative and considered approach to preparation of plans to meet needs of properties and customer

8 Streamlining of feasibility process

CREG - END SEPTEMBER CURRENT CONTRACT YEAR

Endorsement by CREG to review estate strategy, future vacations

CAPITAL INVESTMENT TEAM - OCTOBER - NOVEMBER CURRENT CONTRACT YEAR

Endorsement by CIT to review how proposed annual, 3 year and live LCCE data fit against business plans. Strategic review undertaken to ensure regions budgets are as anticipated.

NORMAN GREVILLE & REGIONAL DIRECTOR APPROVAL - DECEMBER CURRENT CONTRACT YEAR

CAPITAL INVESTMENT TEAM & TST - JANUARY CURRENT CONTRACT YEAR

Creation of Annual and 3 Year Plans for new contract year - DEADLINE 30 JANUARY

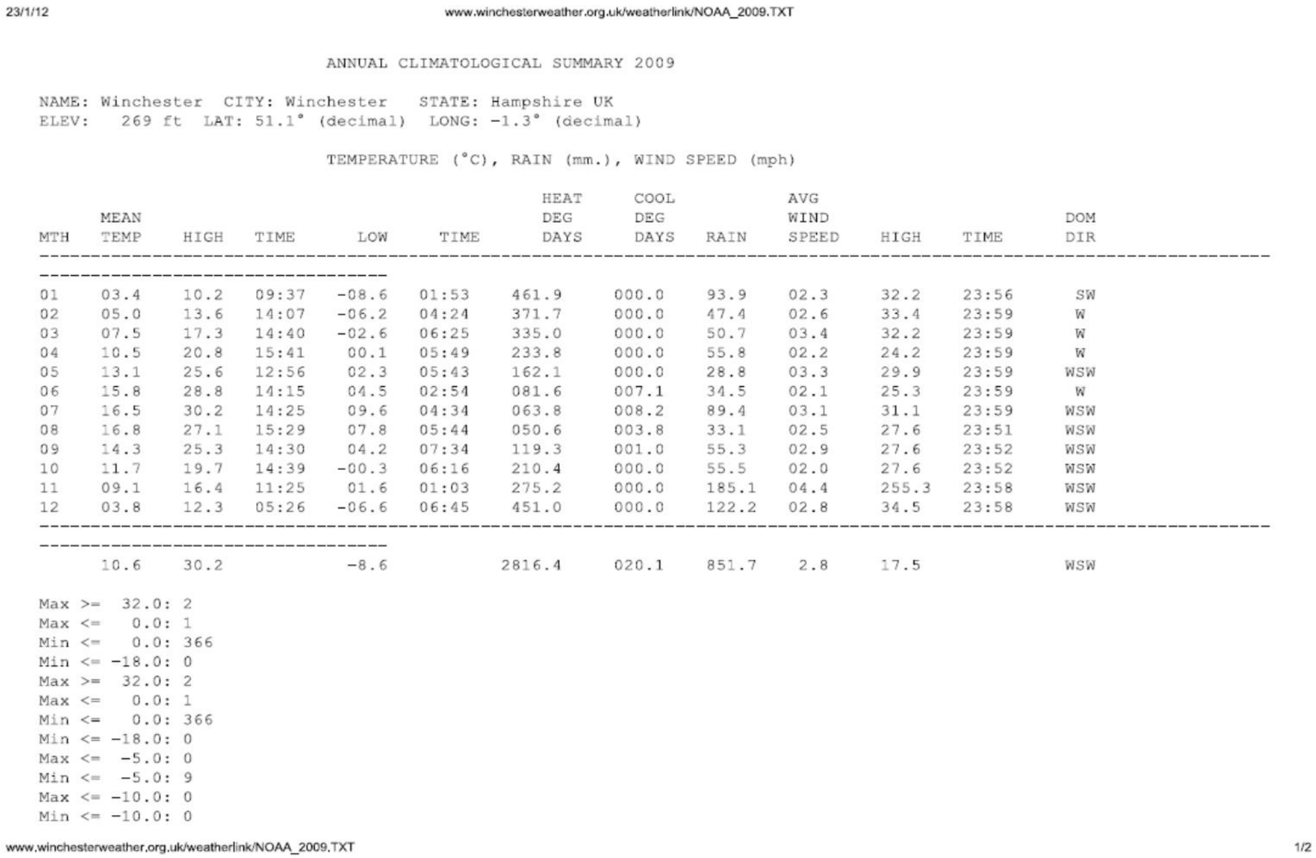
VALIDATION GUIDANCE

1 Instar export analysis should be taken for Asset which is to be surveyed
2 Review of projects listed should be carried out for years 2 & 3 of 3 year plan
3 Review of remaining projects / years should then be carried out considering cycles etc.
4 Review of child projects - are they split accurately?
5 Fields should be pre-populated, including but not limited to, description, condition and proposed spec.
6 The following blank fields should be made available as per attached pro-forma:
a. ***"Grading"*** refers to the anticipated life-cycle of the element (or part thereof)
b. ***"Revised Year"*** refers to the revised suggested year for replacement
c. ***"Revised Cost"*** refers to the revised anticipated cost (this must relate to a change in scope)*
d. ***"Current Condition"*** ("Survey Comments" in Instar) refers to the current condition of the element (or part thereof)
f. ***"Location"*** ("Proposed Specification" in Instar) refers to the location of the works and should include description and quantity [must be sufficient information for occupier]
g. ***"Scope"*** ("Proposed Specification" in Instar) refers to the intended extent of the works including full specification
7 Standard form descriptions are available for popular elements
8 Full review of any further surveys which are required (elect, asbestos etc.)

* All revised costs not associated with a change in scope must be listed with reasons given

Flow chart life cycle management

APPENDIX 13 WINCHESTER WEATHER CONDITIONS



23/1/12 www.winchesterweather.org.uk/weatherlink/NOAA_2009.TXT

```
                            ANNUAL CLIMATOLOGICAL SUMMARY 2009

NAME: Winchester  CITY: Winchester   STATE: Hampshire UK
ELEV:   269 ft  LAT: 51.1° (decimal)  LONG: -1.3° (decimal)

                            TEMPERATURE (°C), RAIN (mm.), WIND SPEED (mph)

                                                 HEAT     COOL           AVG
      MEAN                                       DEG      DEG            WIND                       DOM
MTH   TEMP    HIGH   TIME      LOW     TIME      DAYS     DAYS   RAIN    SPEED    HIGH    TIME      DIR
------------------------------------------------------------------------------------------------------------------------
----------------------------------
01    03.4    10.2   09:37   -08.6   01:53    461.9     000.0    93.9    02.3     32.2    23:56      SW
02    05.0    13.6   14:07   -06.2   04:24    371.7     000.0    47.4    02.6     33.4    23:59      W
03    07.5    17.3   14:40   -02.6   06:25    335.0     000.0    50.7    03.4     32.2    23:59      W
04    10.5    20.8   15:41    00.1   05:49    233.8     000.0    55.8    02.2     24.2    23:59      W
05    13.1    25.6   12:56    02.3   05:43    162.1     000.0    28.8    03.3     29.9    23:59     WSW
06    15.8    28.8   14:15    04.5   02:54    081.6     007.1    34.5    02.1     25.3    23:59      W
07    16.5    30.2   14:25    09.6   04:34    063.8     008.2    89.4    03.1     31.1    23:59     WSW
08    16.8    27.1   15:29    07.8   05:44    050.6     003.8    33.1    02.5     27.6    23:51     WSW
09    14.3    25.3   14:30    04.2   07:34    119.3     001.0    55.3    02.9     27.6    23:52     WSW
10    11.7    19.7   14:39   -00.3   06:16    210.4     000.0    55.5    02.0     27.6    23:52     WSW
11    09.1    16.4   11:25    01.6   01:03    275.2     000.0    185.1   04.4     255.3   23:58     WSW
12    03.8    12.3   05:26   -06.6   06:45    451.0     000.0    122.2   02.8     34.5    23:58     WSW
------------------------------------------------------------------------------------------------------------------------
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Max >=  32.0: 2
Max <=   0.0: 1
Min <=   0.0: 366
Min <= -18.0: 0
Max >=  32.0: 2
Max <=   0.0: 1
Min <=   0.0: 366
Min <= -18.0: 0
Max <=  -5.0: 0
Min <=  -5.0: 9
Max <= -10.0: 0
Min <= -10.0: 0
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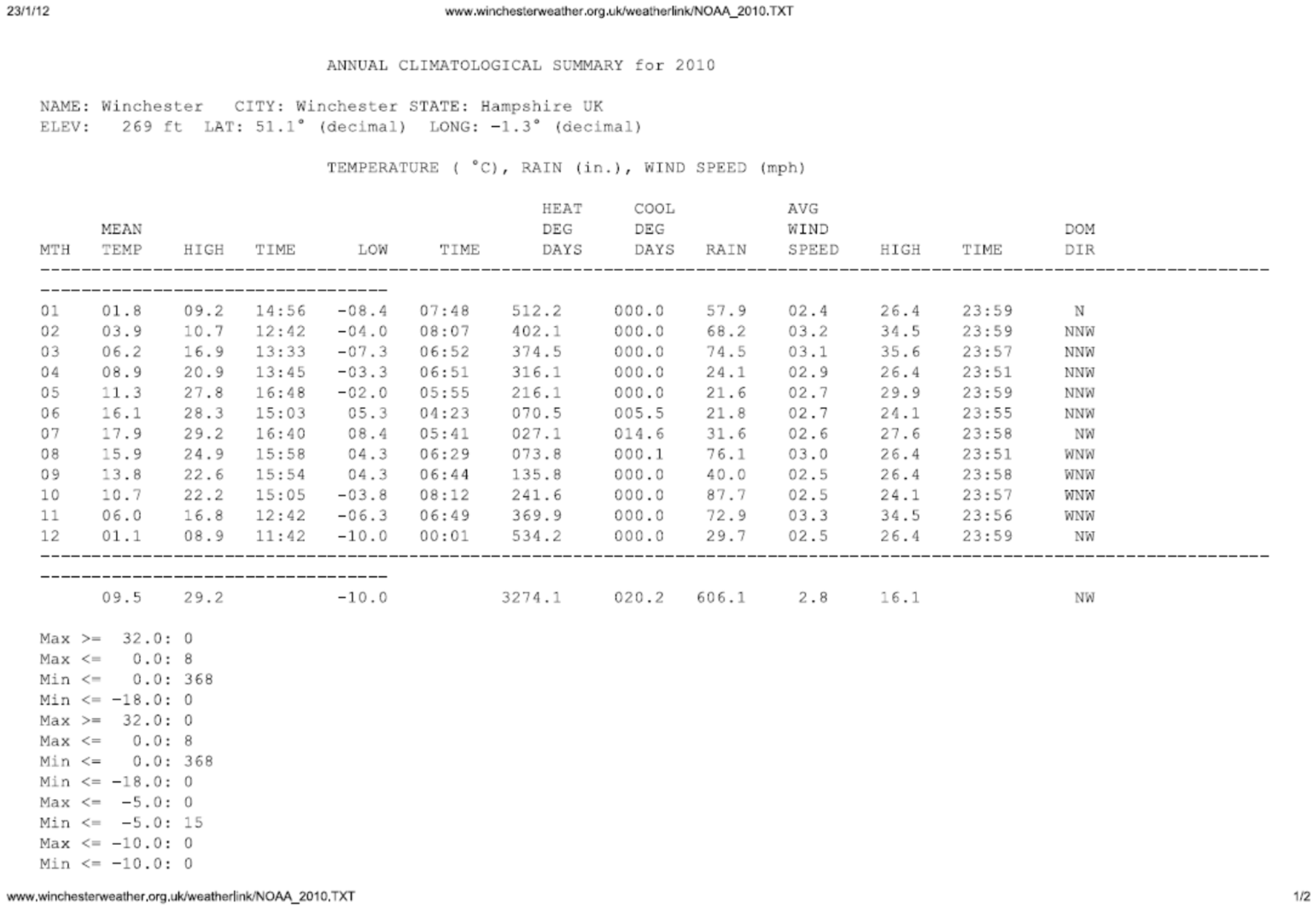
www.winchesterweather.org.uk/weatherlink/NOAA_2009.TXT 1/2

Annual climatological summary 2009, Winchester
Source: Winchesterweather.org.uk/weatherlinkNOAA_2009.TXT



23/1/12 www.winchesterweather.org.uk/weatherlink/NOAA_2010.TXT

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                            ANNUAL CLIMATOLOGICAL SUMMARY for 2010

NAME: Winchester   CITY: Winchester STATE: Hampshire UK
ELEV:   269 ft  LAT: 51.1° (decimal)  LONG: -1.3° (decimal)

                            TEMPERATURE ( °C), RAIN (in.), WIND SPEED (mph)

                                                 HEAT     COOL           AVG
      MEAN                                       DEG      DEG            WIND                       DOM
MTH   TEMP    HIGH   TIME       LOW     TIME      DAYS     DAYS   RAIN    SPEED    HIGH     TIME      DIR
------------------------------------------------------------------------------------------------------------------------
----------------------------------
01    01.8    09.2   14:56   -08.4   07:48    512.2     000.0    57.9    02.4     26.4     23:59      N
02    03.9    10.7   12:42   -04.0   08:07    402.1     000.0    68.2    03.2     34.5     23:59     NNW
03    06.2    16.9   13:33   -07.3   06:52    374.5     000.0    74.5    03.1     35.6     23:57     NNW
04    08.9    20.9   13:45   -03.3   06:51    316.1     000.0    24.1    02.9     26.4     23:51     NNW
05    11.3    27.8   16:48   -02.0   05:55    216.1     000.0    21.6    02.7     29.9     23:59     NNW
06    16.1    28.3   15:03    05.3   04:23    070.5     005.5    21.8    02.7     24.1     23:55     NNW
07    17.9    29.2   16:40    08.4   05:41    027.1     014.6    31.6    02.6     27.6     23:58      NW
08    15.9    24.9   15:58    04.3   06:29    073.8     000.1    76.1    03.0     26.4     23:51     WNW
09    13.8    22.6   15:54    04.3   06:44    135.8     000.0    40.0    02.5     26.4     23:58     WNW
10    10.7    22.2   15:05   -03.8   08:12    241.6     000.0    87.7    02.5     24.1     23:57     WNW
11    06.0    16.8   12:42   -06.3   06:49    369.9     000.0    72.9    03.3     34.5     23:56     WNW
12    01.1    08.9   11:42   -10.0   00:01    534.2     000.0    29.7    02.5     26.4     23:59      NW
------------------------------------------------------------------------------------------------------------------------
----------------------------------
      09.5    29.2           -10.0           3274.1     020.2   606.1     2.8     16.1                NW

Max >=  32.0: 0
Max <=   0.0: 8
Min <=   0.0: 368
Min <= -18.0: 0
Max >=  32.0: 0
Max <=   0.0: 8
Min <=   0.0: 368
Min <= -18.0: 0
Max <=  -5.0: 0
Min <=  -5.0: 15
Max <= -10.0: 0
Min <= -10.0: 0
```
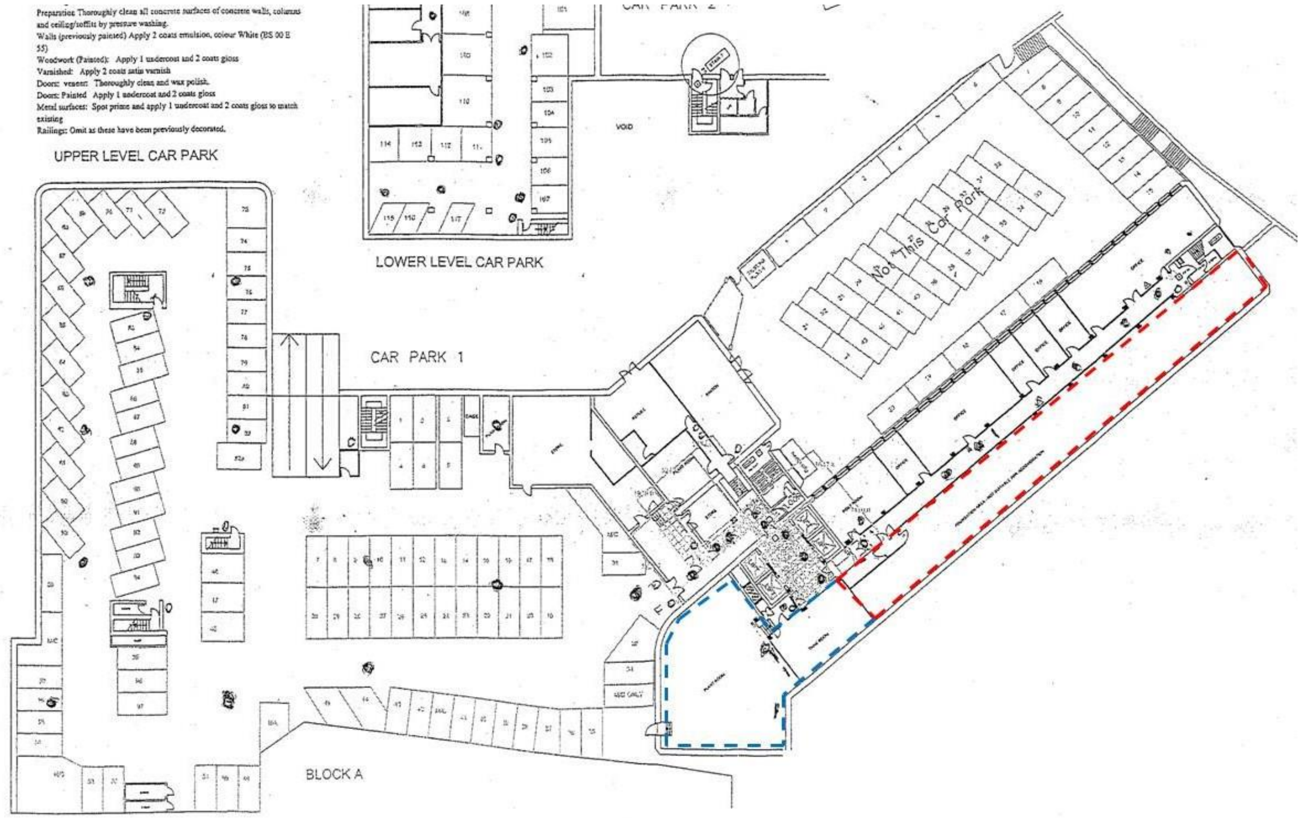

www.winchesterweather.org.uk/weatherlink/NOAA_2010.TXT 1/2

Annual climatological summary 2010, Winchester
Source: Winchesterweather.org.uk/weatherlinkNOAA_2010.TXT

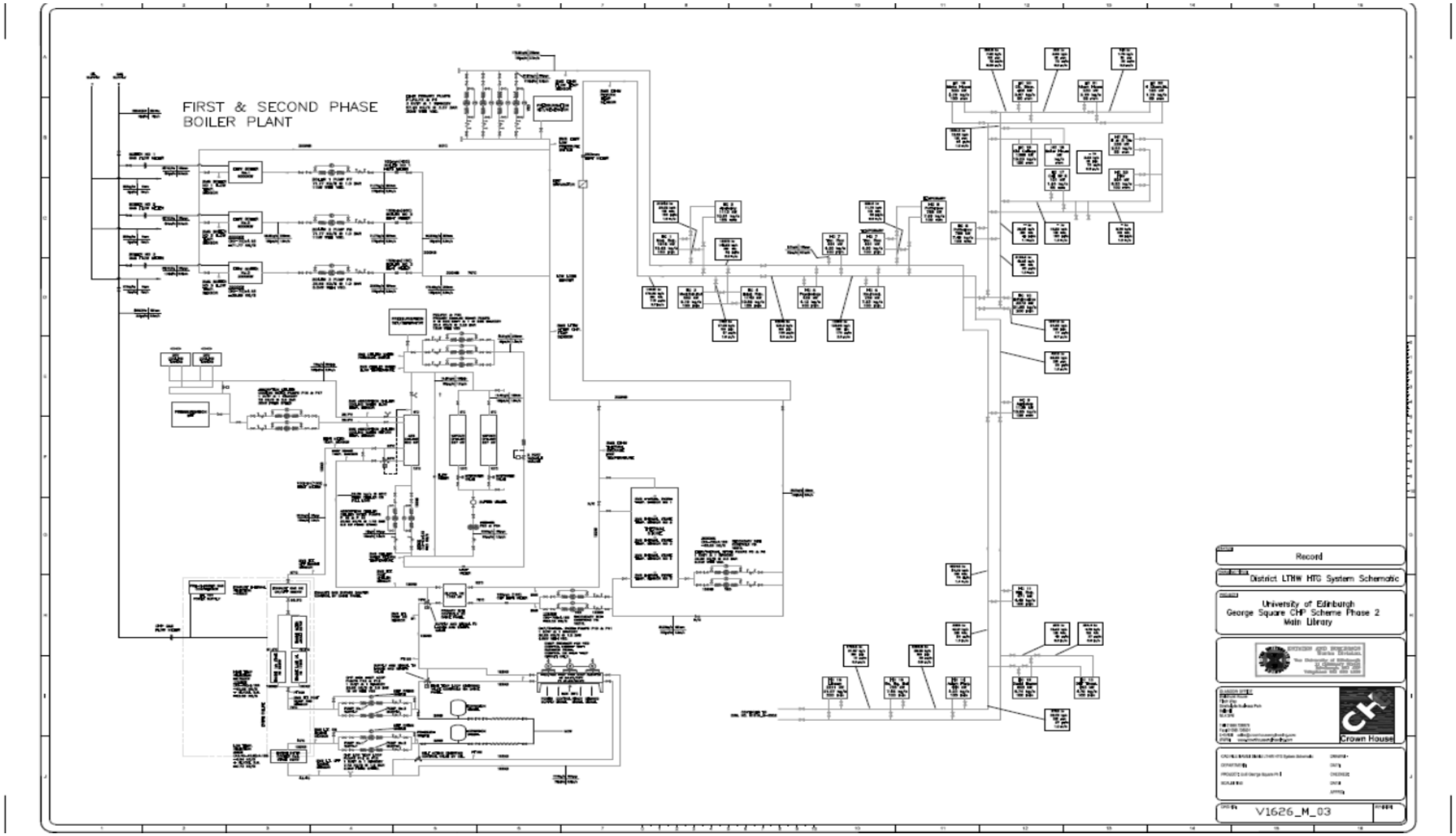
APPENDIX 14 TECHNICAL DRAWINGS OF THE PLANTROOM SERVICES



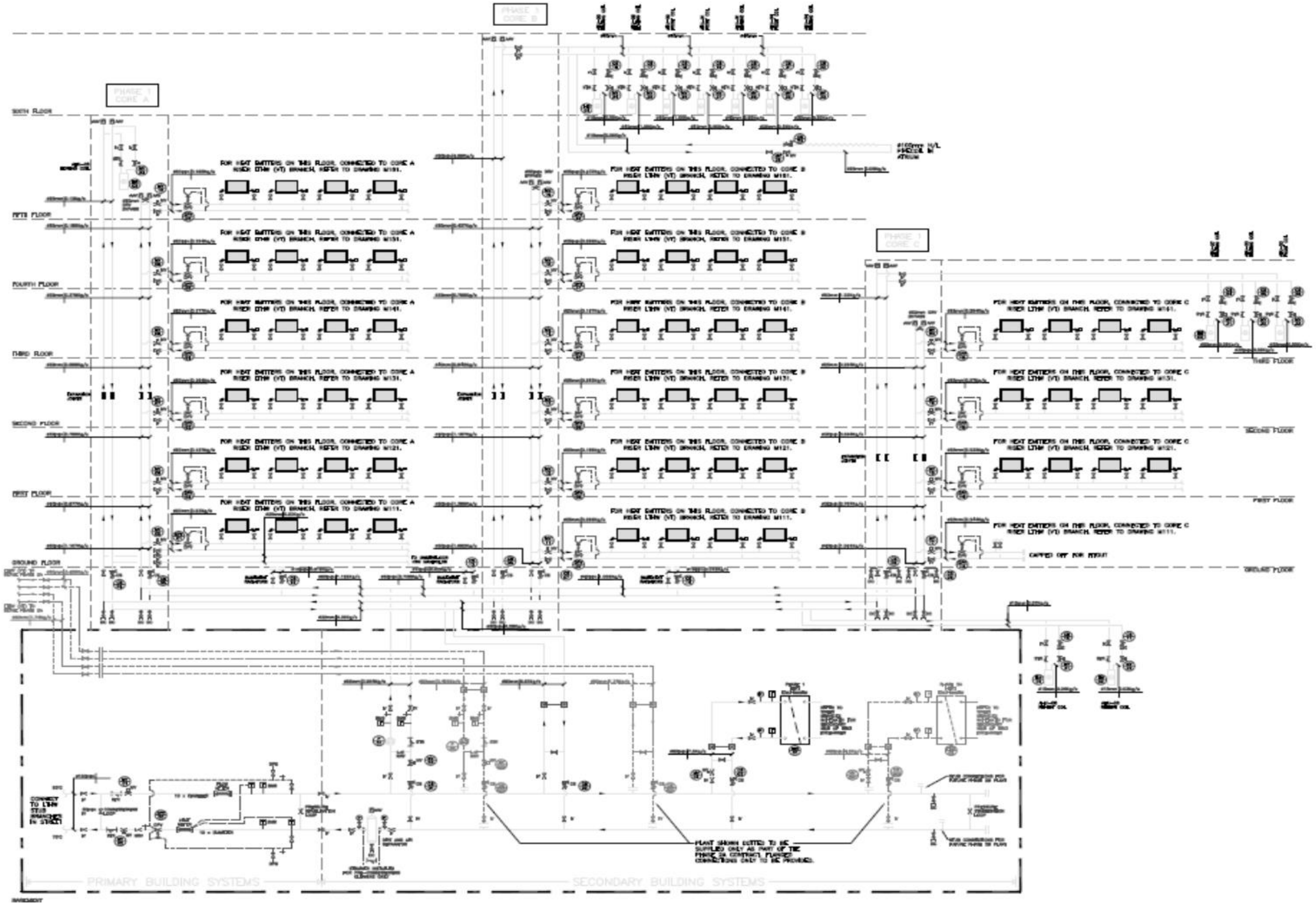
Preparation Thoroughly clean all concrete surfaces of concrete walls, columns and ceiling/soffits by pressure washing.
Walls (previously painted) Apply 2 coats emulsion, colour White (BS 00 E 55)
Woodwork (Painted): Apply 1 undercoat and 2 coats gloss
Varnished: Apply 2 coats satin varnish
Doors: veneer: Thoroughly clean and wax polish.
Doors: Painted Apply 1 undercoat and 2 coats gloss
Metal surfaces: Spot prime and apply 1 undercoat and 2 coats gloss to match existing
Railings: Omit as these have been previously decorated.

Plantroom services for heating (blue highlighted area and for cooling (red highlighted area).

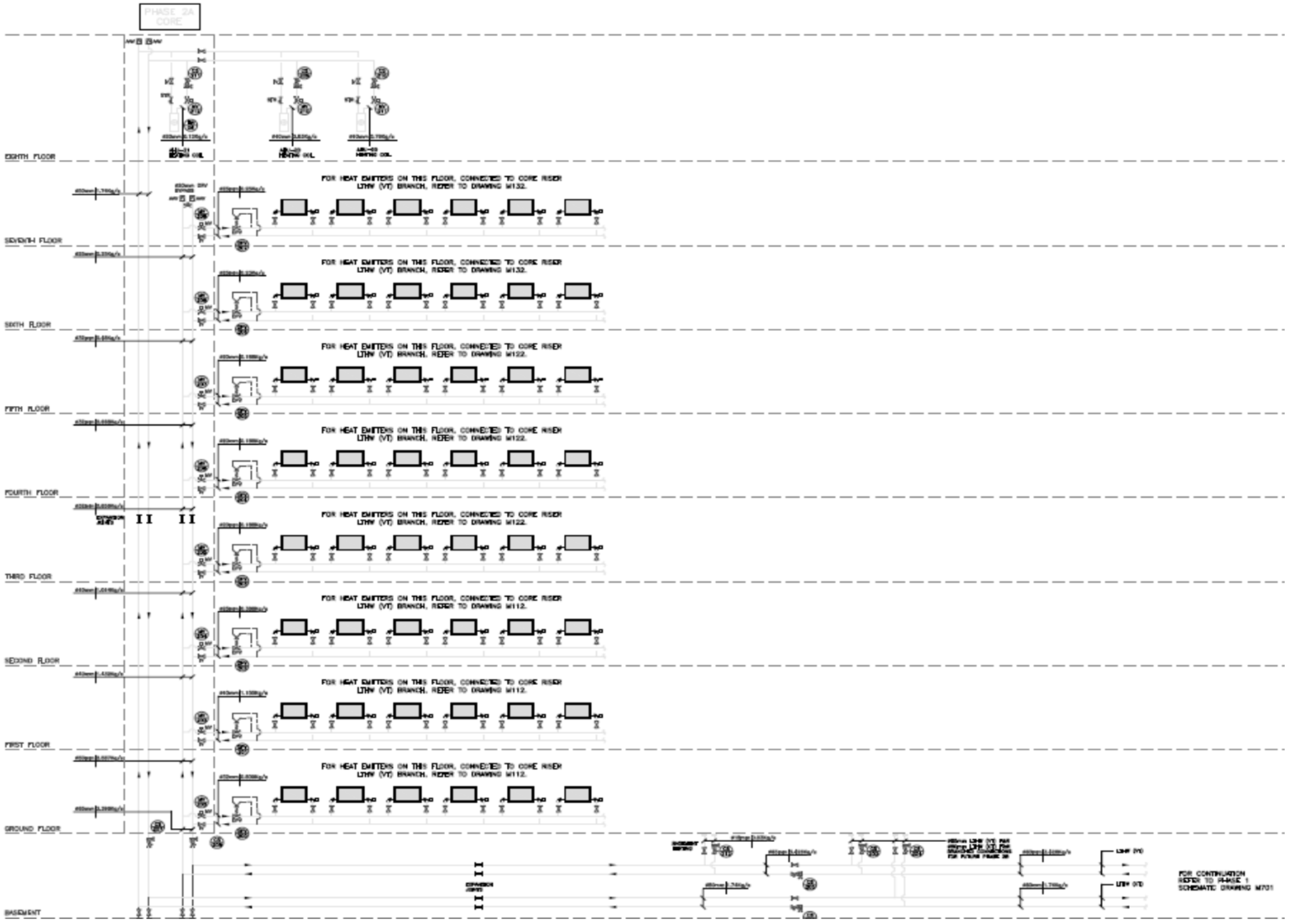
APPENDIX 15 SCHEMATIC DRAWINGS



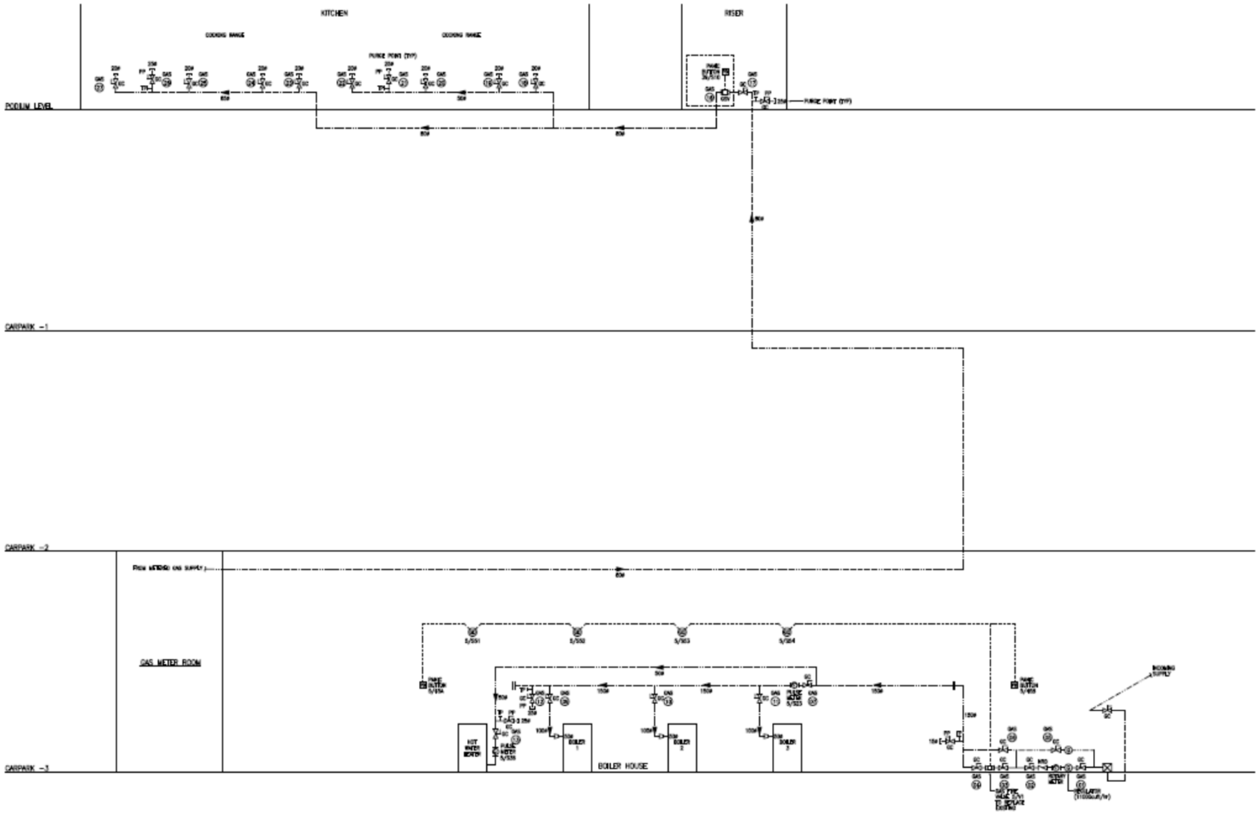
Schematic drawing of the CHP



LTHW heating schematic, phase 1, Informatics

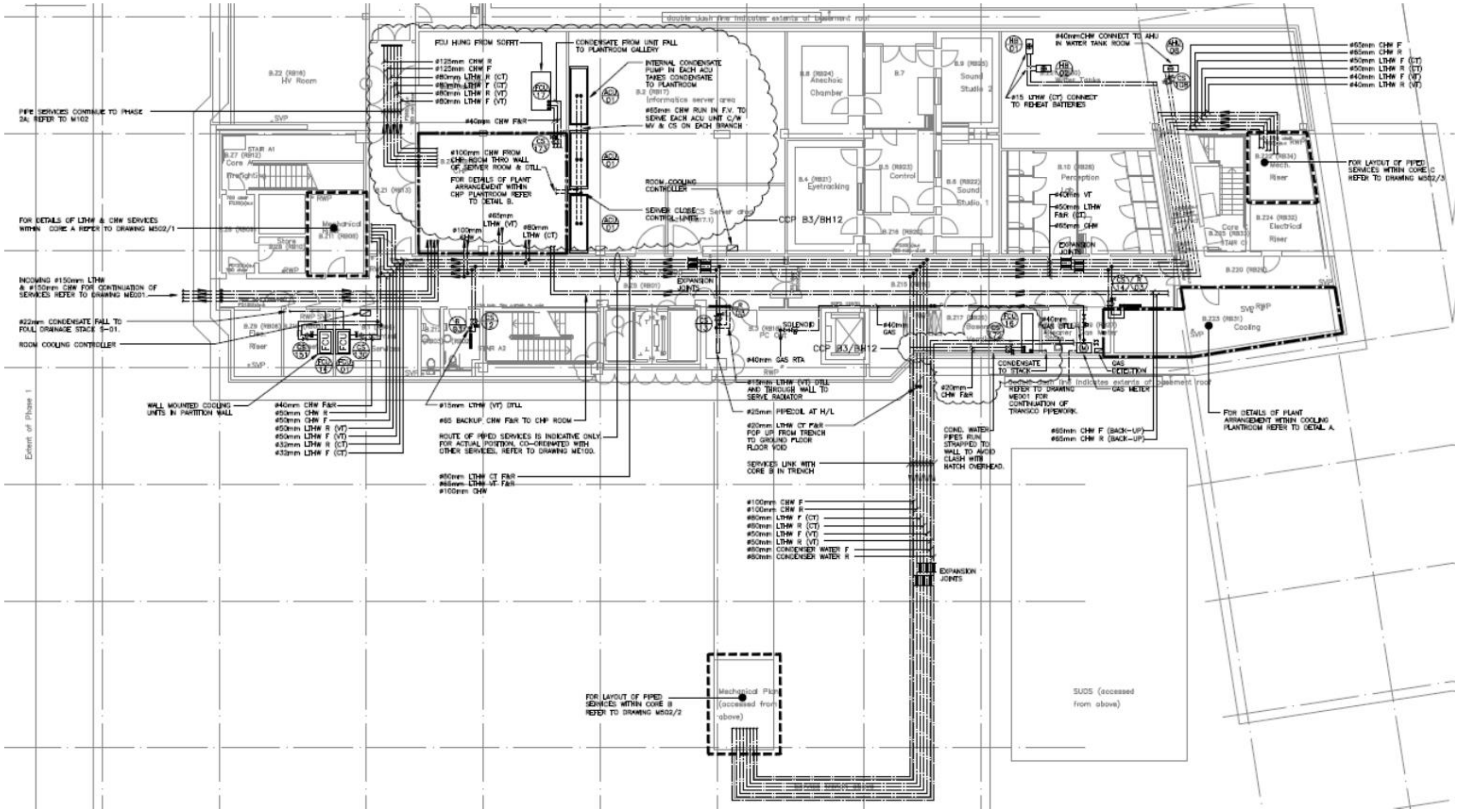


LTHW heating schematic, phase 2a, Dugal Stewart

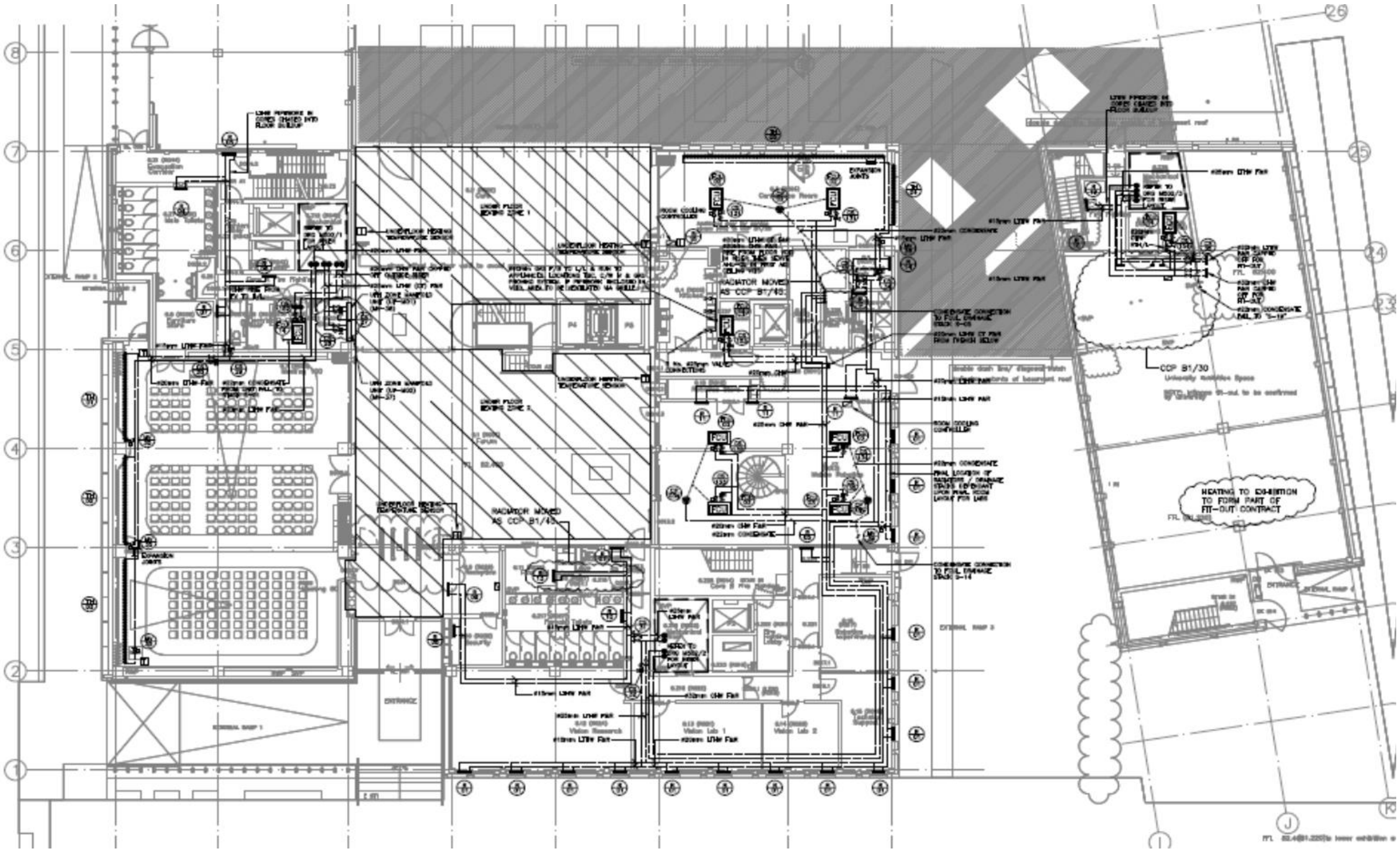


Gas installation schematic

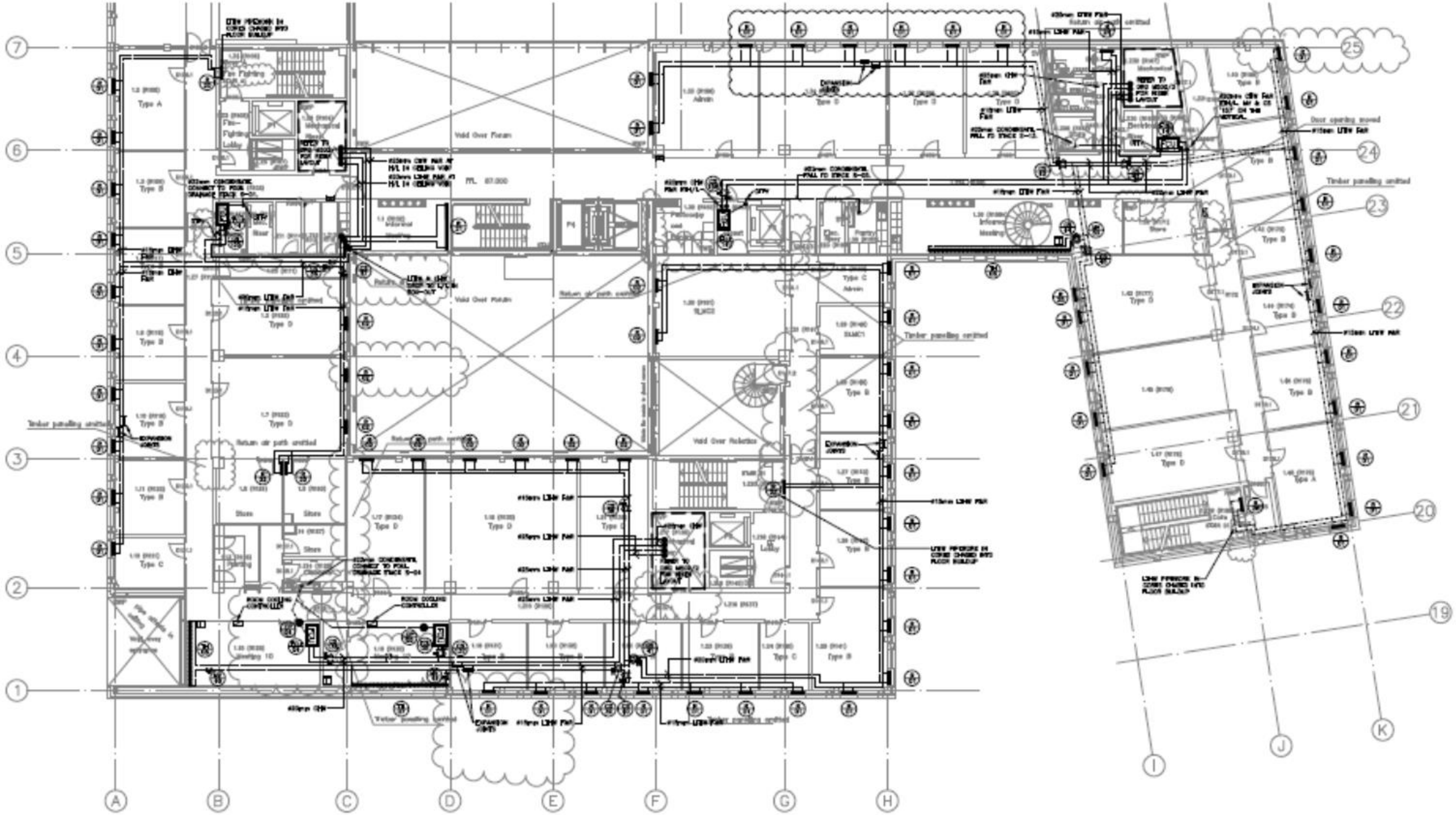
APPENDIX 16: MECHANICAL DRAWINGS OF THE PLANTROOM SERVICES



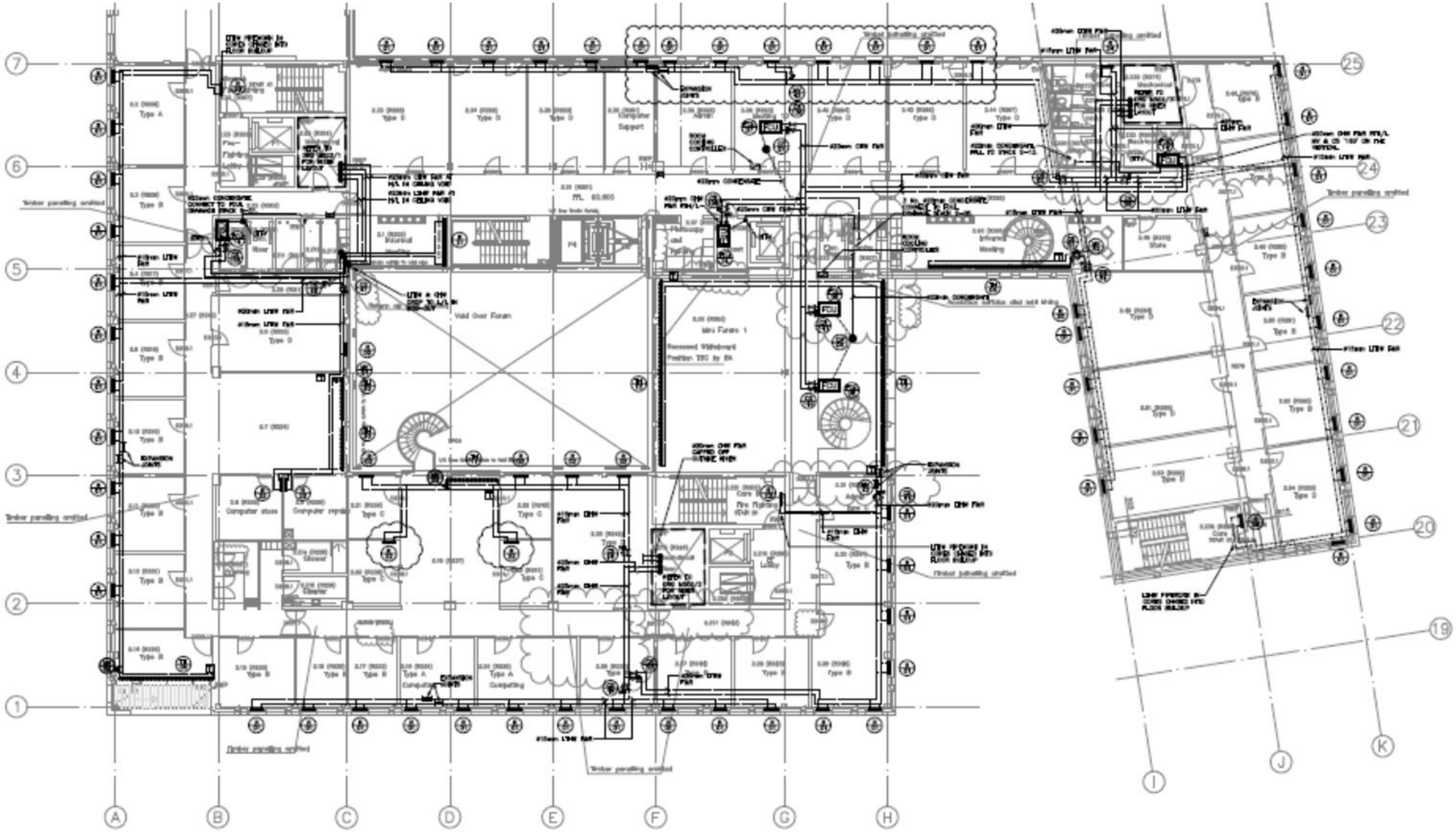
Potterrow Building
LTHW & CHW, phase 1



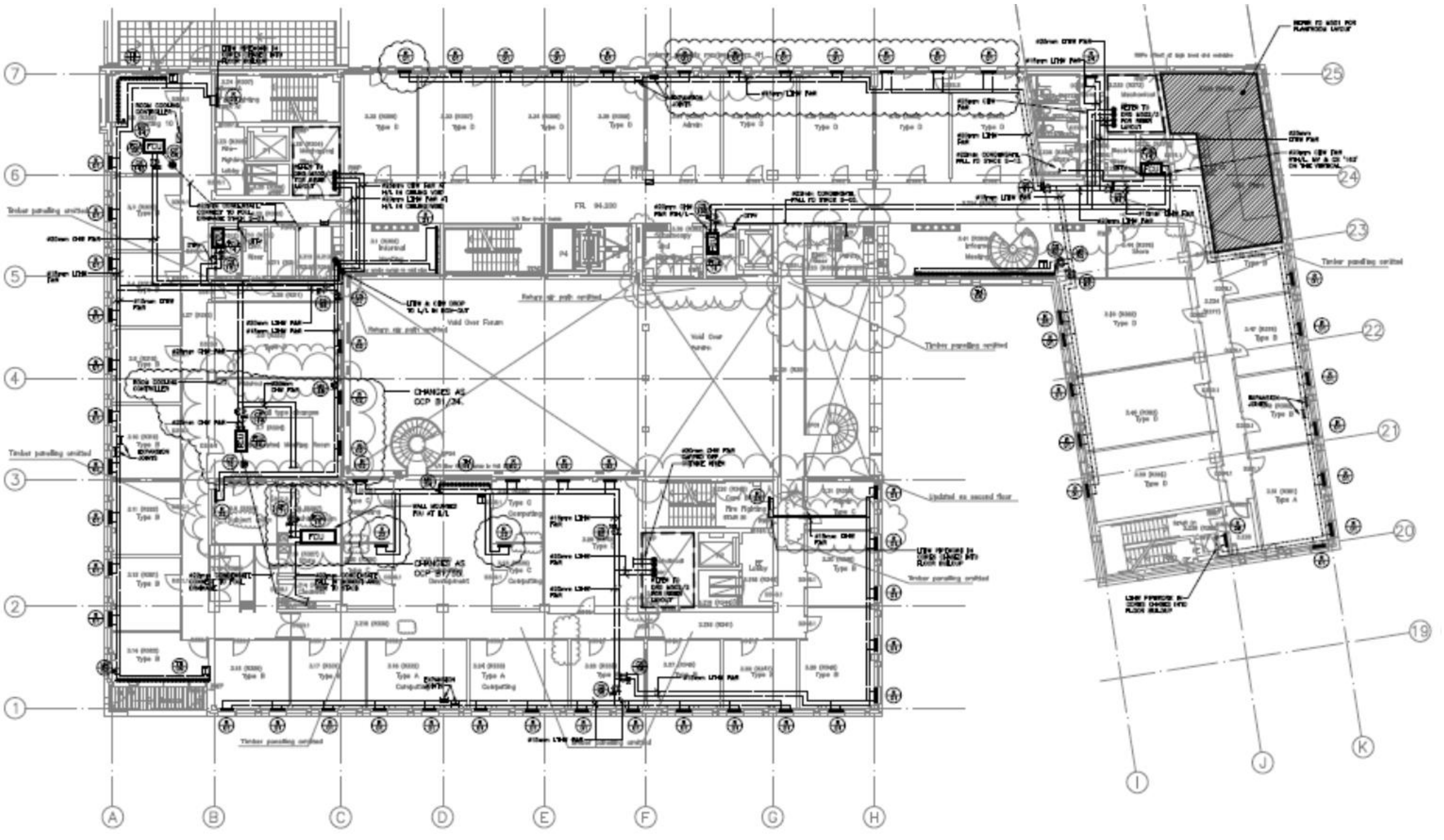
LTHW & CHW, phase 1, ground floor



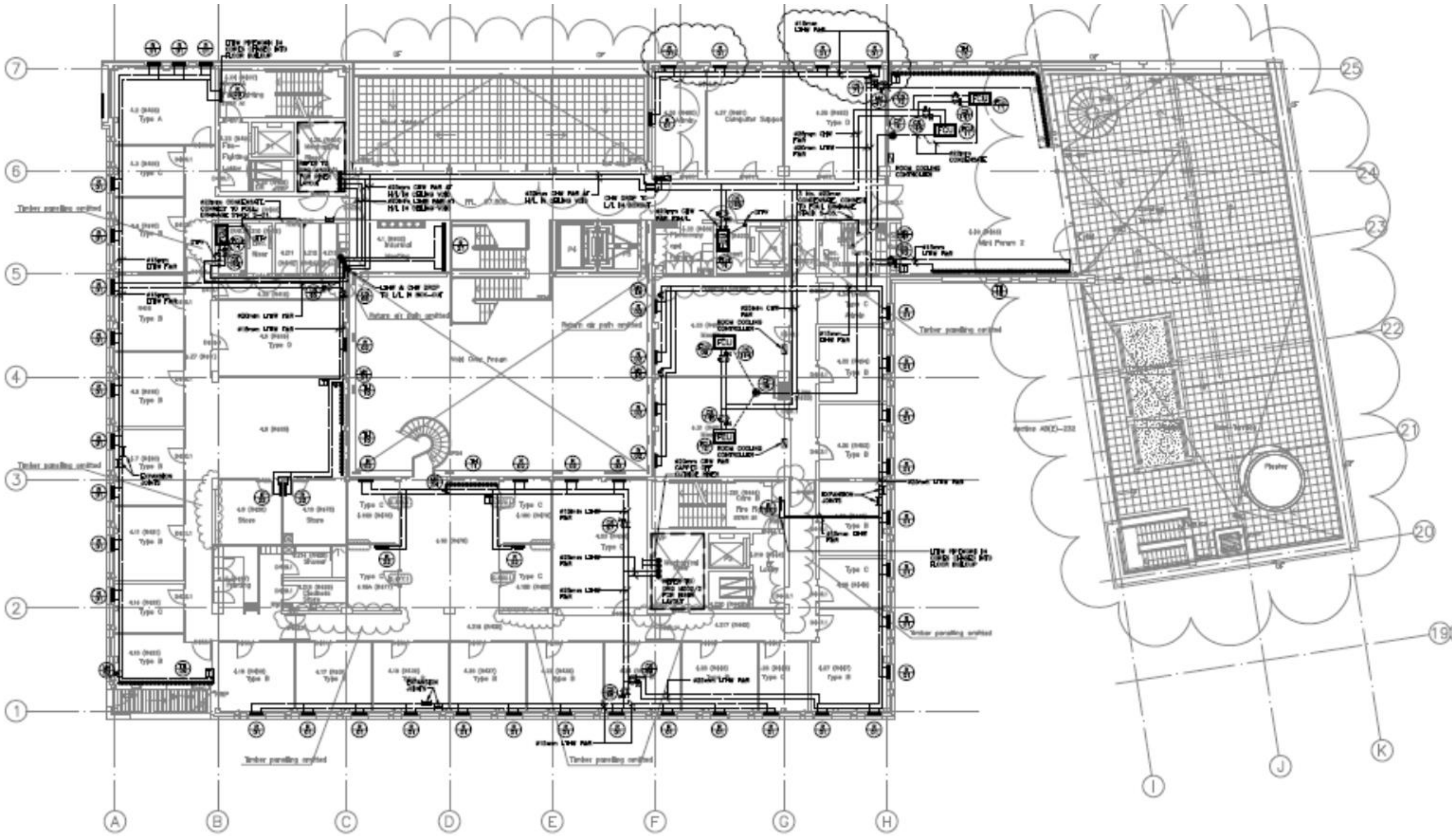
LTHW heating,first floor, phase 1



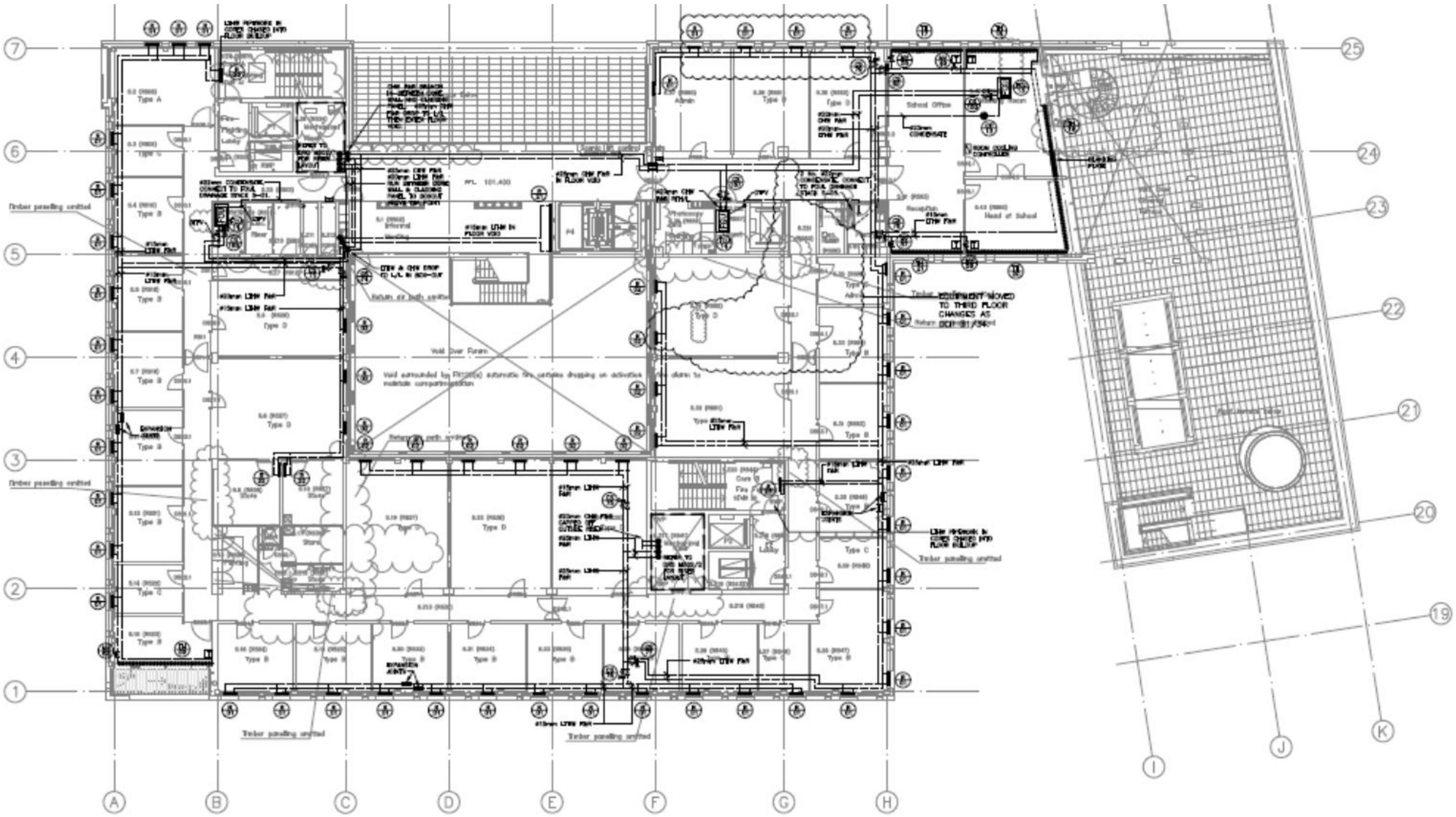
LTHW heating, second floor, phase 1



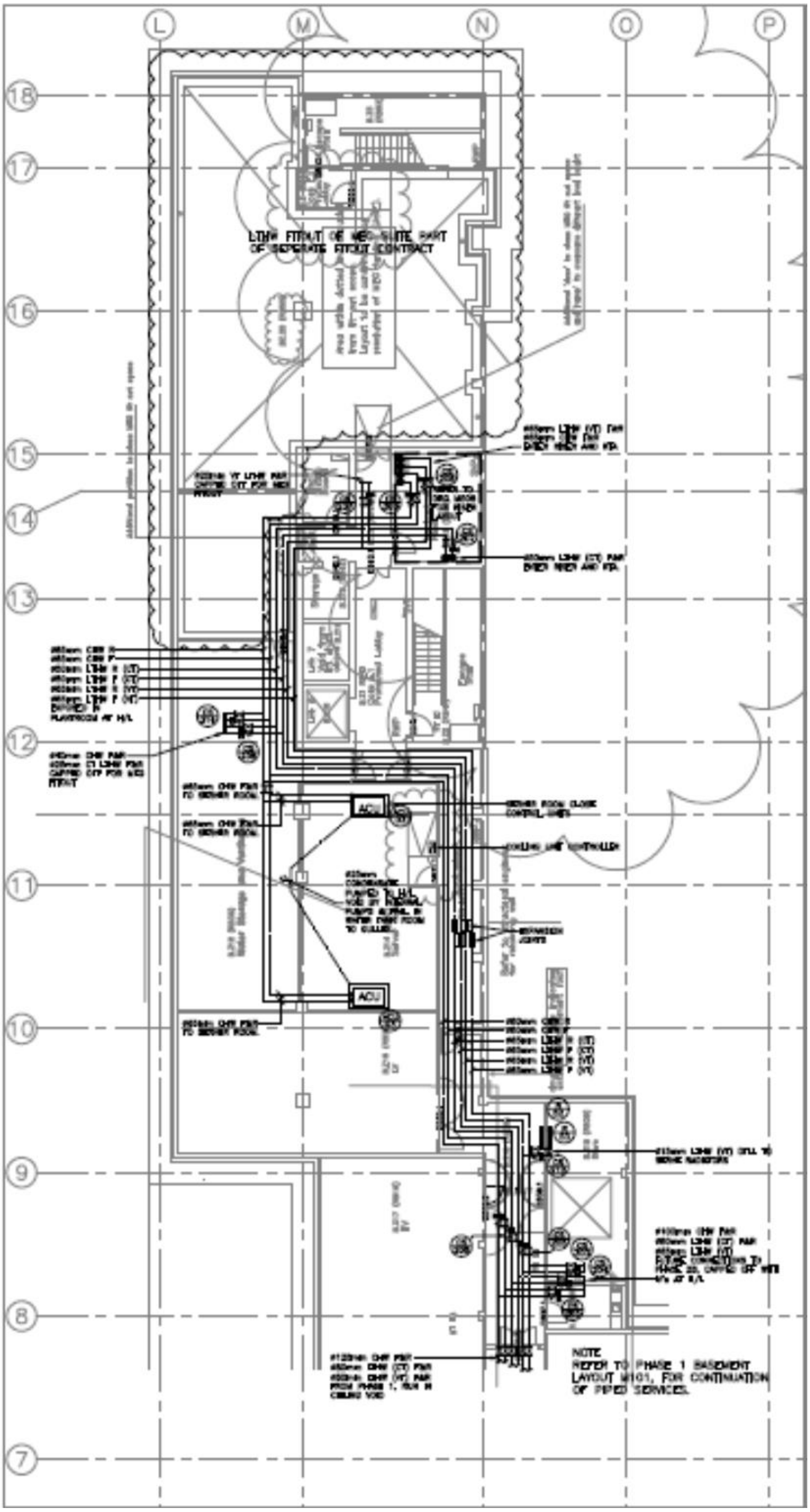
LTHW heating, third floor, phase 1



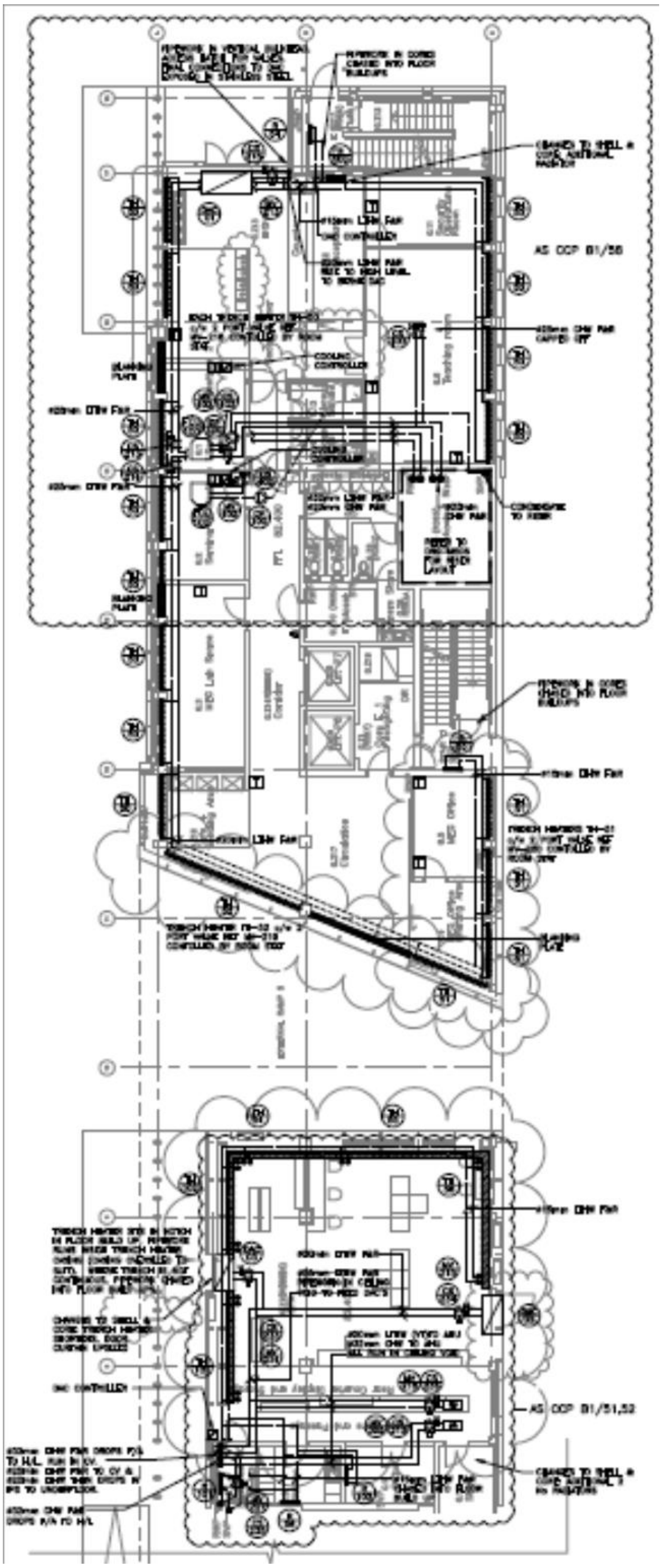
LTHW heating, fourth floor, phase 1



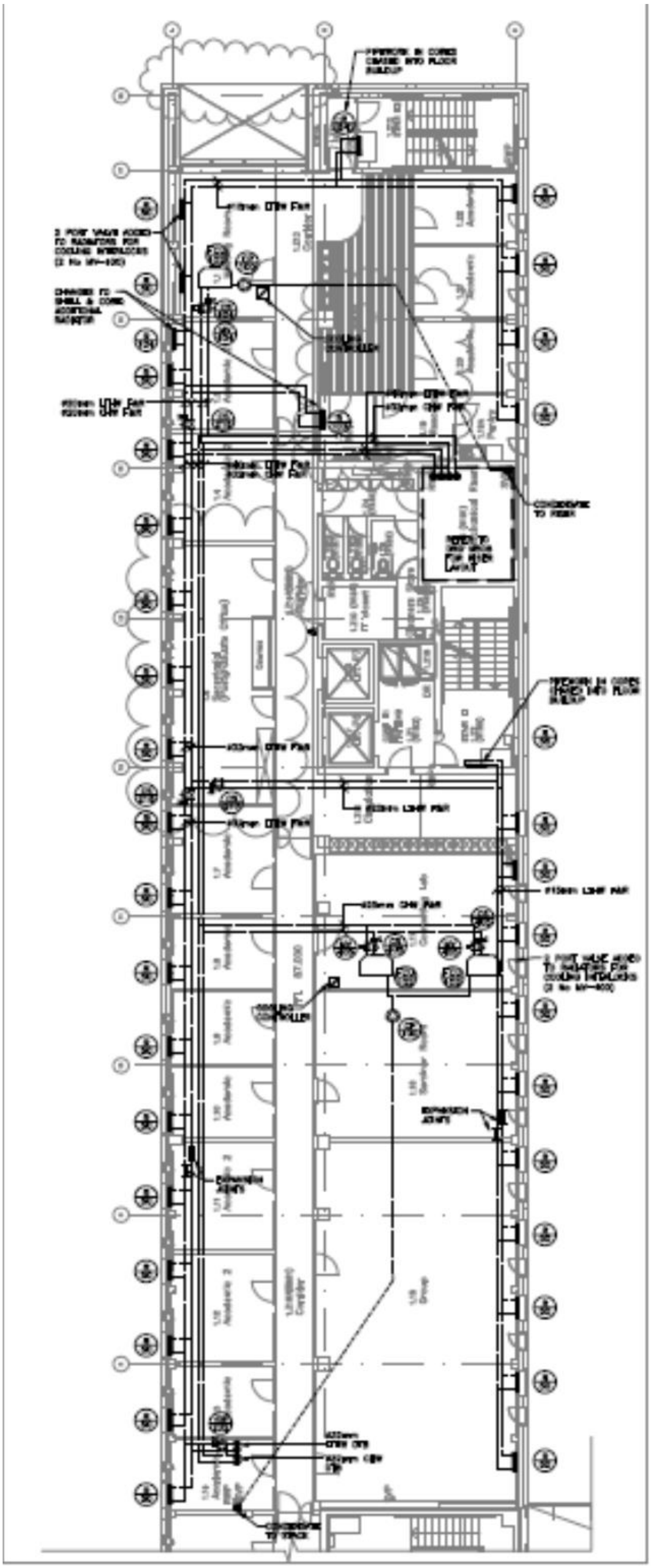
LTHW heating, fifth floor, phase 1



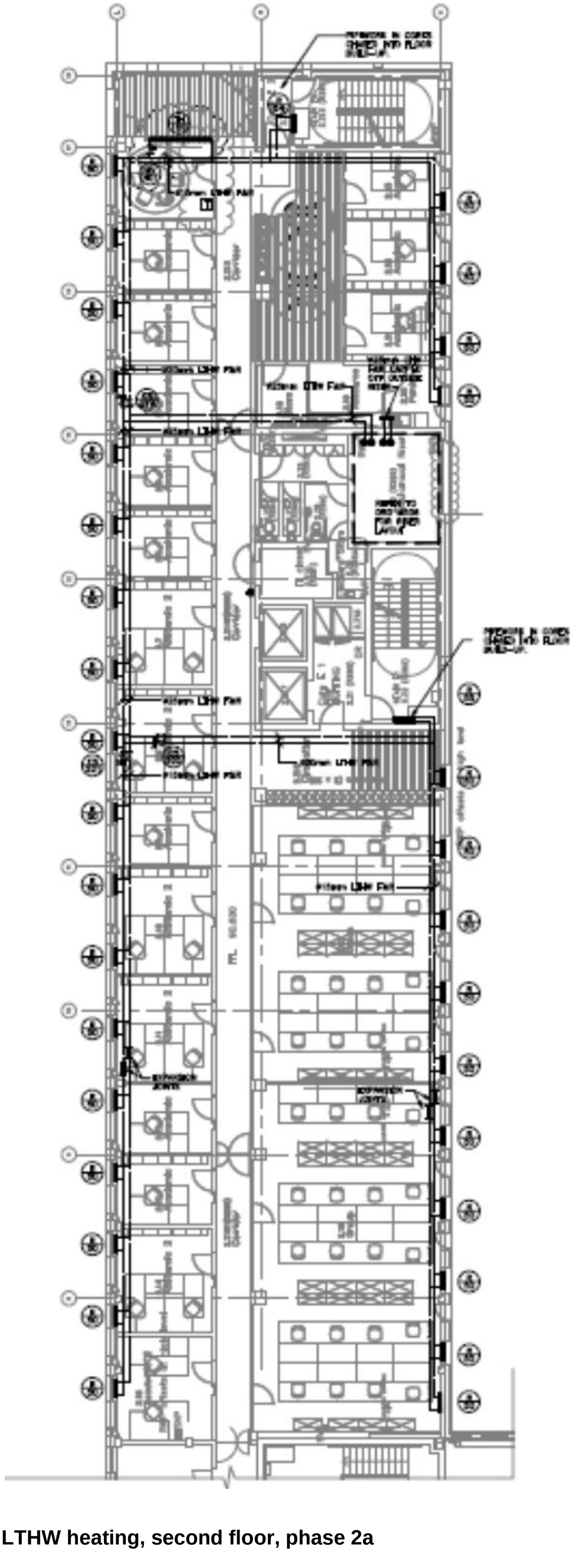
LTHW, basement level, phase 2a



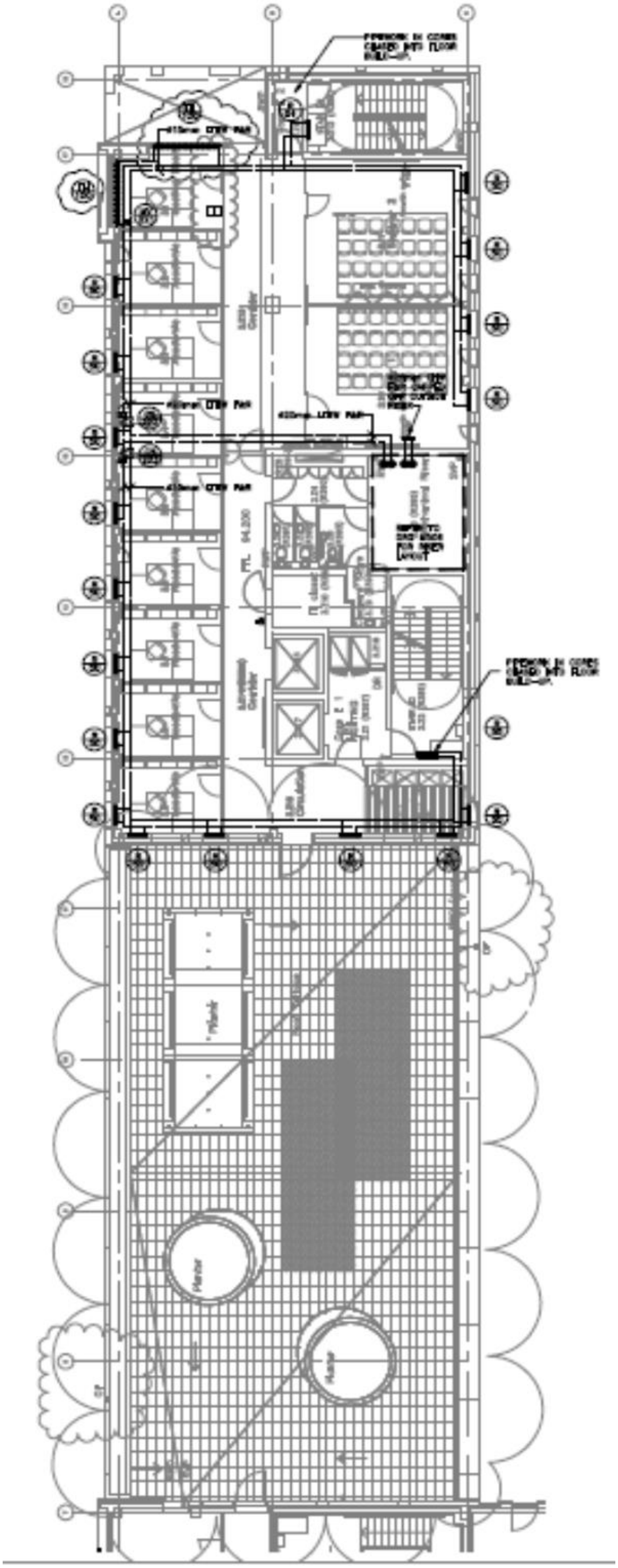
LTHW, ground floor, phase 2a



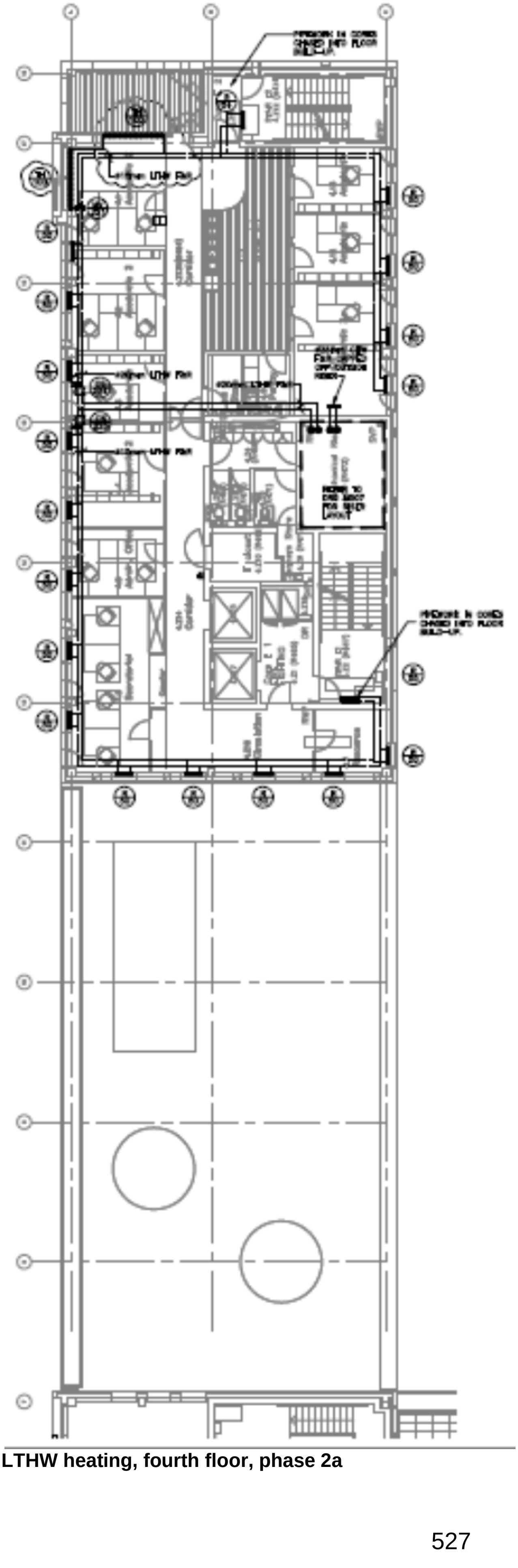
LTHW, first floor, phase 2a



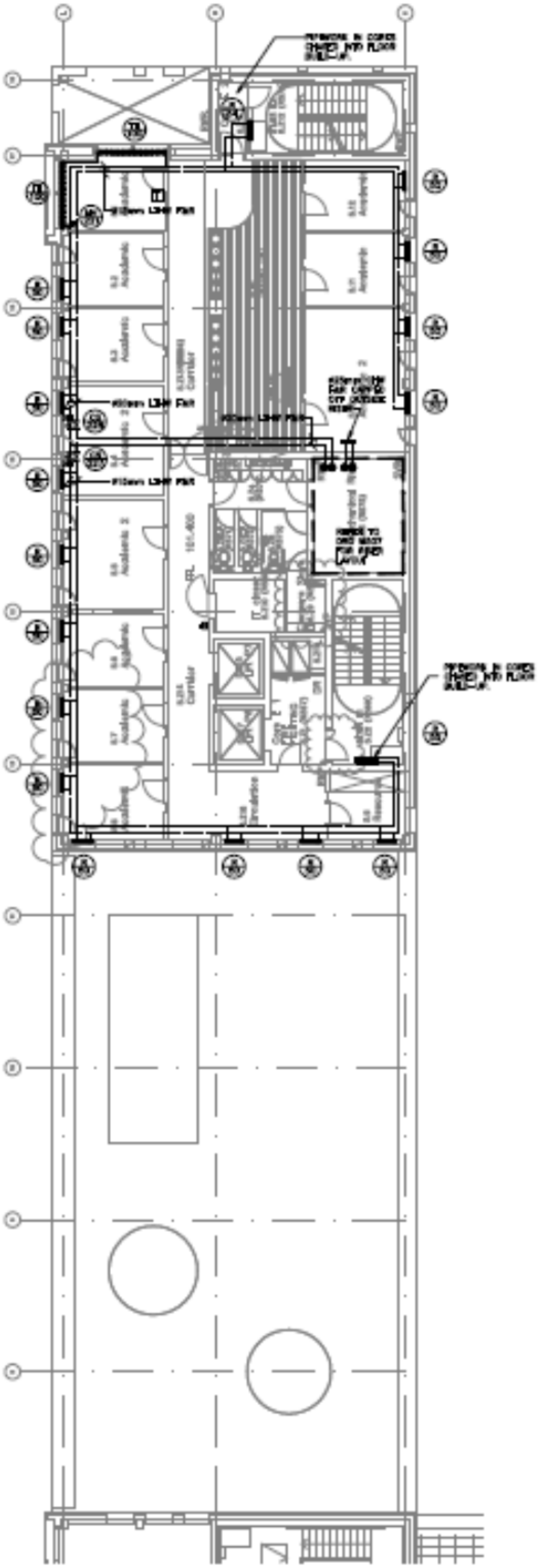
LTHW heating, second floor, phase 2a



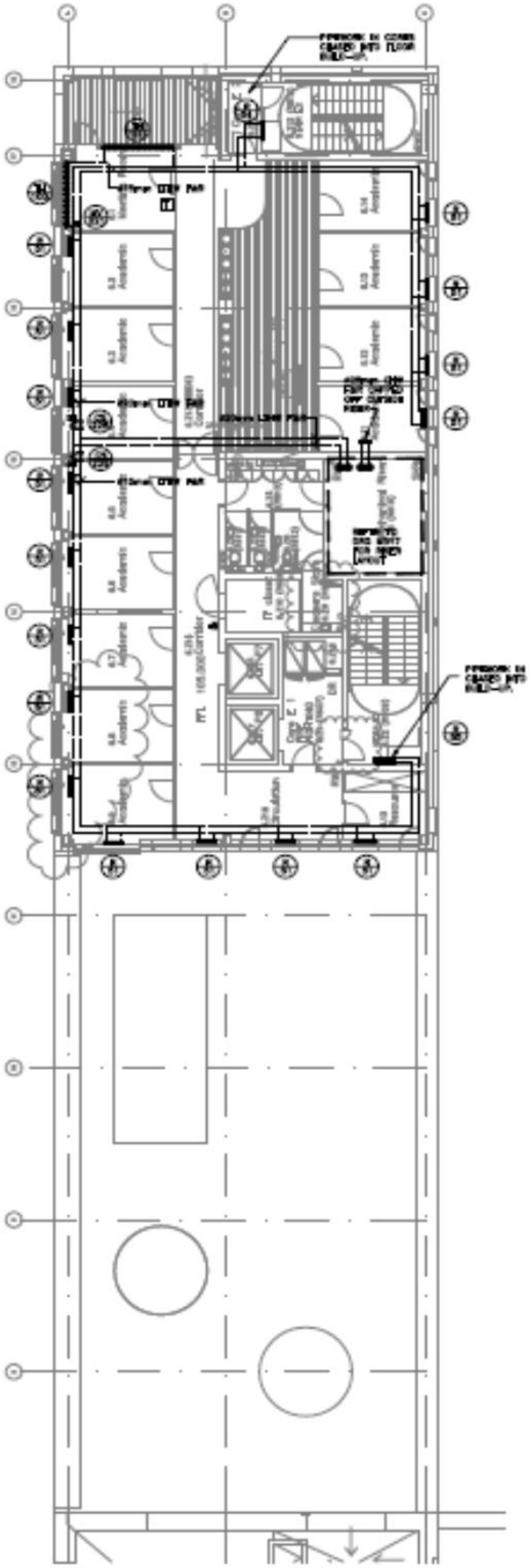
LTHW heating, third floor, phase 2a



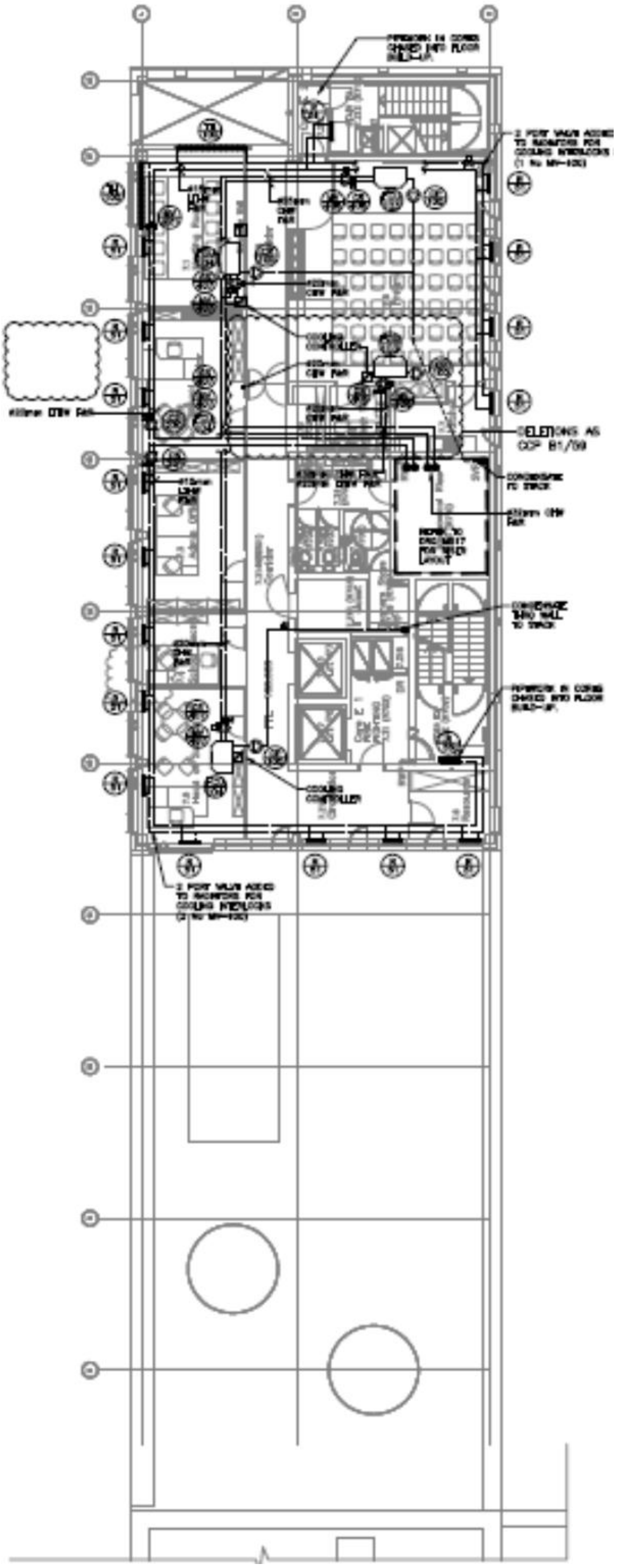
LTHW heating, fourth floor, phase 2a



LTHW heating, fifth floor, phase 2a

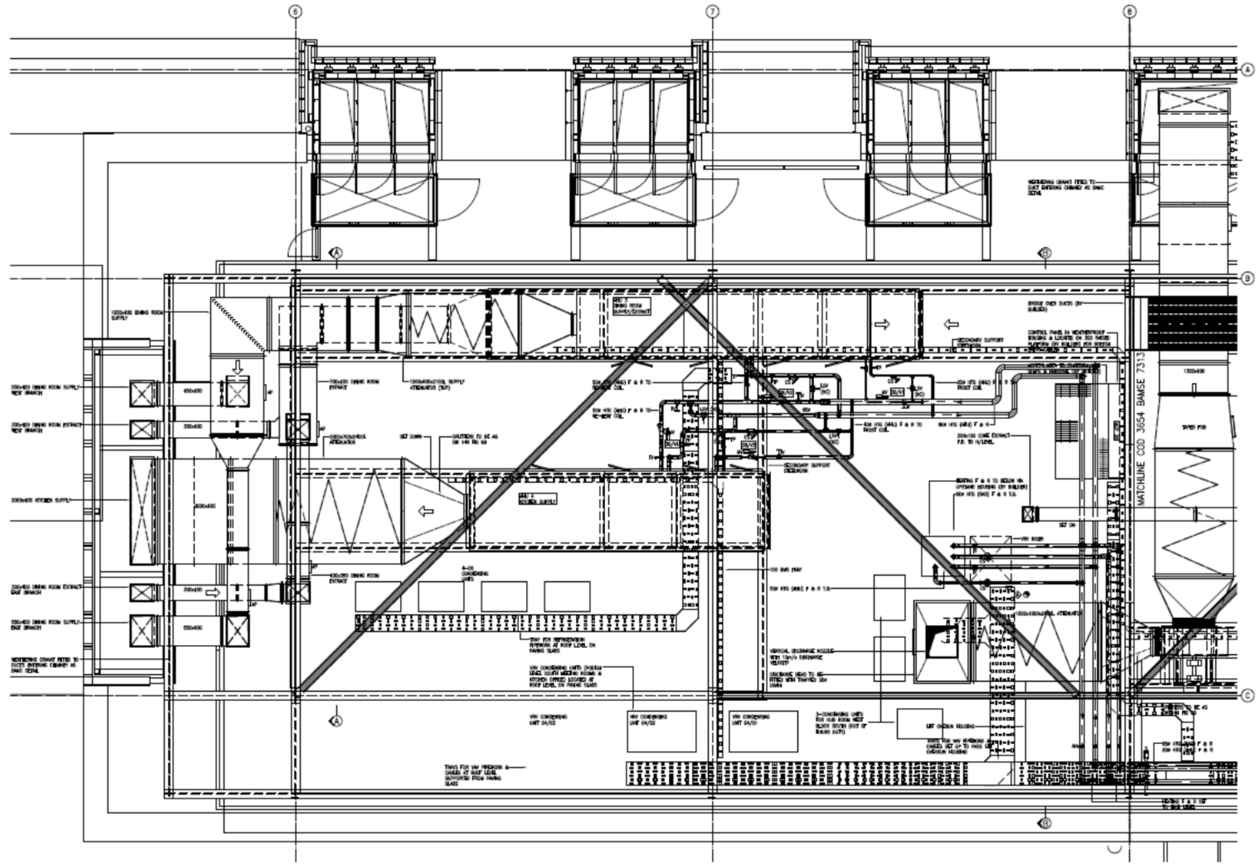


LTHW heating, sixth floor, phase 2a

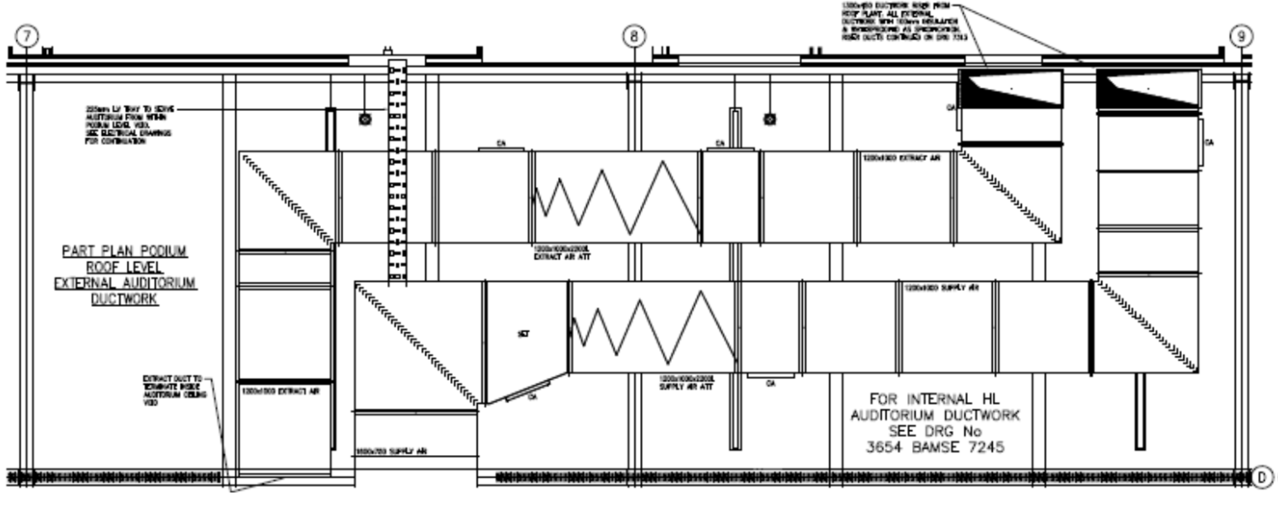


LTHW heating, seventh floor, phase 2a

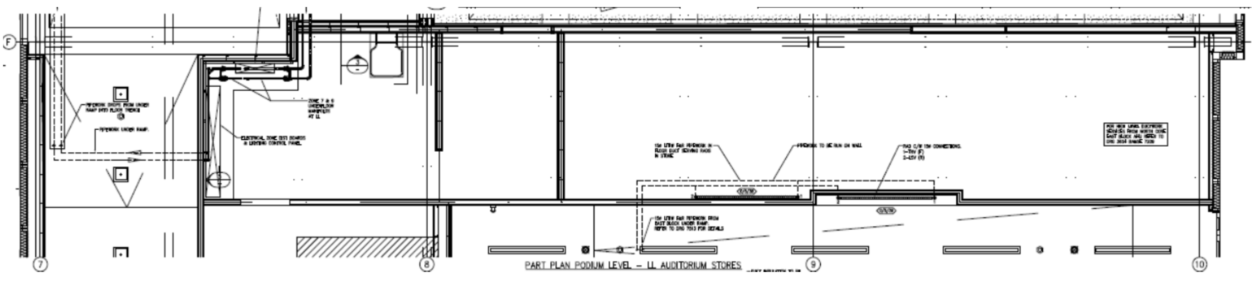
Elizabeth Court II



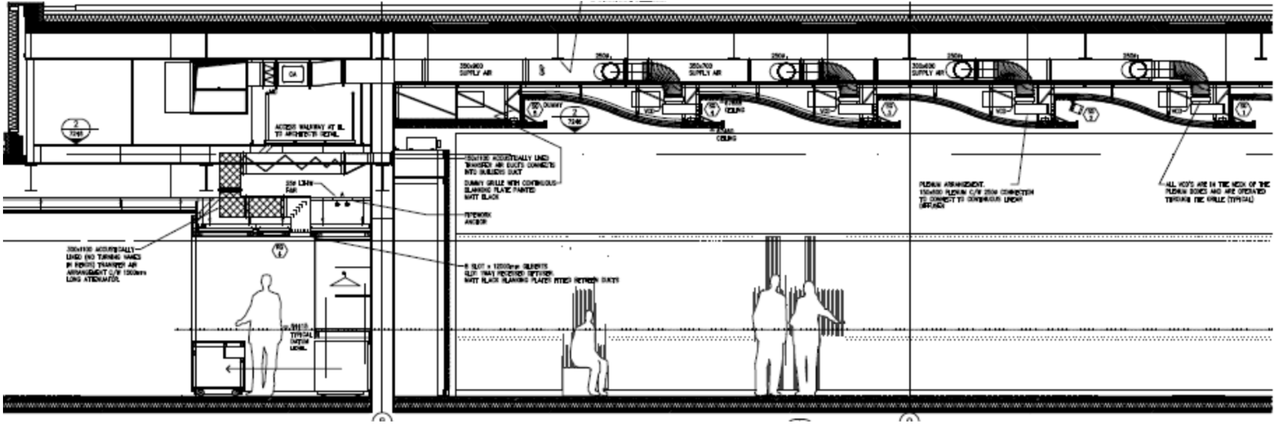
West block level plantroom



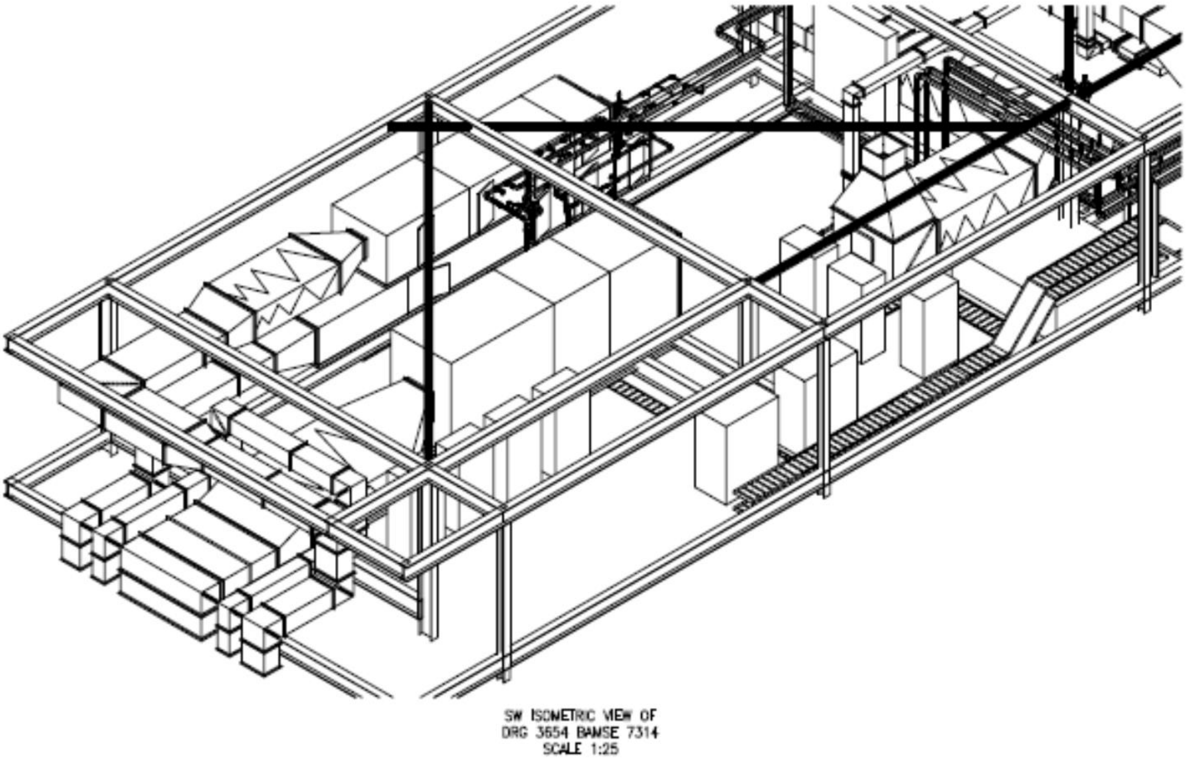
Part plant podium roof leve; External auditorium ductwork



Part plan podium level-auditorium stores



Section from part plan podium level-auditorium stores



Isometric from section

APPENDIX 17 QUALITY ASSURANCE OF THE CHP IN THE POTTERROW SITE, EDINBURGH

Quality Assurance for Combined Heat and Power

Form F2 – CHP Scheme Description

NOTES:

On this Form you need to declare details of the Scheme for which you are applying for CHPQA Certification.

You need to re-submit this form only if there is an addition or change to the Scheme.

Form F1 needs to be kept up-to-date and must relate to the CHP Scheme applying for Certification in this Form.

The most up-to-date version of the CHPQA Standard and Guidance Notes can be found on www.chpqa.com

Guidance Note GN2 has been written to help you complete this Form.

Information provided on this Form will be stored electronically and treated in the strictest commercial confidence. Only the Government or its agents will use it, for the sole purpose of the CHPQA programme including collection and collation of national statistics.

This Form should be completed and returned to, The Administrator, CHPQA programme, B156, Harwell, Didcot, Oxfordshire OX11 0QJ.

1. SCHEME IDENTIFICATION

Site Name	*George Square Energy Centre*	*Site ref.* 5521A*	
Company Name	*University of Edinburgh Utilities Supply Co*	*Scheme ref.*	*[Office use only]*

** The Programme Administrator will provide you with this Site ref. once Form F1 is processed.*

2. ECONOMIC SECTOR

Which sector best describes the site on which your Scheme is located.	Public Administration
e.g. Iron & Steel	See GN12.1 for list

3. SCHEME DESCRIPTION

3.1	Scheme applying for Certification is Existing (tick box)	✓
3.2	CHP fuel billing period (tick box or Other)	Quarterly ✓ Monthly ✓ or Other …………

The following Attachments are required to accompany this form: See GN12.2 to GN12.5

Drawings attached	Drawing No.	Check boxes
3.3 Scheme Line Diagram	GS/SLD/01 [Rev 2]	Enclosed (tick box) ✓
3.4 Scheme Energy Flow Diagram	GS/SEFD/01 [Rev 2]	Enclosed (tick box) ✓
3.5 Annual Heat Profile	GS/AHP/01	Enclosed (tick box) ✓
3.6 Daily Heat Profile	GS/DHP/01	Enclosed (tick box) ✓
3.7 Heat Load Duration Curve	GS/HLDC/01	Enclosed (tick box) ✓

Note:

3.5, 3.6 & 3.7 Are only required for Schemes with a heat rejection facility.

4. *SCHEME DETAILS (LIST OF EQUIPMENT)*

- *Use this table to itemise all prime movers and boilers within your Scheme boundary. See GN12.6.*
- *Identify each prime mover and boiler on your Scheme Line Diagram and in the table below by tag number using the notation in the Guidance Notes. See GN12.3.*
- *Include electrical equivalent of any mechanical power outputs (mechanical power x 1.05) and mark with an asterisk. See GN15.4 to 15.6 & 22.*

Tag Number	*Manufacturer*	*Model/Type*	*Year commissioned*	*Capacity (referenced to ISO conditions)*	
				Heat kW	*Power kWe*
RE(G)1	*GE Jenbacher CHP Unit*	*Jenbacher 612*	*2005*	*1,730 kW*	*1,644 kWe*
FB(HS)1	*BIB Cochran Dual Fuel Boiler*	*Thermax IV*	*2004*	*6,000 kW*	
FB(HS)2	*BIB Cochran Dual Fuel Boiler*	*Thermax IV*	*2004*	*6,000 kW*	
FB(HS)3	*BIB Cochran Dual Fuel Boiler*	*Thermax IV*	*2004*	*3,000 kW*	
Total Power Capacity (as electrical output) = CHPTPC					*1644*

5. SCHEME DETAILS (MONITORING ARRANGEMENTS) *See GN13 & 16*

- *Use this table to list all existing and proposed metering stations (including. the meters by which you are billed) for your Scheme inputs and outputs. See GN12.7 to 12.13*
- *Identify each meter by tag number using the notation in the Guidance Notes. (Each meter should be identified on your Scheme line and energy flow diagrams).See GN12.3*
- *Provide details of all export metering (heat and electricity). See GN15.10 & 16.5*
- *Attach details of any indirect methods used to derive unmetered inputs or outputs (include below the monitoring upon which these rely). See GN20 to GN22*
- *Identify the meter uncertainty % (=100 – accuracy of reading %), attach supporting calculations. See GN23*

Tag Number	*Serial Number*	*Year Installed*	*Model/Type*	*Metered Service*	*Outputs*		*Uncertainty*
					Range	*Units*	
M1(FQ)	*77948*	*2004*	*IMAC Systems Ltd. Type EA650*	*Gas Boiler No 1*	*65-1000*	*cu.m/hr*	*0.1% to 0.27%*
M2(FQ)	*77947*	*2004*	*IMAC Systems Ltd. Type EA650*	*Gas Boiler No 2*	*65-1000*	*cu.m/hr*	*0.1% to 0.27%*
M3(FQ)	*77777*	*2004*	*IMAC Systems Ltd. Type EA250*	*Gas Boiler No 3*	*25-400*	*cu.m/hr*	*0.1% to 0.27%*
M4(HQ)	*4674491*	*2004*	*Kamstrup Multical 150/400*	*Heat Meter Boiler No 1*	*4-800*	*kWh*	*±1+0.01%*
M5(HQ)	*4660291*	*2004*	*Kamstrup Multical 150/400*	*Heat Meter Boiler No 2*	*4-800*	*kWh*	*±1+0.01%*
M6(HQ)	*4660424*	*2004*	*Kamstrup Multical 150/150*	*Heat Meter Boiler No 3*	*1.5-300*	*kWh*	*±1+0.01%*
M7(FQ)	*77776*	*2004*	*IMAC Systems Ltd. Type EA250*	*CHP Gas Flow Meter*	*25-400*	*cu.m/hr*	*0.1% to 0.27%*
M8(HQ)	*4779250*	*2005*	*Sontex 100/100*	*Heat Meter Abs Chiller*	*2-200*	*kWh*	*±1+0.01%*
M9(HQ)	*4660109*	*2004*	*Kamstrup Multical 250/1000*	*Site Heat Meter*	*10-1800*	*kWh*	*±1+0.01%*
M10(EQ)	*N/A*	*2004*	*Jenbacher Diane Unit*	*CHP Electricity Meter*	*N/A*	*MWh*	*±1.5%*
M11 (EQ)	*N503P43761*	*2005*	*ELSTER A1700*	*Electricity*	*N/A*	*kWh*	*1.5%*
M12(FQ)	*3525*	*1980*	*British Gas*	*Main Gas Meter*	*100-10,000*	*ACFH*	*2%*

Tag Number	Serial Number	Year Installed	Model/Type	Metered Service	Outputs		Uncertainty
					Range	Units	
M13(FQ)	P33124/2006	2007	Common Quantometer CPT-01	Process Gas Sub-meter	20 - 400	Cu.m/hr	2%
M14(HQ)	4460233	2004	Kamstrup Multical 100/100	CHP Heat Meter	1-200	kWh	±1+0.01%

Q1. Have you attached additional sheets? (tick box) No X3 If YES, enter number of attached sheets ___________.

6. SCHEME CAPACITY

- *Enter details of your Scheme's capacities (referenced to ISO conditions)* *See GN12.14*

6.1 CHP Total Power Capacity - CHPTPC	*(from Section 4)*	*1,644 kWe*
6.2 CHP MaxHeat	*(from Section 3.7)*	*1,730 kW*
6.3 CHP Total Power Capacity under MaxHeat conditions	*(using Scheme H:P)*	*1,644 kWe*

7. ADDITIONAL EQUIPMENT

- *Use this table to list additional equipment (e.g. plant often described as parasitic plant) essential to the operation of the Scheme but not described elsewhere* *See GN12.15 for list*

Item	*Manufacturer (if known)*	*Model (if known)*	*Number installed*	*Normally running*	*Used at start-up*	*Used rarely*	*Estimated Energy Consumption*	
				(Tick just one box)			*kWe*	*kWth*
1				*3*	*3*	*3*		
2				*3*	*3*	*3*		
3				*3*	*3*	*3*		
4				*3*	*3*	*3*		
5				*3*	*3*	*3*		

Item	*Manufacturer* *(if known)*	*Model* *(if known)*	*Number* *installed*	*Normally running*	*Used at start-up*	*Used rarely*	*Estimated Energy Consumption*	
6				*3*	*3*	*3*		
7				*3*	*3*	*3*		
8				*3*	*3*	*3*		
9				*3*	*3*	*3*		
10				*3*	*3*	*3*		
Total (kWe and kWth) normally running								

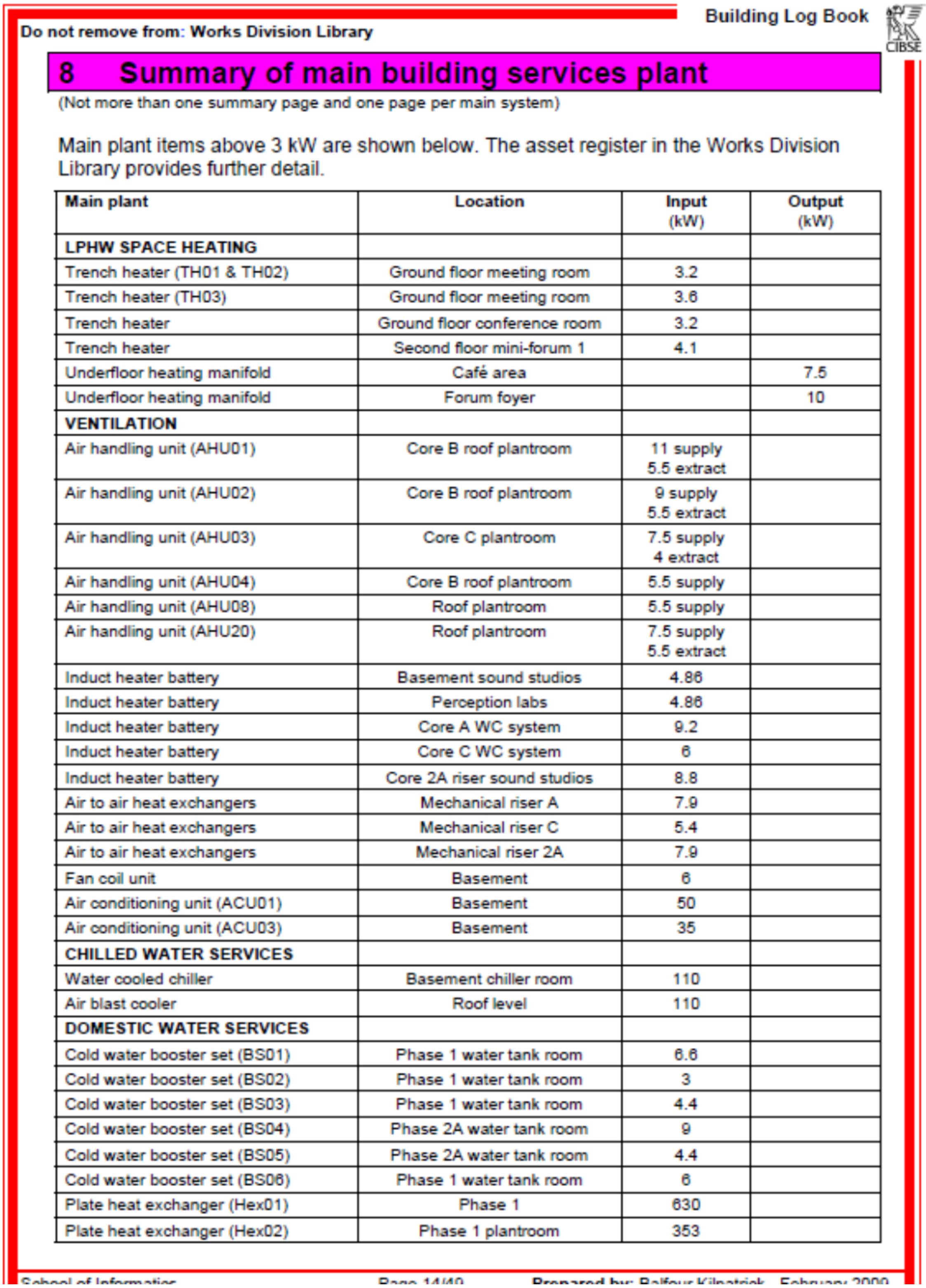
APPENDIX 18 COST OF THE CHP INVESTMENT IN THE POTTERROW SITE, EDINBURGH

Potterrow Development

CHP vs Conventional System for Phase 1 only

Building Services Costs	**Cost**	
Conventional system	£	140.000
CHP system	£	40.000
Cost Saving	**£**	**100.000**
Basement Construction Costs		
Conventional system	£	182.000
CHP system	£	98.000
Cost Saving	**£**	**84.000**
TOTAL CONSTRUCTION COST SAVING	**£**	**184.000**
Add for Preliminaries at 15%	£	27.600
Add for Contingency at 7.5%	£	15.870
Add for inflation @ 6%	£	13.648
ANTICIPATED COST SAVING INCLUDING ON-COSTS	**£**	**241.118**

APPENDIX 19 BUILDING LOG BOOK NOTES FOR THE HEATING SYSTEM, POTTERROW BUILDING



8 Summary of main building services plant

(Not more than one summary page and one page per main system)

Main plant items above 3 kW are shown below. The asset register in the Works Division Library provides further detail.

Main plant	Location	Input (kW)	Output (kW)
LPHW SPACE HEATING			
Trench heater (TH01 & TH02)	Ground floor meeting room	3.2	
Trench heater (TH03)	Ground floor meeting room	3.6	
Trench heater	Ground floor conference room	3.2	
Trench heater	Second floor mini-forum 1	4.1	
Underfloor heating manifold	Café area		7.5
Underfloor heating manifold	Forum foyer		10
VENTILATION			
Air handling unit (AHU01)	Core B roof plantroom	11 supply 5.5 extract	
Air handling unit (AHU02)	Core B roof plantroom	9 supply 5.5 extract	
Air handling unit (AHU03)	Core C plantroom	7.5 supply 4 extract	
Air handling unit (AHU04)	Core B roof plantroom	5.5 supply	
Air handling unit (AHU08)	Roof plantroom	5.5 supply	
Air handling unit (AHU20)	Roof plantroom	7.5 supply 5.5 extract	
Induct heater battery	Basement sound studios	4.86	
Induct heater battery	Perception labs	4.86	
Induct heater battery	Core A WC system	9.2	
Induct heater battery	Core C WC system	6	
Induct heater battery	Core 2A riser sound studios	8.8	
Air to air heat exchangers	Mechanical riser A	7.9	
Air to air heat exchangers	Mechanical riser C	5.4	
Air to air heat exchangers	Mechanical riser 2A	7.9	
Fan coil unit	Basement	6	
Air conditioning unit (ACU01)	Basement	50	
Air conditioning unit (ACU03)	Basement	35	
CHILLED WATER SERVICES			
Water cooled chiller	Basement chiller room	110	
Air blast cooler	Roof level	110	
DOMESTIC WATER SERVICES			
Cold water booster set (BS01)	Phase 1 water tank room	6.6	
Cold water booster set (BS02)	Phase 1 water tank room	3	
Cold water booster set (BS03)	Phase 1 water tank room	4.4	
Cold water booster set (BS04)	Phase 2A water tank room	9	
Cold water booster set (BS05)	Phase 2A water tank room	4.4	
Cold water booster set (BS06)	Phase 1 water tank room	6	
Plate heat exchanger (Hex01)	Phase 1	630	
Plate heat exchanger (Hex02)	Phase 1 plantroom	353	

System Name - **Gas Suppression**

A gas suppression system has been provided to protect property in both of the server rooms (Phase 1 and Phase 2A basements). This shall provide protection to both the rooms and the associated floor voids.

The gas suppression panel has been interlinked to the fire alarm system. Motorised dampers on all ductwork entering the server rooms close prior to an Inergen emission. Once the discharge has taken place, a local controller can be manually operated to allow a dedicated fan to provide fume clearance of any discharged contaminants. After this is accomplished, the other dampers can be re-opened from the controller to allow normal ventilation to continue.

System Name - **Heating**

The provision of heat to the building has been provided from the University's central Combined Heat and Power network. This network provides LTHW to the Potterrow site.

The University network supplies water at up to 90°C but a more typical winter supply temperature is 80°C. The network is variable flow to respond to heat demands from the different buildings on campus.

Incoming LTHW pipework has been insulated in phenolic foam and routed in the basement corridor to the Phase 1 Heat Exchanger Room. Here it forms a main header from which the following supplies have been taken off:

- Phase 1 Variable Temperature Circuit
- Phase 1 Constant Temperature Circuit
- Phase 1 DHWS Plate Heat Exchanger
- Phase 2A and 2B Variable Temperature Circuit (Blanked connections on 2B only)
- Phase 2A and 2B Constant Temperature Circuit (Blanked connections on 2B only)
- Phase 2A DHWS Plate Heat Exchanger & Phase 2B Exchanger (Blanked connections on 2B only)

The Phase 2A circuits have initially only provide heat to Phase 2A, but have been sized to allow for future Phase 2B loads.

System pressurisation suitable for the full height of the building, expansion and chemical dosing has been provided from the central CHP network. A 150mm diameter microbubble deaeration and dirt separation unit, of suitable size and capacity, has been provided within the plant room and interconnected to the main distribution system.

Design Parameters

External Conditions	–5°C 100% RH
LTHW flow temperature from CHP	80°C
LTHW return temperature	60°C
Static Head Available from CHP	80 kPa

The incoming LTHW has been enabled by the activation of the 2-port valve on the incomer. This valve operates in tandem with the 2 port on the return. This enables whenever the BMS registers a demand for heat from one of the circuits described above. This can also be overridden by the BEMS user, in the event of a catastrophic leak. The heating system starts and stops according to building occupancy by an optimiser with 7 day program allowing different occupancy times to be set for each day of the week if required. The system is also temperature controlled and responds to internal and external temperature conditions to maintain comfortable conditions within the building and to conserve energy.

LTHW circuits are metered and submetered with main incoming heat meters capable of giving pulsed output.

Variable Temperature LTHW Systems

Weather-compensated Low Temperature Hot Water has been distributed throughout the building serving radiators, trench heaters and over-door heaters. Variable speed circulating pumps provide this secondary distribution. The pumps have been provided with a pressure gauge at the inlet and outlet and DP switch. In the event of pump failure, the nature of the central CHP network is such that the available system head from the network ensures a reduced flow is available to the building until the pump can be replaced.

The heating pumps modulate their flowrate to maintain a constant system pressure as valves close in areas of the system when heating is not required, whilst still maintaining their minimum flowrate. This allows electrical energy savings to be made in times of low heating demand. A DP sensor located at a representative location on the index run of each circuit enables this. Each main LTHW branch includes a differential pressure valve in the riser to ensure that LTHW flowrate can be modulated without pressure fluctuations adversely affecting upstream plant.

Constant Temperature LTHW Systems

Constant temperature LTHW circuits have been provided to serve the Air-Handling Units' heater batteries. The underfloor heating circuits are also be fed from these CT circuits. Each circuit operates on the residual head from the CHP system of 80kPa.

Each coil is controlled by a 2 port valve ensuring that the system operates in a variable flow mode, in sympathy with the central CHP system. Each main LTHW branch includes a differential pressure valve in the riser to ensure that LTHW flowrate can be modulated without pressure fluctuations adversely affecting upstream plant.

Design Parameters

Internal Heating Design Conditions

Room Description	**Temp. °C (+/-2)**	**Humidity %RH (+/-%)**
Offices / General	21	No control
Meeting Rooms	21	No control
Forum Space	21	No control
Reception	21	No control
Atrium Roof Space	16	No control
WCs	19	No control
Stair wells	19	No control
Stores	16	No control
Plantrooms	Min 5	No control

Emitters

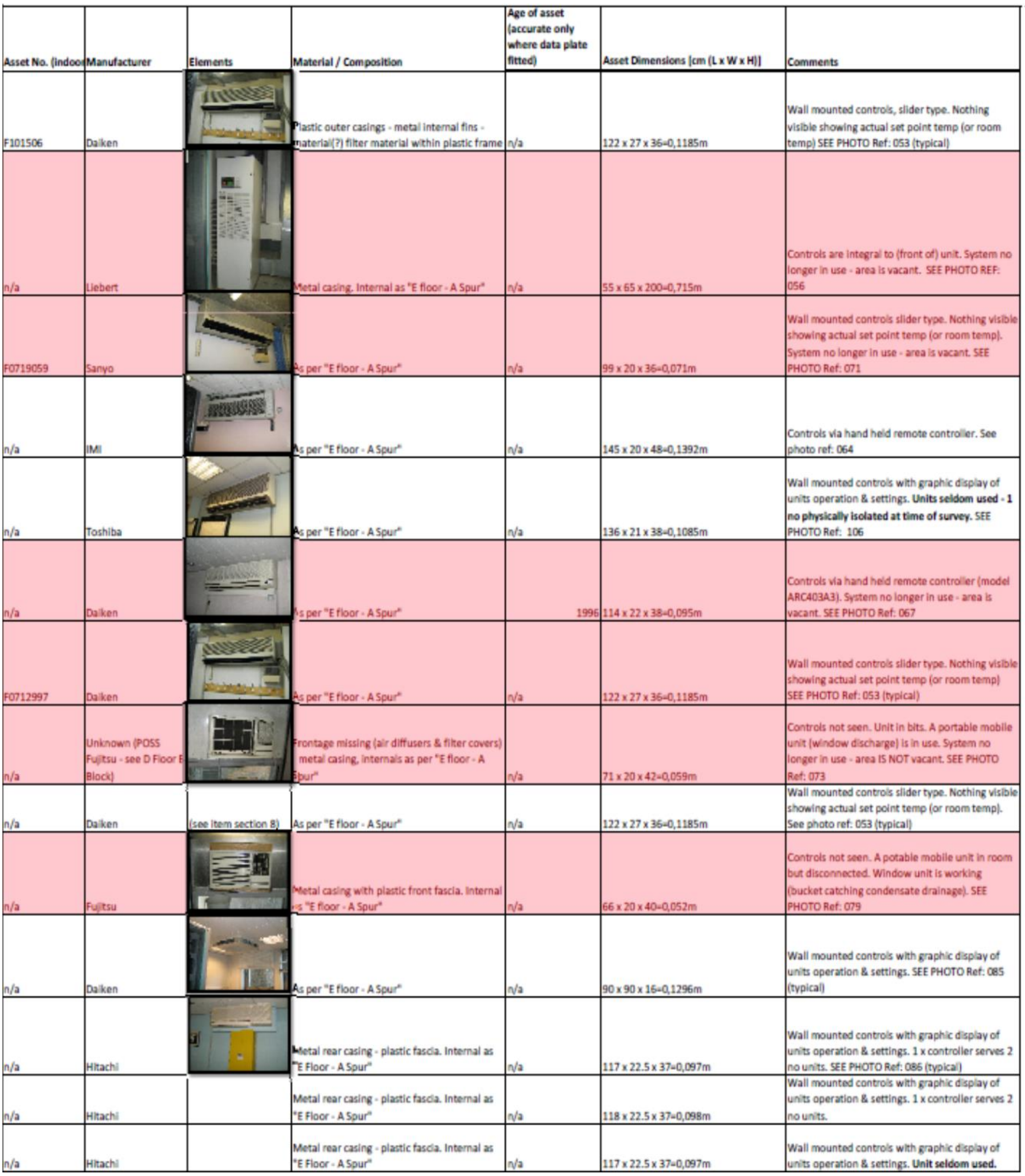
Generally, heat emitters are low profile radiators with integral valving (TRV in the horizontal). Pipework from the floor void servicing each radiator has been completely concealed in the radiator legs.

Radiators are located in relation to the structural grid to maximise the flexibility of the space.

Underfloor heating has been provided to certain ground floor areas. The system shall be fed from the CT LTHW circuit into each of the underfloor heating manifolds. The manifold contains a blending valve to mix the water down to the manufacturer's design temperature, a local pump and a flow meter for each loop. A shut-off valve prevents any flow in excess of 50°C should the control valve fail to prevent cracking of the slab.

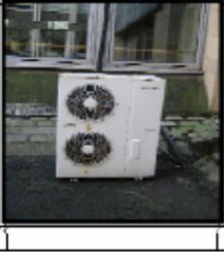
Perimeter trench heating has been provided in certain locations. Trench heating has been generally be controlled by a 2-port valve controlled by local room stat.

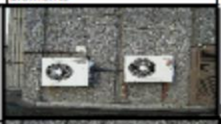
APPENDIX 20 RECORDING AND MEASUREMENT SURVEY OF THE COOLING EQUIPMENT IN ARGYLE HOUSE

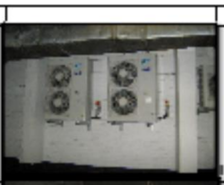


Asset No. (indoor	Manufacturer	Elements	Material / Composition	Age of asset (accurate only where data plate fitted)	Asset Dimensions [cm (L x W x H)]	Comments
F101506	Daiken		Plastic outer casings - metal internal fins - material(?) filter material within plastic frame	n/a	122 x 27 x 36=0,1185m	Wall mounted controls, slider type. Nothing visible showing actual set point temp (or room temp) SEE PHOTO Ref: 053 (typical)
n/a	Liebert		Metal casing. Internal as "E floor - A Spur"	n/a	55 x 65 x 200=0,715m	Controls are integral to (front of) unit. System no longer in use - area is vacant. SEE PHOTO REF: 056
F0719059	Sanyo		As per "E floor - A Spur"	n/a	99 x 20 x 36=0,071m	Wall mounted controls slider type. Nothing visible showing actual set point temp (or room temp). System no longer in use - area is vacant. SEE PHOTO Ref: 071
n/a	IMI		As per "E floor - A Spur"	n/a	145 x 20 x 48=0,1392m	Controls via hand held remote controller. See photo ref: 064
n/a	Toshiba		As per "E floor - A Spur"	n/a	136 x 21 x 38=0,1085m	Wall mounted controls with graphic display of units operation & settings. **Units seldom used - 1 no physically isolated at time of survey.** SEE PHOTO Ref: 106
n/a	Daiken		As per "E floor - A Spur"	1996	114 x 22 x 38=0,095m	Controls via hand held remote controller (model ARC403A3). System no longer in use - area is vacant. SEE PHOTO Ref: 067
F0712997	Daiken		As per "E floor - A Spur"	n/a	122 x 27 x 36=0,1185m	Wall mounted controls slider type. Nothing visible showing actual set point temp (or room temp) SEE PHOTO Ref: 053 (typical)
n/a	Unknown (POSS Fujitsu - see D Floor B Block)		Frontage missing (air diffusers & filter covers) metal casing, internals as per "E floor - A Spur"	n/a	71 x 20 x 42=0,059m	Controls not seen. Unit in bits. A portable mobile unit (window discharge) is in use. System no longer in use - area IS NOT vacant. SEE PHOTO Ref: 073
n/a	Daiken	(see item section 8)	As per "E floor - A Spur"	n/a	122 x 27 x 36=0,1185m	Wall mounted controls slider type. Nothing visible showing actual set point temp (or room temp). See photo ref: 053 (typical)
n/a	Fujitsu		Metal casing with plastic front fascia. Internal as "E floor - A Spur"	n/a	66 x 20 x 40=0,052m	Controls not seen. A potable mobile unit in room but disconnected. Window unit is working (bucket catching condensate drainage). SEE PHOTO Ref: 079
n/a	Daiken		As per "E floor - A Spur"	n/a	90 x 90 x 16=0,1296m	Wall mounted controls with graphic display of units operation & settings. SEE PHOTO Ref: 085 (typical)
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	117 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings. 1 x controller serves 2 no units. SEE PHOTO Ref: 086 (typical)
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	118 x 22.5 x 37=0,098m	Wall mounted controls with graphic display of units operation & settings. 1 x controller serves 2 no units.
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	117 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings. **Unit seldom used.**

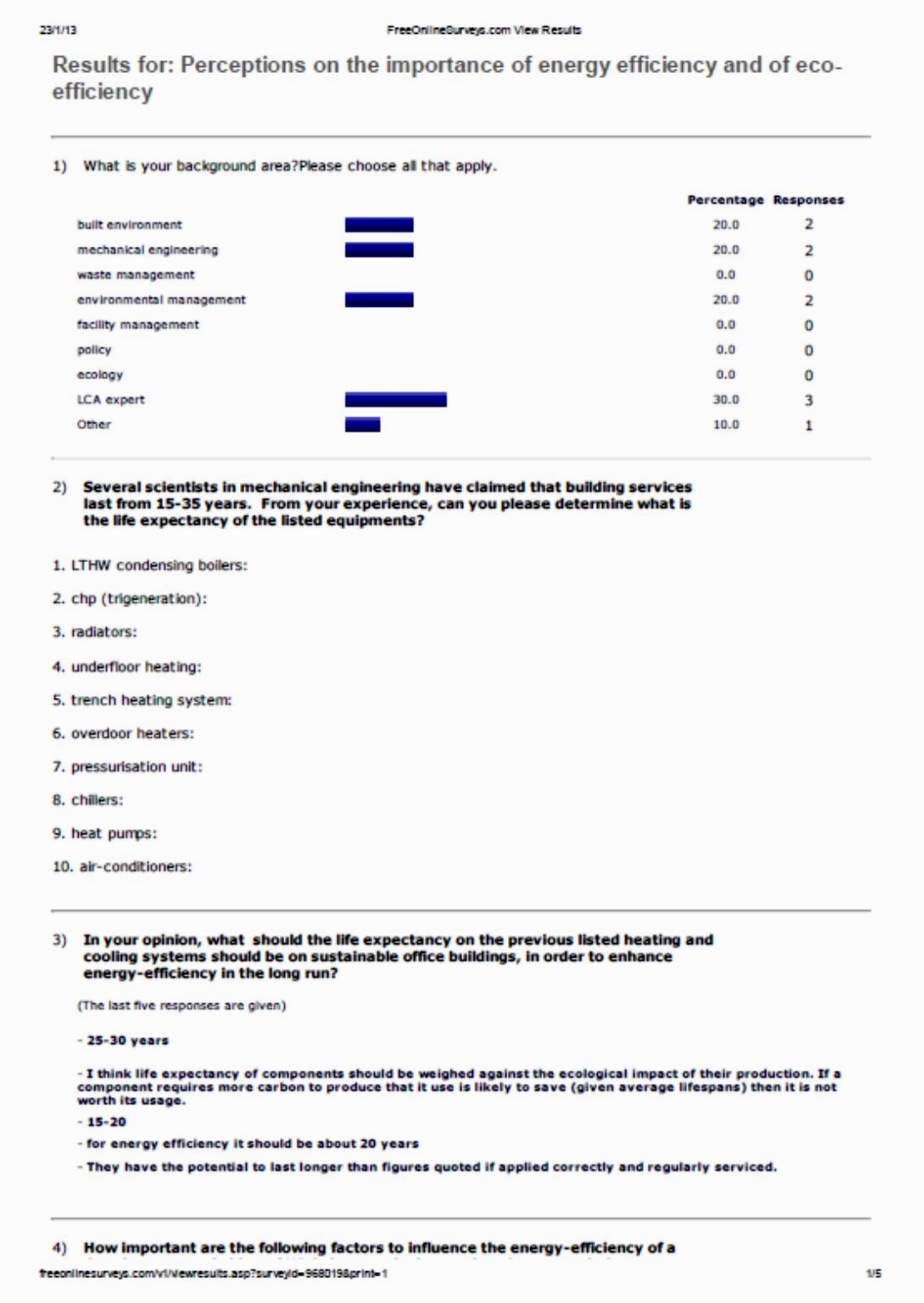
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	118 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings.
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	119 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings. **Unit & office seldom used.**
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	120 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings.
n/a	Daiken		As per "E floor - A Spur"	n/a	90 x 90 x 16=0,1296m	Wall mounted controls with graphic display of units operation & settings. SEE PHOTO Ref: 085 (typical)
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	117 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings. **Unit NOT used.**
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	118 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings.
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	119 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units operation & settings. **Unit NOT used.**
n/a	Hitachi		Metal rear casing - plastic fascia. Internal as "E Floor - A Spur"	n/a	120 x 22.5 x 37=0,097m	Wall mounted controls with graphic display of units & operation. **4 x units, no longer in use - area is vacant**.
n/a	Daiken		Unknown - no access to establish outer casing. Inners expected to be	n/a	no access to measure	controls not seen. 2 x units, no longer in use - area is vacant. See photo ref: 109
n/a	Daiken		As per "E floor - A Spur"	n/a	79 x 20 x 37=0,0584m	Wall mounted controls with graphic display of units operation & settings. **Unit NOT used**. SEE PHOTO Ref: 111
n/a	Daiken		As per "E floor - A Spur"	1997	130 X 60 X 19=0,1482m	Wall mounted controls with graphic display of units operation & settings. See photo ref: 101

Manufacturer	Model No.	Elements	Cooling Type	No. of installed assets	Age of asset	Asset Dimensions [cm (L x W x H)]
Toshiba	RAV-200AH		heat pump	2	n/a	87 X 30 X 73=0,1905m
Daiken	RR100B7V3B			1	2005	90 X 30 X 114=0,3078m
Daiken	R71FJ7W1		heat recovery/cond	2	1997	81 x 32 x 84=0,2177m
Toshiba	unknown	(same element as section 4)	heat recovery/cond	1	n/a	114 x 55 x 135=0,8464m
Daiken	RP71B7V1		heat pump	1	n/a	88 x 32 x 84=0,2365m
Hitachi	16BT6		refrigeration	2	n/a	140 x 77 x 155=1,6709m
Mitsubishi	Mr Slim - PU-P71YGAA			1	2005	90 x 33 x 82=0,2435m
Mitsubishi	Mr Slim - PU-P71YGAA			1	2005	91 x 33 x 82=0,2435m
Daiken	R60D7W1		heat pumps	1	1996	88 x 35 x 63=0,1940m
Hitachi	unknown	(same item as section 10)		1	n/a	89 x 29 x 86=0,2219m
Sanyo	SAP-C182G5		heat pumps	2	n/a	83 x 30 x 62=0,1543m
IMI	Impact 80L	(same item as section 12)		1	n/a	100 x 29 x 65=0,1885m
Daiken	Skyair - R71BBV1		heat pumps	3	n/a	81 x 29 x 88 =0,2067m
Suzushi - High Cool	92CA406C		heat pumps	1	n/a	85 x 29 x 112=0,2760m
Liebert	LSC07E			1	n/a	

Manufacturer	Model No.	Elements	Cooling Type	No. of installed assets	Age of asset	Asset Dimensions [cm (L x W x H)]
Toshiba	RAV-200AH		heat pump	2	n/a	87 X 30 X 73=0,1905m
Daiken	RR100B7V3B			1	2005	90 X 30 X 114=0,3078m
Daiken	R71FJ7W1		heat recovery/cond	2	1997	81 x 32 x 84=0,2177m
Toshiba	unknown	(same element as section 4)	heat recovery/cond	1	n/a	114 x 55 x 135=0,8464m
Daiken	RP71B7V1		heat pump	1	n/a	88 x 32 x 84=0,2365m
Hitachi	16BT6		refrigeration	2	n/a	140 x 77 x 155=1,6709m
Mitsubishi	Mr Slim - PU-P71YGAA			1	2005	90 x 33 x 82=0,2435m
Mitsubishi	Mr Slim - PU-P71YGAA			1	2005	91 x 33 x 82=0,2435m
Daiken	R60D7W1		heat pumps	1	1996	88 x 35 x 63=0,1940m
Hitachi	unknown	(same item as section 10)		1	n/a	89 x 29 x 86=0,2219m
Sanyo	SAP-C182G5		heat pumps	2	n/a	83 x 30 x 62=0,1543m
IMI	Impact 80L	(same item as section 12)		1	n/a	100 x 29 x 65=0,1885m
Daiken	Skyair - R71BBV1		heat pumps	3	n/a	81 x 29 x 88 =0,2067m
Suzushi - High Cool	92CA406C		heat pumps	1	n/a	85 x 29 x 112=0,2760m

Fujitsu	AFY18ACD-W			1	n/a	
Daiken	RZQ100D7VIB		heat pumps	2	n/a	88 x 32 x 132=0,3717
Daiken	RP71B7W1		heat pumps	1	2002	no access to measure
IMI	unclear. Nos taken from data plate: 55099039 - serial no. 0543486		heat pumps	2	n/a	no access to measure
Daiken	unknown			1	n/a	no access to measure
Daiken	unknown			1	n/a	no access to measure

APPENDIX 21 ONLINE QUESTIONNAIRE SURVEY RESULTS (FROM COMBINED STAKEHOLDER GROUPS)



23/1/13 FreeOnlineSurveys.com View Results

Results for: Perceptions on the importance of energy efficiency and of eco-efficiency

1) What is your background area?Please choose all that apply.

	Percentage	Responses
built environment	20.0	2
mechanical engineering	20.0	2
waste management	0.0	0
environmental management	20.0	2
facility management	0.0	0
policy	0.0	0
ecology	0.0	0
LCA expert	30.0	3
Other	10.0	1

2) **Several scientists in mechanical engineering have claimed that building services last from 15-35 years. From your experience, can you please determine what is the life expectancy of the listed equipments?**

1. LTHW condensing boilers:
2. chp (trigeneration):
3. radiators:
4. underfloor heating:
5. trench heating system:
6. overdoor heaters:
7. pressurisation unit:
8. chillers:
9. heat pumps:
10. air-conditioners:

3) **In your opinion, what should the life expectancy on the previous listed heating and cooling systems should be on sustainable office buildings, in order to enhance energy-efficiency in the long run?**

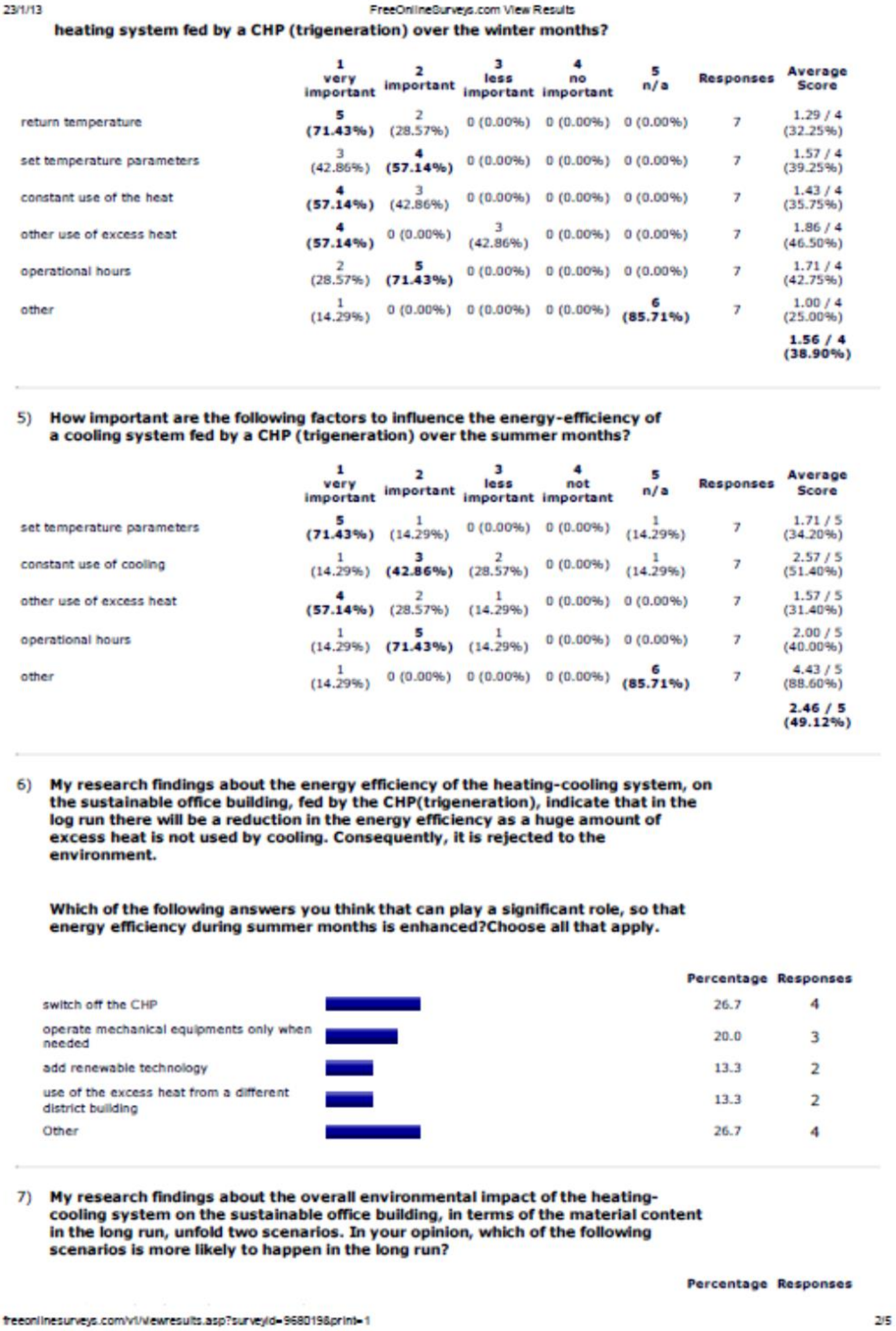
(The last five responses are given)

- **25-30 years**

- **I think life expectancy of components should be weighed against the ecological impact of their production. If a component requires more carbon to produce that it use is likely to save (given average lifespans) then it is not worth its usage.**
- **15-20**
- **for energy efficiency it should be about 20 years**
- **They have the potential to last longer than figures quoted if applied correctly and regularly serviced.**

4) **How important are the following factors to influence the energy-efficiency of a**

freeonlinesurveys.com/v1/viewresults.asp?surveyid=968019&print=1 1/5



heating system fed by a CHP (trigeneration) over the winter months?

	1 very important	2 important	3 less important	4 no important	5 n/a	Responses	Average Score
return temperature	**5 (71.43%)**	2 (28.57%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.29 / 4 (32.25%)
set temperature parameters	3 (42.86%)	**4 (57.14%)**	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.57 / 4 (39.25%)
constant use of the heat	**4 (57.14%)**	3 (42.86%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.43 / 4 (35.75%)
other use of excess heat	**4 (57.14%)**	0 (0.00%)	3 (42.86%)	0 (0.00%)	0 (0.00%)	7	1.86 / 4 (46.50%)
operational hours	2 (28.57%)	**5 (71.43%)**	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.71 / 4 (42.75%)
other	1 (14.29%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	**6 (85.71%)**	7	1.00 / 4 (25.00%)
							1.56 / 4 (38.90%)

5) **How important are the following factors to influence the energy-efficiency of a cooling system fed by a CHP (trigeneration) over the summer months?**

	1 very important	2 important	3 less important	4 not important	5 n/a	Responses	Average Score
set temperature parameters	**5 (71.43%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	1 (14.29%)	7	1.71 / 5 (34.20%)
constant use of cooling	1 (14.29%)	**3 (42.86%)**	2 (28.57%)	0 (0.00%)	1 (14.29%)	7	2.57 / 5 (51.40%)
other use of excess heat	**4 (57.14%)**	2 (28.57%)	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	1.57 / 5 (31.40%)
operational hours	1 (14.29%)	**5 (71.43%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	2.00 / 5 (40.00%)
other	1 (14.29%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	**6 (85.71%)**	7	4.43 / 5 (88.60%)
							2.46 / 5 (49.12%)

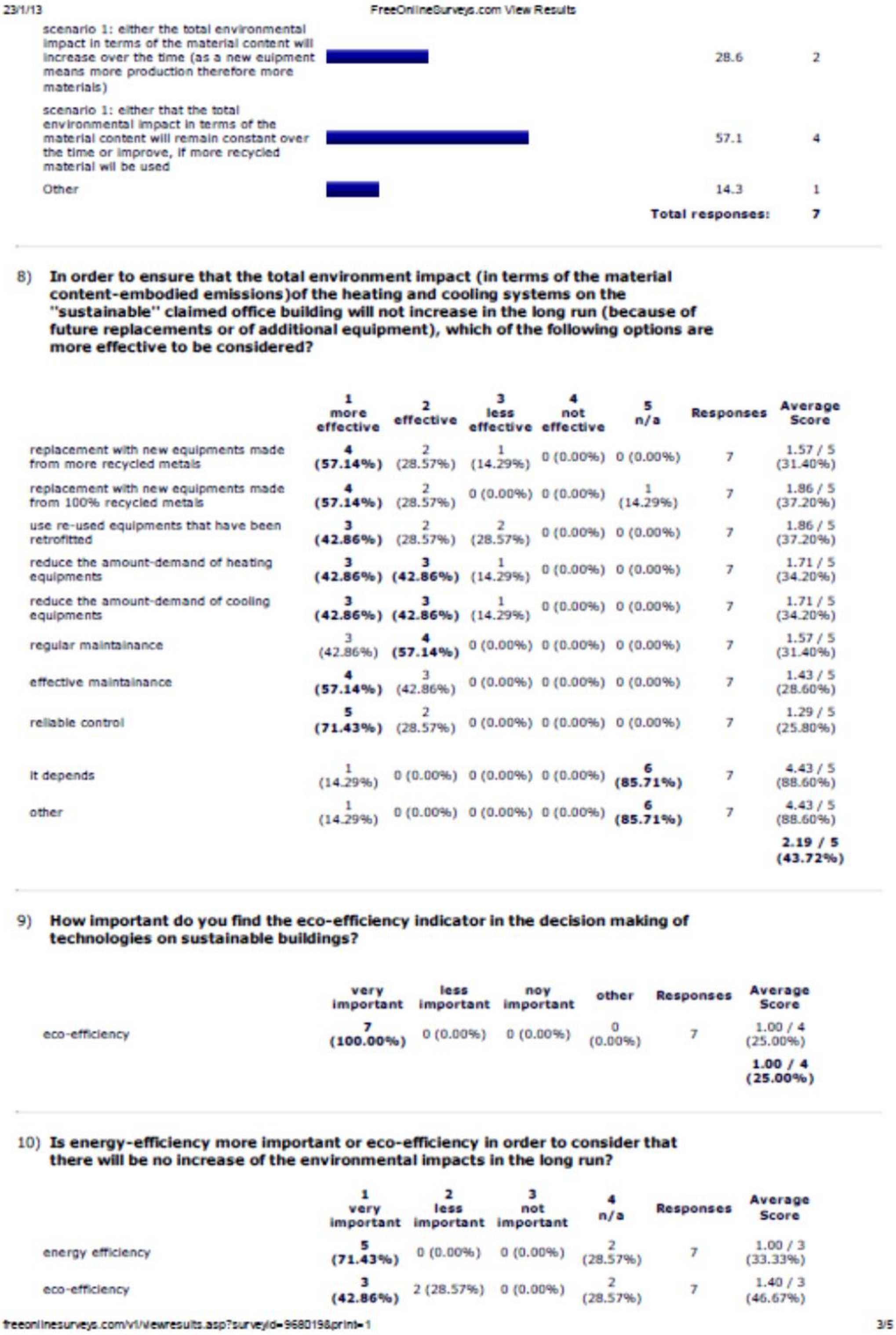
6) **My research findings about the energy efficiency of the heating-cooling system, on the sustainable office building, fed by the CHP(trigeneration), indicate that in the log run there will be a reduction in the energy efficiency as a huge amount of excess heat is not used by cooling. Consequently, it is rejected to the environment.**

Which of the following answers you think that can play a significant role, so that energy efficiency during summer months is enhanced?Choose all that apply.

	Percentage	Responses
switch off the CHP	26.7	4
operate mechanical equipments only when needed	20.0	3
add renewable technology	13.3	2
use of the excess heat from a different district building	13.3	2
Other	26.7	4

7) **My research findings about the overall environmental impact of the heating-cooling system on the sustainable office building, in terms of the material content in the long run, unfold two scenarios. In your opinion, which of the following scenarios is more likely to happen in the long run?**

Percentage Responses



scenario 1: either the total environmental impact in terms of the material content will increase over the time (as a new euipment means more production therefore more materials)	28.6	2
scenario 1: either that the total environmental impact in terms of the material content will remain constant over the time or improve, if more recycled material wil be used	57.1	4
Other	14.3	1
Total responses:		**7**

8) **In order to ensure that the total environment impact (in terms of the material content-embodied emissions)of the heating and cooling systems on the "sustainable" claimed office building will not increase in the long run (because of future replacements or of additional equipment), which of the following options are more effective to be considered?**

	1 more effective	**2 effective**	**3 less effective**	**4 not effective**	**5 n/a**	**Responses**	**Average Score**
replacement with new equipments made from more recycled metals	**4 (57.14%)**	2 (28.57%)	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	1.57 / 5 (31.40%)
replacement with new equipments made from 100% recycled metals	**4 (57.14%)**	2 (28.57%)	0 (0.00%)	0 (0.00%)	1 (14.29%)	7	1.86 / 5 (37.20%)
use re-used equipments that have been retrofitted	**3 (42.86%)**	2 (28.57%)	2 (28.57%)	0 (0.00%)	0 (0.00%)	7	1.86 / 5 (37.20%)
reduce the amount-demand of heating equipments	**3 (42.86%)**	**3 (42.86%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	1.71 / 5 (34.20%)
reduce the amount-demand of cooling equipments	**3 (42.86%)**	**3 (42.86%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	1.71 / 5 (34.20%)
regular maintainance	3 (42.86%)	**4 (57.14%)**	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.57 / 5 (31.40%)
effective maintainance	**4 (57.14%)**	3 (42.86%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.43 / 5 (28.60%)
reliable control	**5 (71.43%)**	2 (28.57%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.29 / 5 (25.80%)
it depends	1 (14.29%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	**6 (85.71%)**	7	4.43 / 5 (88.60%)
other	1 (14.29%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	**6 (85.71%)**	7	4.43 / 5 (88.60%)
							2.19 / 5 (43.72%)

9) **How important do you find the eco-efficiency indicator in the decision making of technologies on sustainable buildings?**

	very important	**less important**	**noy important**	**other**	**Responses**	**Average Score**
eco-efficiency	**7 (100.00%)**	0 (0.00%)	0 (0.00%)	0 (0.00%)	7	1.00 / 4 (25.00%)
						1.00 / 4 (25.00%)

10) **Is energy-efficiency more important or eco-efficiency in order to consider that there will be no increase of the environmental impacts in the long run?**

	1 very important	**2 less important**	**3 not important**	**4 n/a**	**Responses**	**Average Score**
energy efficiency	**5 (71.43%)**	0 (0.00%)	0 (0.00%)	2 (28.57%)	7	1.00 / 3 (33.33%)
eco-efficiency	**3 (42.86%)**	2 (28.57%)	0 (0.00%)	2 (28.57%)	7	1.40 / 3 (46.67%)

both	**6 (85.71%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	1.14 / 3 (38.00%)
						1.18 / 3 (39.18%)

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11) **By 2050 the UK has to achieve 80% of green house emissions. Government has already set out its policy that new homes will be zero carbon from 2016, and an ambition that new schools, public sector non-domestic buildings and other nondomestic buildings will be zero carbon from 2016, 2018 and 2019 respectively. The UK Low Carbon Transition Plan sets out proposals and policies for meeting the first three carbon budgets, and achieving the 34% reduction target by 2020.**

Which of the following combination-options are most effective to achieve zero carbon in the near future, considering only energy efficiency?

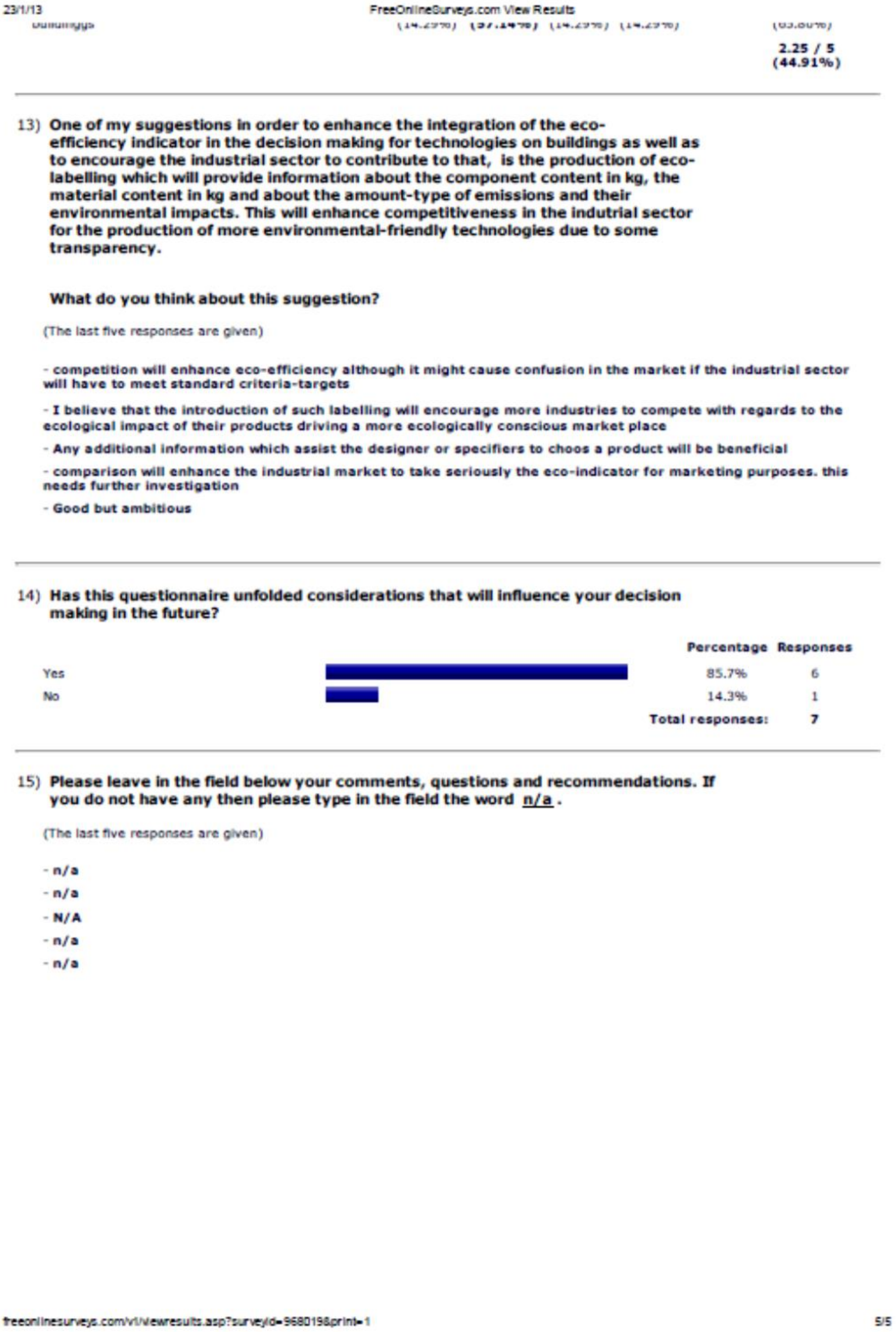
	1 most effective	**2 effective**	**3 less effective**	**4 not effective**	**5 n/a**	**Responses**	**Average Score**
retrofitting existing buildings with energy efficient technologies	0 (0.00%)	**5 (71.43%)**	1 (14.29%)	0 (0.00%)	1 (14.29%)	7	2.57 / 5 (51.40%)
retrofitting existing buildings with passive strategies and energy efficienct technology	2 (28.57%)	**4 (57.14%)**	0 (0.00%)	0 (0.00%)	1 (14.29%)	7	2.14 / 5 (42.80%)
existing buildings with renewable technology only	1 (14.29%)	1 (14.29%)	**3 (42.86%)**	1 (14.29%)	1 (14.29%)	7	3.00 / 5 (60.00%)
retrofitting with passive strategies, energy efficient technology and with renewables	**3 (42.86%)**	1 (14.29%)	2 (28.57%)	0 (0.00%)	1 (14.29%)	7	2.29 / 5 (45.80%)
new buildings with passive strategies adaptation and with energy efficient technologies	1 (14.29%)	**5 (71.43%)**	0 (0.00%)	0 (0.00%)	1 (14.29%)	7	2.29 / 5 (45.80%)
new buildings with passive strategies adaptation- energy efficient technologies-renewables	**5 (71.43%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	1 (14.29%)	7	1.71 / 5 (34.20%)
add only renewables in existing and new buildinggs	1 (14.29%)	**2 (28.57%)**	**2 (28.57%)**	1 (14.29%)	1 (14.29%)	7	2.86 / 5 (57.20%)
other	0 (0.00%)	0 (0.00%)	0 (0.00%)	0 (0.00%)	**7 (100.00%)**	7	5.00 / 5 (100.00%)
							2.73 / 5 (54.65%)

---

12) **By 2050 the UK has to achieve 80% of green house emissions. Government has already set out its policy that new homes will be zero carbon from 2016, and an ambition that new schools, public sector non-domestic buildings and other nondomestic buildings will be zero carbon from 2016, 2018 and 2019 respectively. The UK Low Carbon Transition Plan sets out proposals and policies for meeting the first three carbon budgets, and achieving the 34% reduction target by 2020.**

Which of the following combination-options are most effective to achieve zero carbon in the near future, considering energy efficiency and eco-efficiency?

	1 most effective	**2 effective**	**3 less effective**	**4 not effective**	**5 n/a**	**Responses**	**Average Score**
retrofitting existing buildings with energy efficient technologies	1 (14.29%)	**3 (42.86%)**	2 (28.57%)	1 (14.29%)	0 (0.00%)	7	2.43 / 5 (48.60%)
retrofitting existing buildings with passive strategies and energy efficienct technology	2 (28.57%)	**4 (57.14%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	1.86 / 5 (37.20%)
existing buildings with renewable technology only	2 (28.57%)	0 (0.00%)	**4 (57.14%)**	1 (14.29%)	0 (0.00%)	7	2.57 / 5 (51.40%)
retrofitting with passive strategies, energy efficient technology and with renewables	**3 (42.86%)**	2 (28.57%)	2 (28.57%)	0 (0.00%)	0 (0.00%)	7	1.86 / 5 (37.20%)
new buildings with passive strategies adaptation and with energy efficient technologies	1 (14.29%)	**5 (71.43%)**	1 (14.29%)	0 (0.00%)	0 (0.00%)	7	2.00 / 5 (40.00%)
new buildings with passive strategies adaptation- energy efficient technologies-renewables	**4 (57.14%)**	2 (28.57%)	0 (0.00%)	1 (14.29%)	0 (0.00%)	7	1.71 / 5 (34.20%)
add only renewables in existing and new	0 (0.00%)	1	**4**	1	1	7	3.29 / 5



2.25 / 5 (44.91%)

13) **One of my suggestions in order to enhance the integration of the eco-efficiency indicator in the decision making for technologies on buildings as well as to encourage the industrial sector to contribute to that, is the production of eco-labelling which will provide information about the component content in kg, the material content in kg and about the amount-type of emissions and their environmental impacts. This will enhance competitiveness in the indutrial sector for the production of more environmental-friendly technologies due to some transparency.**

What do you think about this suggestion?

(The last five responses are given)

- **competition will enhance eco-efficiency although it might cause confusion in the market if the industrial sector will have to meet standard criteria-targets**
- **I believe that the introduction of such labelling will encourage more industries to compete with regards to the ecological impact of their products driving a more ecologically conscious market place**
- **Any additional information which assist the designer or specifiers to choos a product will be beneficial**
- **comparison will enhance the industrial market to take seriously the eco-indicator for marketing purposes. this needs further investigation**
- **Good but ambitious**

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14) **Has this questionnaire unfolded considerations that will influence your decision making in the future?**

	Percentage	Responses
Yes	85.7%	6
No	14.3%	1
	Total responses:	**7**

---

15) **Please leave in the field below your comments, questions and recommendations. If you do not have any then please type in the field the word n/a .**

(The last five responses are given)

- **n/a**
- **n/a**
- **N/A**
- **n/a**
- **n/a**

APPENDIX 22 INTERVIEW REMARKS

Argyle House

Attendance: FM manager of the Argyle House, Lorna Murray, Telereal Trillium company
Refurbishment
Internal fit outs have been refurbished, not the structure itself. Heating and cooling system types Cooling are only to comms rooms Heating control is the ceiling, through the building and the control is nonexistent. So the heating zone is on and off without control which was not considered those days and it is oil fired. A lot of oil is consumed because it is a huge building and the population is about 300.Only a few floor are occupied just now.
Openable windows or mechanical ventilation
Openable windows are better adjusted to the seasons and occupant’s demands.
Energy certification
n/a yet in Scotland. Performance certificate are available but not displayed as we did not have public coming to the building.
Window structure
Windows are original; they have not been replaced since 1960s. Double glazed
Insulation
Insulations wise are just a concrete slab. No insulations.
Observations-indoor temperature
The internal temperature was comfortable.
How is the indoor temperature controlled?
There is no local control for each floor just switching on and off. It is poor in that sense. The south side is quite nice and warm but for the north side you have to wait until it comes from this side. By switching on the heating in the morning you can come in the north side of the building and feel very warm so how we control that is by opening the windows a wee bit. If we switch the heating on all the radiators gradually will provide heat in the building even in the unoccupied floors.
POE

Monthly maintenance on the heating systems and obliges to undertake controls audits each year. We do not actually need it as the building is so big and without occupancy really. Distribution boards have been used to check on heat losses but not as such to evaluate it. Thermographic survey for heating losses is kind of extreme for this building.
Replacement
We are not looking at replacing them. They are basic in their operations. Assets types show the maintenance. There is no use interface. Air cons operate 24 hours per day to maintain temperatures in certain rooms-server rooms. Monday to Friday from 10 am. Weekends' heating is off. Heating is on for few hours in the morning.
Comfort
Comfort is a perception thing. Occupants look at the thermometer and if they feel cold they open heating.
Radiators
They perform fine, well designed at that time. Placed under the windows.
Future plan
We are aware of what we should be doing; teams should be looking for the most energy efficient models. We are getting smarter in that case! This is a landlord building there is not much you can do about it. We have the heating capacity and gas could be used by doing some replacements in the plantroom but this is a landlord building. So everything that has to do with major replacement apart from the air-cons is not our responsibility. We need a good case forward to upgrade things so we just try to maintain it in the best possible way we can. Also we have to put a project to the service partners to replace something.
Regular maintenance on the systems
You can check the maintenance frequencies (appendices).
Parameters
Monday to Friday the building is open from 6am to 10 pm. Weekend 8-6.weekends heating is off, only portable heaters in that case. Certain temperature by the time the client comes to occupy the building, up to 21 degrees by 9 in the morning and 16 before that. So heaters are on from 6 in the morning. Server rooms air-cons are on all the time and they are about 12 years old since the occupants moved there. Winter times oil order every two weeks. From June to oct no order. But meters are checked every fortnight. Oil storage tanks are there since 1968.Engineers do annual visits.
Satisfaction about the indoor temperatures
Ridiculous temperatures! Cooling 24 and heating 21. Is that comfortable? Heating and cooling systems fight on each other.

Potterrow Building

Attendance: Adam Kirk Bennetts Associates, Graeme Gidney Associate Director Burro Happold Engineering, in the Potterrow building

The significance of the POE

A CHP located offsite across the building provides all the heating and cooling in the building. To get manufacturing details for the CHP might be difficult to traise as there are loads of other buildings connected to it in the site. Utility information on the building is advice to make decisions whether the building is low energy efficient or not. From an engineering and architectural perspective we understand how much energy the building actually consumes, what is less and more difficult to understand is how people actually operate it and this why POE is so important. The feedback that we get from different buildings was energy efficient measures have been used is that buildings are still on benchmark levels. When choosing comparison samples choose them based on what makes for you energy efficiency so that you can make this clear. From the old buildings what you get is the actually energy usage but you will get from this building is the predicted energy use with metering. The building is up running for a year. The interesting part to discuss is how that does stand up against to what it was predicted? The Elizabeth Courts II is actually doing as predicted looking at the POE.

Cooling system

Is mixed-mode system. Ventilation is a significant aspect to heating and cooling as it can have an impact if not operated efficiently. Peak lopping type of cooling is what has been used in rooms where to many people use it like in meeting rooms where fan coils is used. Supplementary cooling comes from opening the windows although when there is a need to achieve set temperatures using cooling the windows must be shut and mechanical ventilation is on which has an element to try to maintain temperature conditions within acceptable and recognized norms according to the contract criteria.

You can really predict for how long the systems will last in a building. We have seen building over 400 years old having the same systems, there might be some adaptation but who really know for how long they will last, it could be 25 years but it could be forever as in the Argyle House. Conventional buildings with current-state-of-the art buildings can have similar type systems but the difference is in the efficiencies. What you really have to look at is the seasonal energy efficiency ratio of a chiller and the energy efficiency of the boiler which gives a broad picture for a first

comparison.
Heating system
Floor heating is important to the building. The underfloor heating is presented in the drawings with hatched areas which shows the output achieved (then the pipework is designed), fed by water from the CHP, and then a series of manifolds are fed from this constant temperature hot water and manifold do the mixing in temperature send lower temperature water to the underfloor heating. Water is the by-product of the power generation process. Trench heaters are located in seminar rooms and then there is a series of radiators in the rooms. Where the chp staff comes in, it has a plate heat exchanger, a series of heating pumps to supply each of these circuits (trench heaters at variable temperatures, underfloor heating at constant temperature).
What happens to waste heat?
Waste heat in the summer occurs as heating temperatures in the summer are very low, the absorption regeneration chiller takes the waste heat and transforms it into cooling. Where the compressor refrigeration gets the cooling from expanding the gas through a pump, It is a chemical reaction between to chemical products that when you actually heat them the fractionation process gives the cooling. Waste heat is separately metered. There is a heat reincarnation.
Ventilation
Basically there is the building is natural ventilated but there is also mechanical ventilation air-handling units located in the roof and in level 3, supplies air in the floor which has a form of cooling as well due its recovery system, cooling the air to the appropriate indoor temperatures. The ventilation units supply which actually supplies air in the access floors and it also has extraction in the atrium space, collected from the plant area in the roof. So what you get is the beneficial effects of the temperature stratification in that atrium space.
How is energy efficiency declared by a manufacture?
In terms of measuring the impacts in the production phase and how manufacturers have test it a technology as energy efficient there are standardized assumption been used . Coming up with your own assumption and the testing it and coming up with a figure that cannot directly be compared, there is a registration type system where the manufacturer register their company and they will have to test their equipments based on the EU standards and then they produce the efficiencies. Performance has to be comparable

Elizabeth Courts II

Interview with Neil Broadman, FM manager of the Elizabeth Court II

Most data collection has been collected from distance through semi-structured and structured questionnaires (see appendices). The research in this thesis is ongoing and iterative (see the methodology chapter). In the first site visit the discussion with the FM manager could not be recorded due to noise from the visitors. The FM manager spoke about the building's characteristics, showed around the building and provided first data collection. Some remarks from the development's philosophy are shown in two videos, included in a CD in the appendices;

Tom Delay, the chief executive from the Carbon Trust talks about the importance of recycling existing material in reducing embodied emissions *''embodied energy efficiency in the refurbishment process will be to cost savings over many years thereafter [...] tenants demand it''*(Carbon Trust 2012a).

Steve Clow, head of architecture from the Hampshire County Council states that *''we have taken the view that if you did something more significant and strip back the building to the building frame you get significantly more benefits[...]the reason that the county council is doing it is both for energy efficiency and space utilisation''*(Carbon Trust 2012a).

Dr Mark Williamson, director of innovations of the Carbon Trust informs that advice for the scheme has been provided using the 'low carbon building accelerator programme'. This development *''encourages thinking for the carbon saving agenda alongside other priorities for projects''*(Carbon Trust 2012a). Further to that he mentioned that the development followed a 4 stage process that involves at the end the annual monitoring of the building so that they could see in the reality what they have achieved.

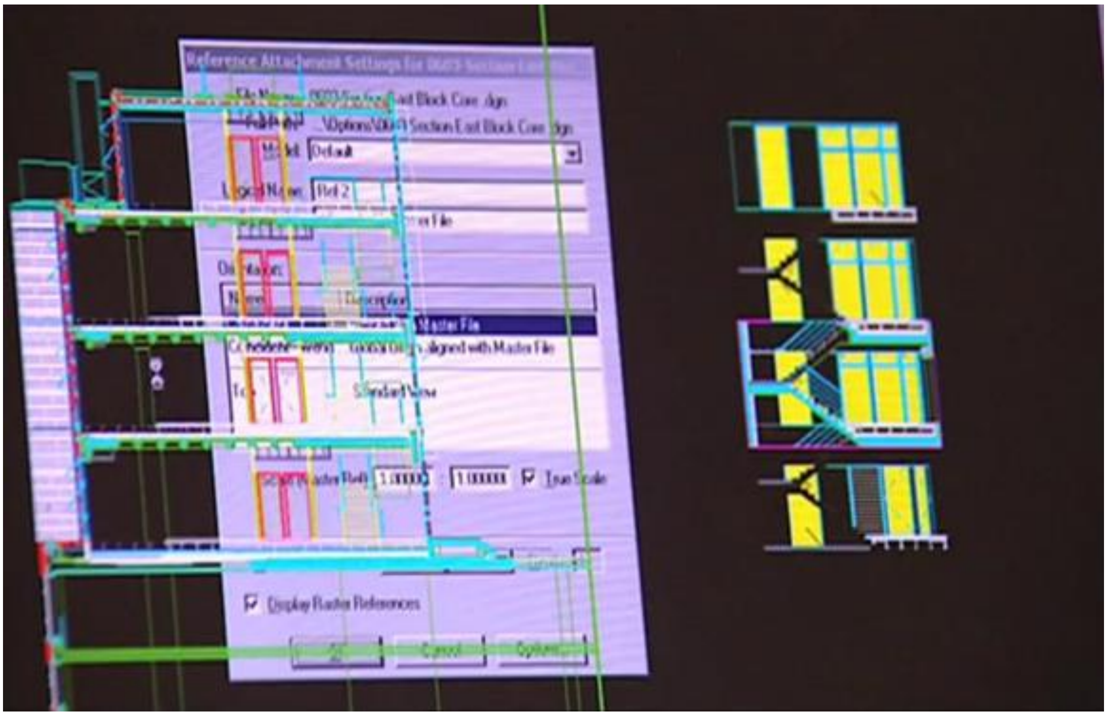


Figure: Image from the Low Carbon Accelerator Programme

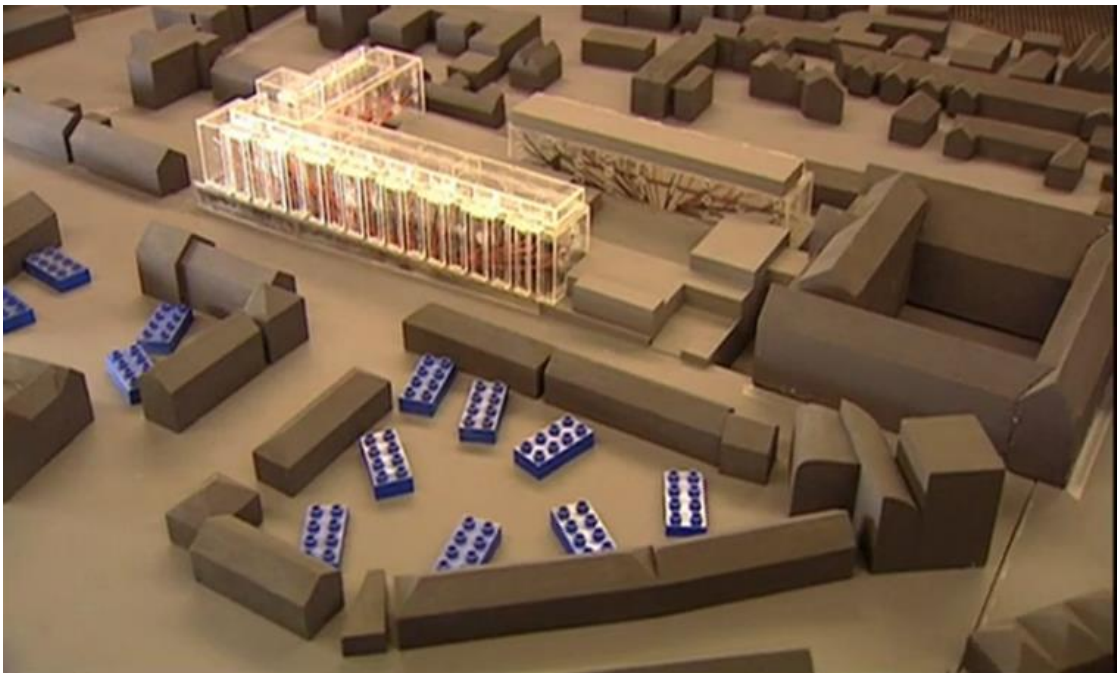


Figure: Wind technology testing

Figure: P0E Monitoring.

Peter Fisher, the architect from the Bennetts Associates architects, explains what the most important characteristics of the building design are; there is *‘’too much emphasis on buildings that they look green and new examples that are fundamentally quite bad buildings that just have few PVs and winderbines however it is much more sensible to simply not require the energy to find clever ways of regenerating it. By having air moving across the top of the ducts creates suction inside the windthrough which allows air to come across through floorplates and then up the ducts which opens into the windthrough at the top’’*(Carbon Trust 2012a).

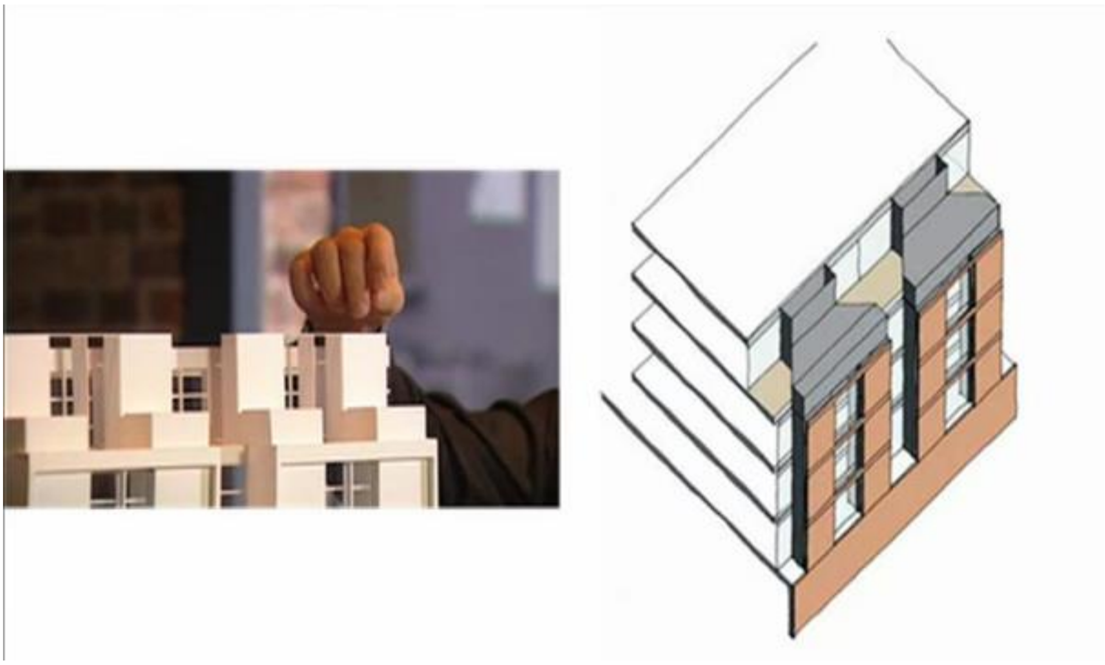


Figure: Suction ducts and the windtrough on the top of the building.

Figure: Row of the windthroughs on the top of the building.

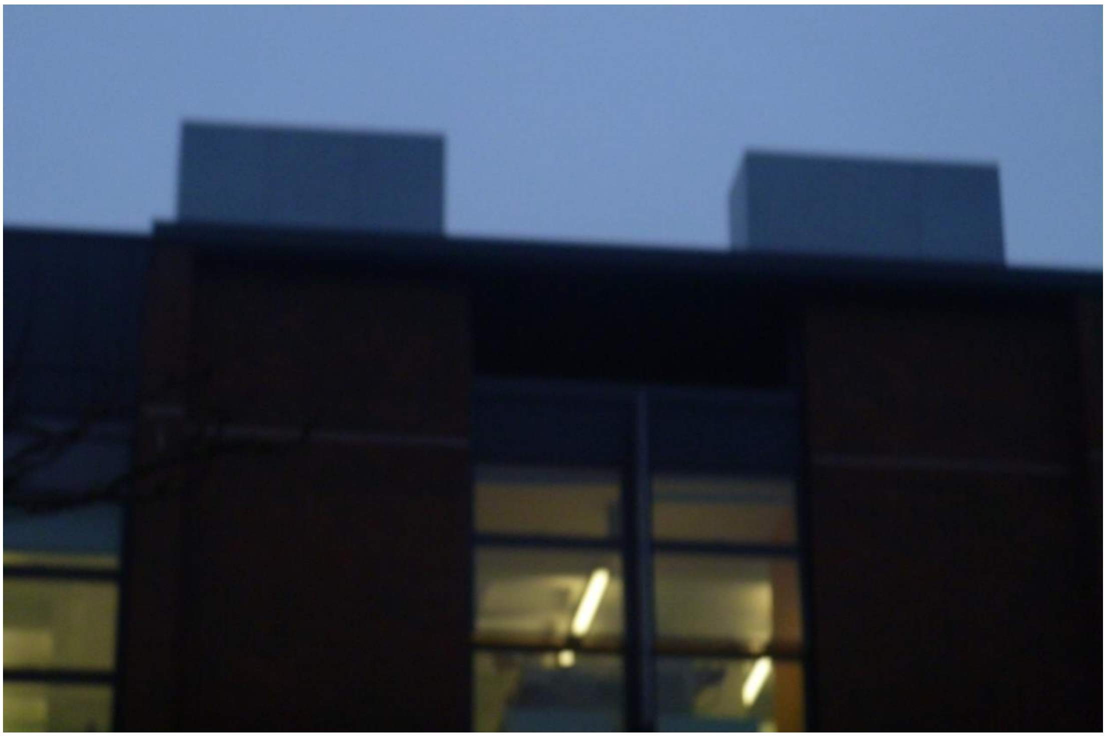


Figure: A closer look of the windthroughs

Tom Delay concludes that ‘’we know that commercial building represent a significant change of the built environment in UK and that these buildings are refurbished on a regular basis if we can just get that refurbishment cycle to take a slightly longer term view in terms of investing energy efficiency, investing in green technology it will have a massive impact over time in the efficiency that we see throughout buildings and our over carbon emissions in UK’’(Carbon Trust 2012a).

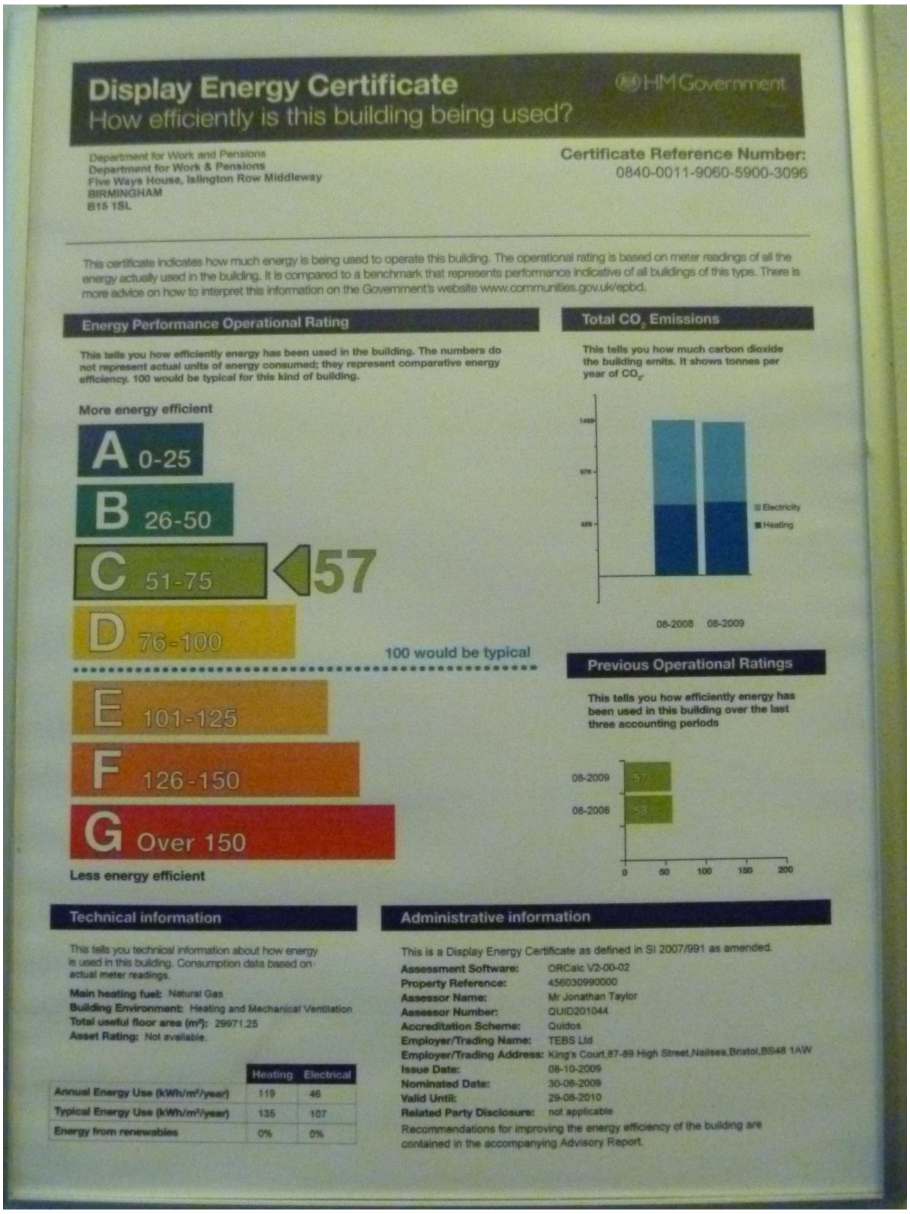
Five Ways House

Attendance: Robert Collins, former FM manager of the Five Ways House
Refurbishment
Internally a number of times Telereal trillium has been in the building for 13 years. A numbers of refurbishment in terms of the heating systems we have increased the boiler capacity. So that would have happened as a life cycle replacement project. Using a Life Cycle Replacement. Demonstrate value for money. ex. if we have a recommendation as part of the feasibility to change something we will keep the once that still operate. That’s why we have kept old systems. We have PPM in all assets in the building so if a radiator deteriorates the service partner would change it or retrofit it. Trillium has the contract with client for 20 years to provide all the facility management in the building, which includes Life Cycle Replacement. This building is occupied by DWP. There is money to do the life cycle replacements every five years, for instance to change the carpet and the air-conditioners. 8 years are remaining of the contract but we are very careful in saving money.
Management
In terms of being energy efficient when we do Life Cycle Replacement, that is one of the requirements. We are dear to be industry practice and because of the building regulations, heating replacements is a requirement. We would take a proactive approach to make things more environmental friendly. We can put modern equipment. ‘Rise or aware’ is out attitude. We are given targets each year from our client to reduce energy consumption to save money from bills enhance energy efficiency pay back time considerations PMP delivers Life Cycle Works; the programme has to be give to this people to deliver. The Capital Investment Team (CIT), have building surveyors and an input from the BS (building services) teams, these people will do a condition survey of the building and they will repeat that in three years time. Also I provide them with recommendation and guidance. If something falls over, I would say to these people that we need to change it when they are in emergency. CIT holds the money, so the plan becomes reviewed and it has to be justifiable. We look at the remaining life year of the equipments that we have and if we have two year remaining let’s say then we are in serious danger that

this equipment will fall over. Boilers are repaired every three months (see the Life Cycle Management Plan diagramme in the appendices).
Occupancy
About 600 occupants. Building opens at 6:45 in the morning until 7 at night.
Parameters
6:00 am to prepare. 18 degrees have to be met based on the contact requirements. 7:15 heating is on.
Feeling to temperature
The agreed temperatures are contractual temperatures. All staff is entitled to turn the thermostatic valves on and off. The actual temperature and operation is controlled by the service partners. The heating is on and up to a temperature that some feel ok with it and some not.BMS control. Operationally FM wise they cannot cater to individual complains. There has to be a group. The method of operation of the heating systems is time schedule, set points and locally control of the TRB. Set point on 28 degrees. 4 zones and vulnerability. It is all dictated by our client. We have a restricted approach and we need to be careful.
Ventilation-cooling
Offices are naturally ventilated. Servers 24hours on 25 degrees.
BREEAM
Robert Collins, BREEAM assessor *‘’It is a show business a piece of paper that shows what has been achieved but the it is all generated’’.*

APPENDIX 23 ENERGY PERFORMANCE CERTIFICATE

Five Ways House



Display Energy Certificate
How efficiently is this building being used?

HM Government

Department for Work and Pensions
Department for Work & Pensions
Five Ways House, Islington Row Middleway
BIRMINGHAM
B15 1SL

Certificate Reference Number:
0840-0011-9060-5900-3096

This certificate indicates how much energy is being used to operate this building. The operational rating is based on meter readings of all the energy actually used in the building. It is compared to a benchmark that represents performance indicative of all buildings of this type. There is more advice on how to interpret this information on the Government's website www.communities.gov.uk/epbd.

Energy Performance Operational Rating

This tells you how efficiently energy has been used in the building. The numbers do not represent actual units of energy consumed; they represent comparative energy efficiency. 100 would be typical for this kind of building.

More energy efficient

A 0-25
B 26-50
C 51-75 57
D 76-100
100 would be typical
E 101-125
F 126-150
G Over 150

Less energy efficient

Total CO_2 Emissions

This tells you how much carbon dioxide the building emits. It shows tonnes per year of CO_2.

Previous Operational Ratings

This tells you how efficiently energy has been used in this building over the last three accounting periods

Technical information

This tells you technical information about how energy is used in this building. Consumption data based on actual meter readings.

Main heating fuel: Natural Gas
Building Environment: Heating and Mechanical Ventilation
Total useful floor area (m^2): 29971.25
Asset Rating: Not available.

	Heating	Electrical
Annual Energy Use ($kWh/m^2/year$)	119	46
Typical Energy Use ($kWh/m^2/year$)	135	107
Energy from renewables	0%	0%

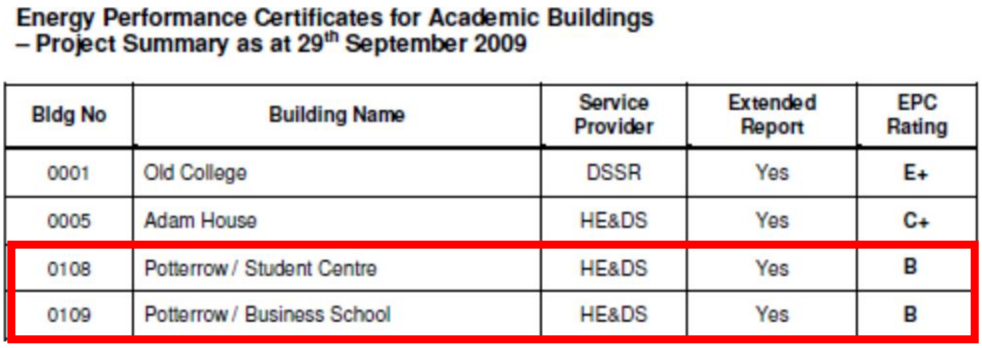
Administrative information

This is a Display Energy Certificate as defined in SI 2007/991 as amended.

Assessment Software: ORCalc V2-00-02
Property Reference: 456030990000
Assessor Name: Mr Jonathan Taylor
Assessor Number: QUID201044
Accreditation Scheme: Quidos
Employer/Trading Name: TEBS Ltd
Employer/Trading Address: King's Court,87-89 High Street,Nailsea,Bristol,BS48 1AW
Issue Date: 08-10-2009
Nominated Date: 30-08-2009
Valid Until: 29-08-2010
Related Party Disclosure: not applicable

Recommendations for improving the energy efficiency of the building are contained in the accompanying Advisory Report.

Potterrow

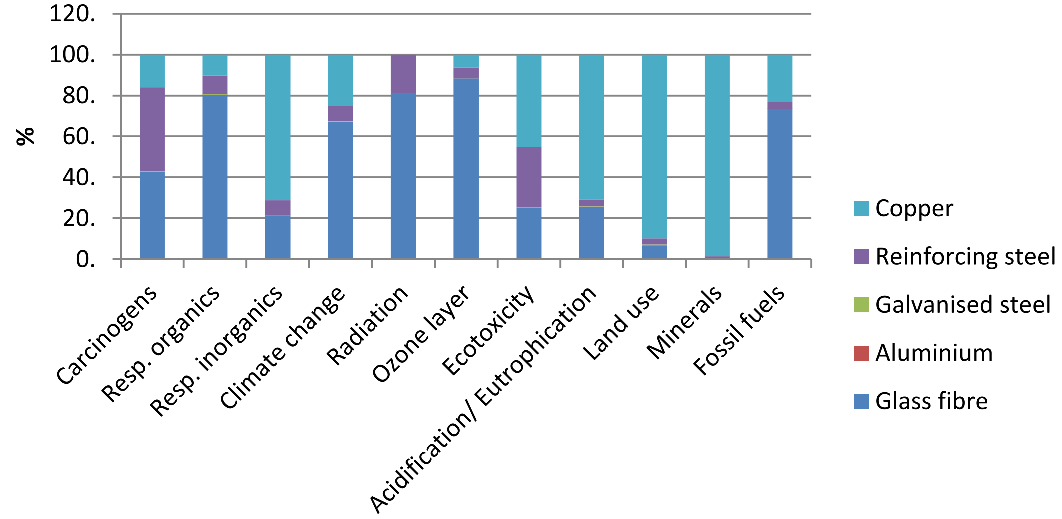


Energy Performance Certificates for Academic Buildings – Project Summary as at 29th September 2009

Bldg No	Building Name	Service Provider	Extended Report	EPC Rating
0001	Old College	DSSR	Yes	**E+**
0005	Adam House	HE&DS	Yes	**C+**
0108	Potterrow / Student Centre	HE&DS	Yes	**B**
0109	Potterrow / Business School	HE&DS	Yes	**B**

APPENDIX 24 LCA CHARACTERISATION, NORMALISATION AND WEIGHTING RESULTS

Raw materials-heating system-Argyle House



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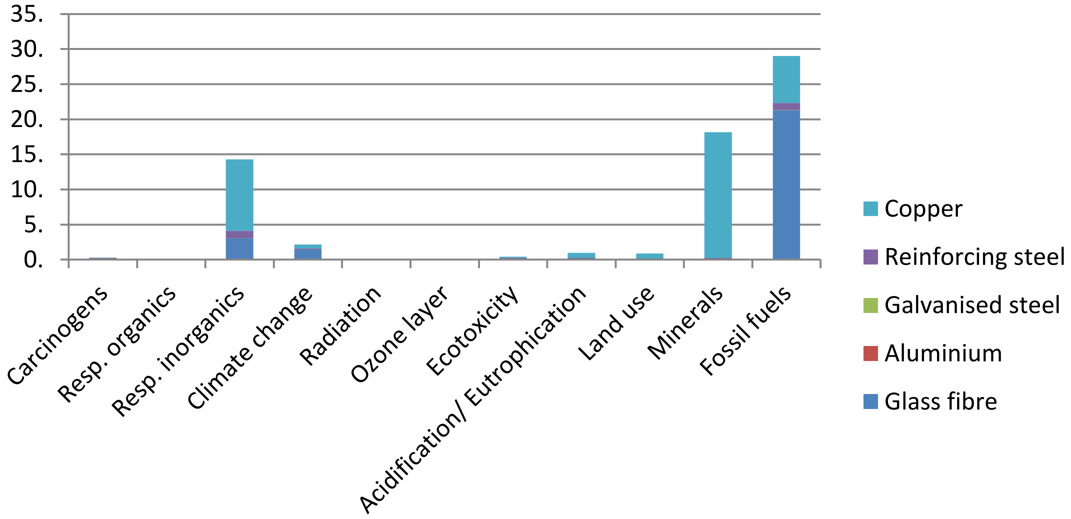

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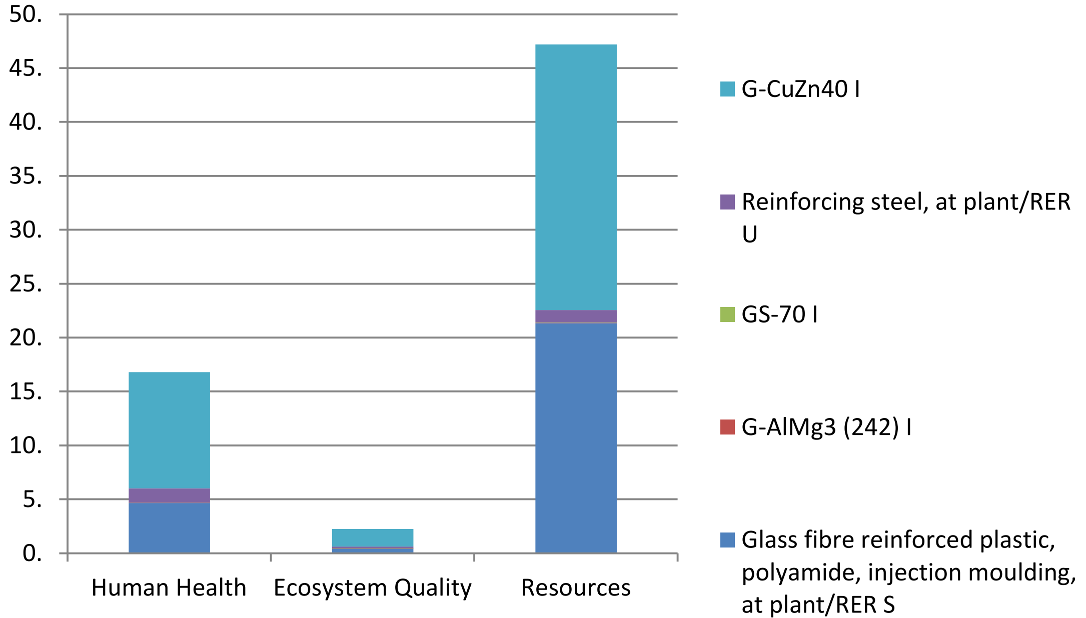

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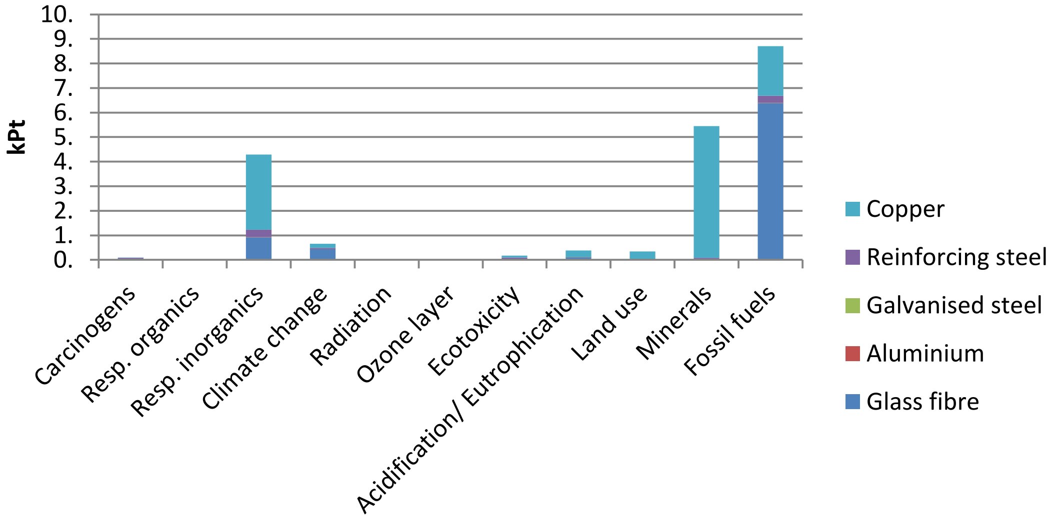

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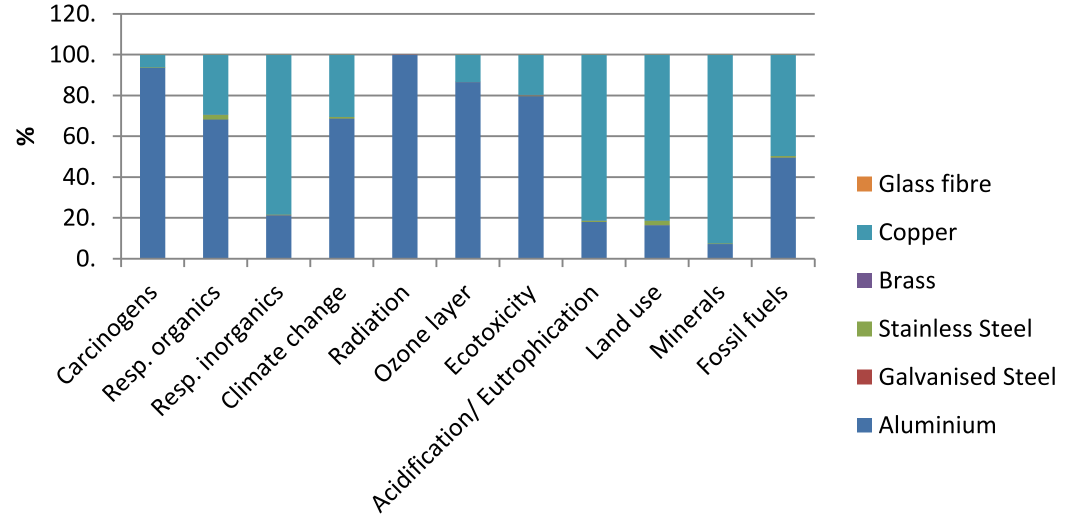
Raw materials-heating system-Potterrow building



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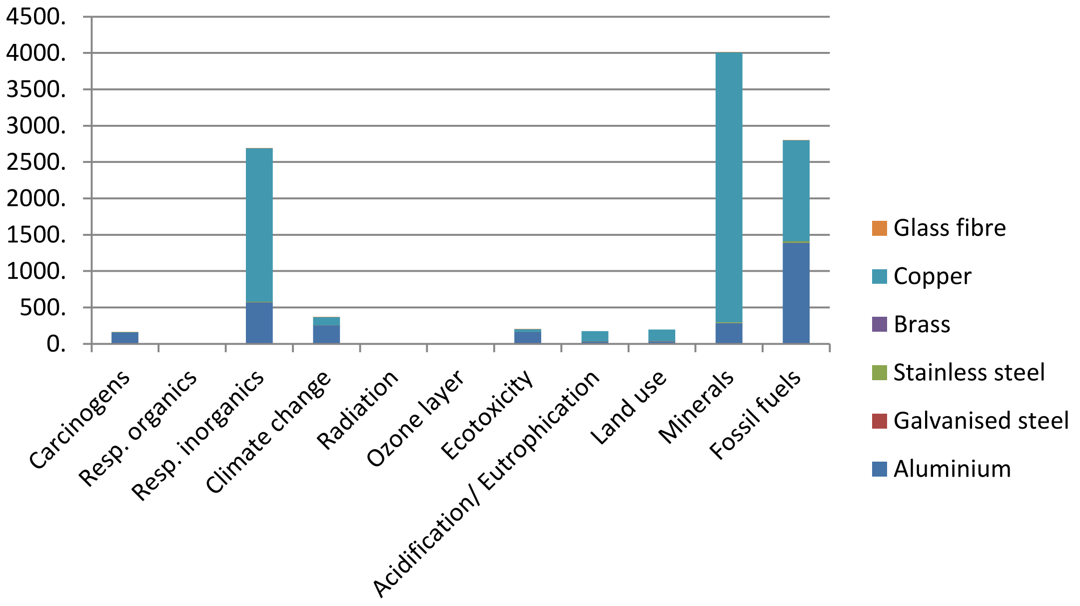

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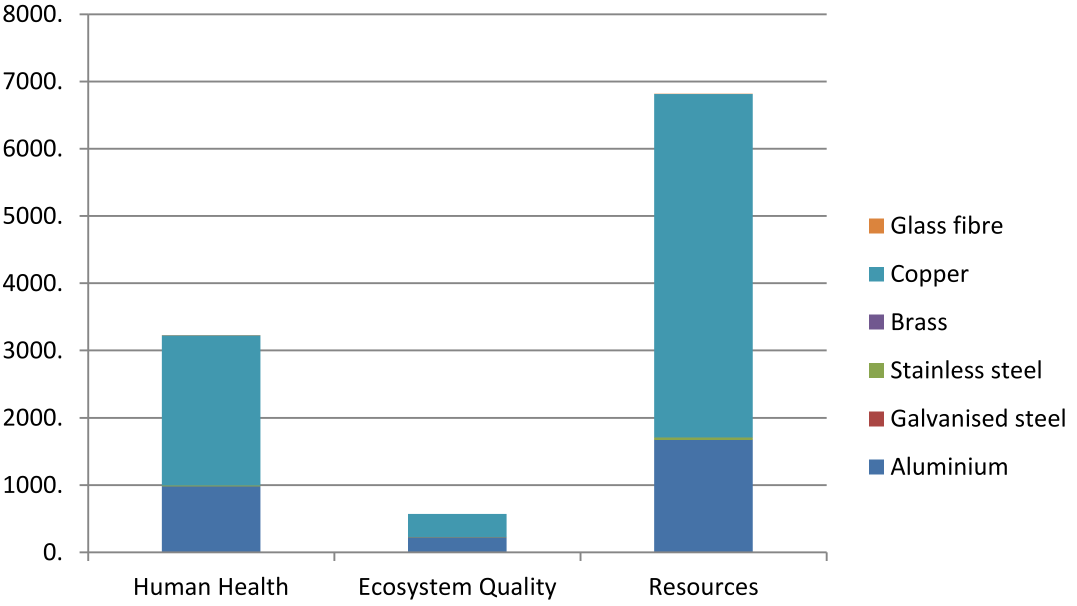

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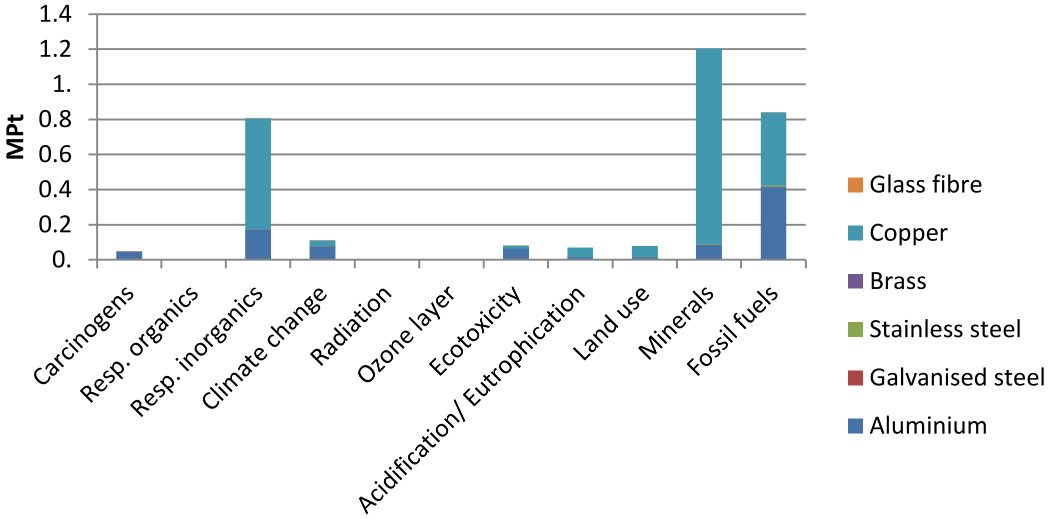

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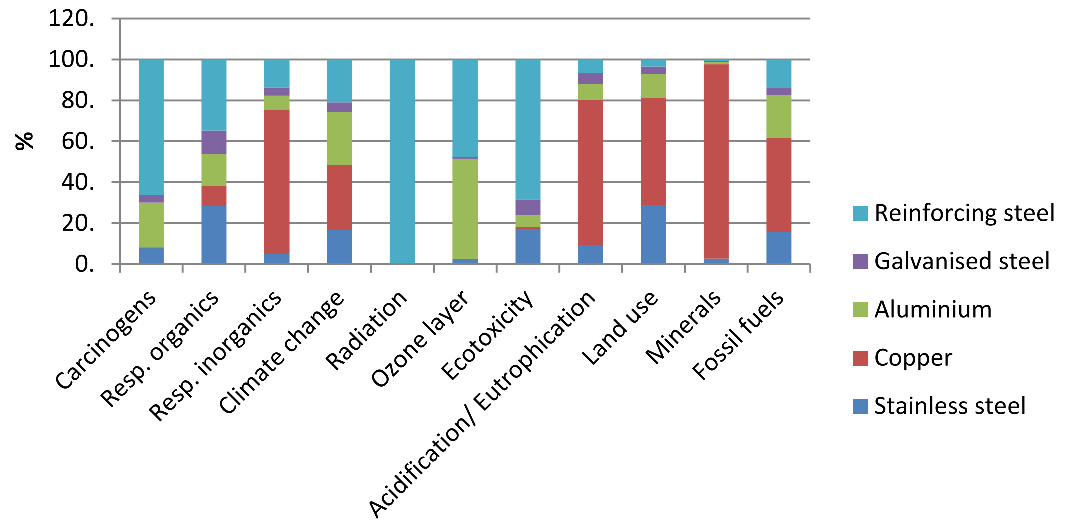
Raw-materials-cooling system-Argyle House



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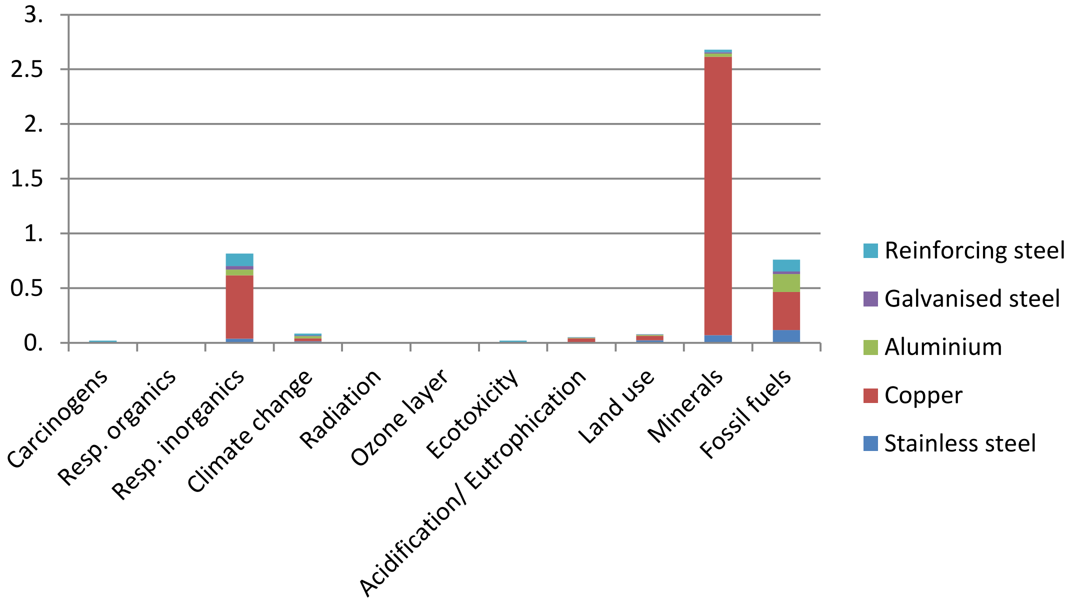

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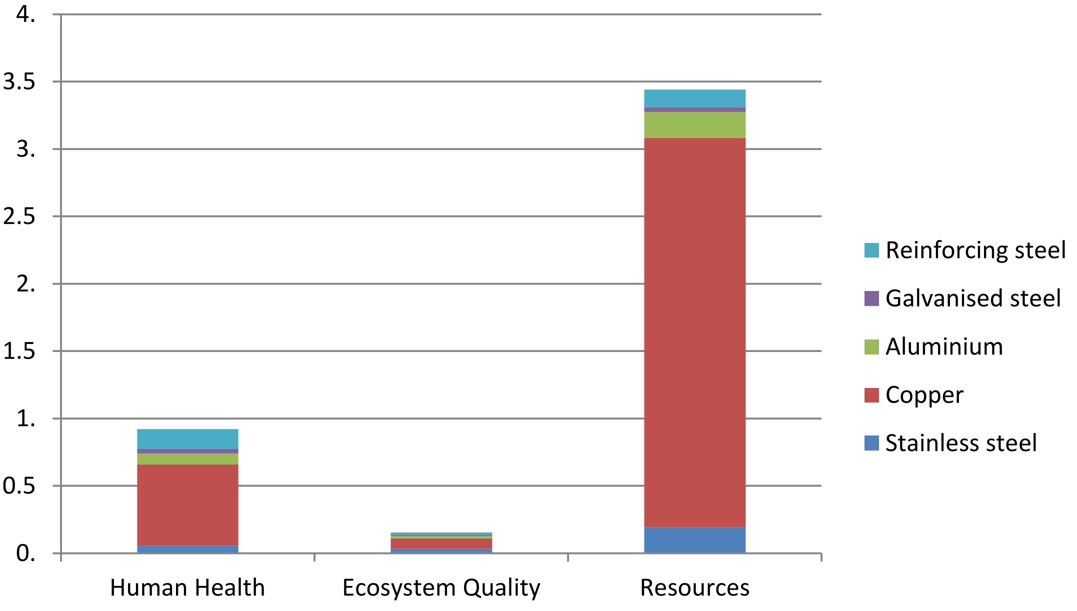

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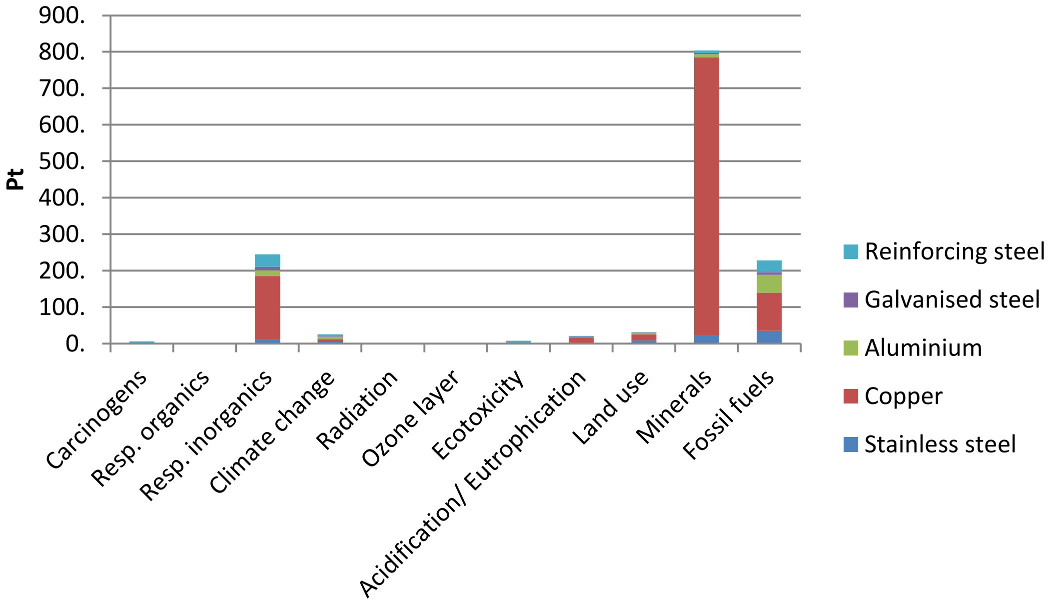

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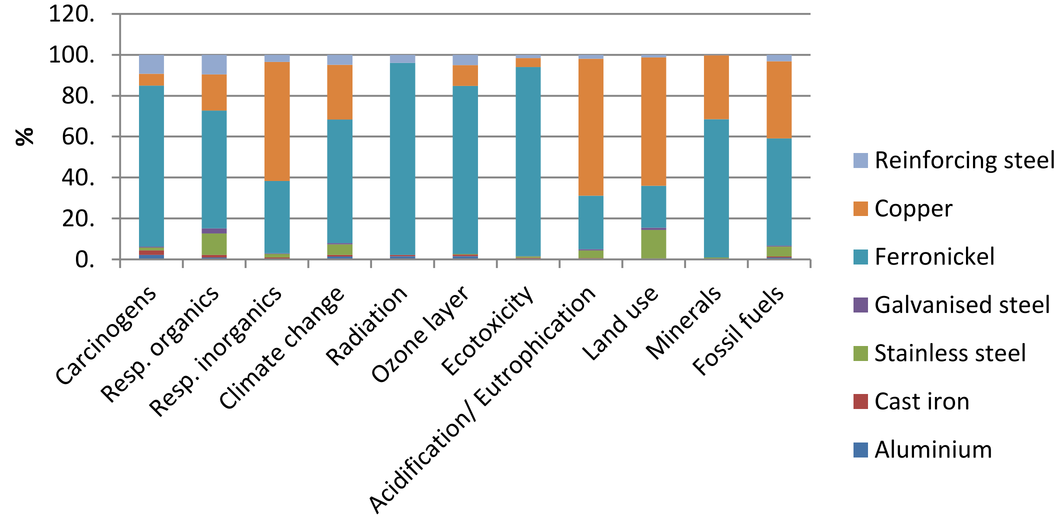
Raw-materials-cooling system-Potterrow building



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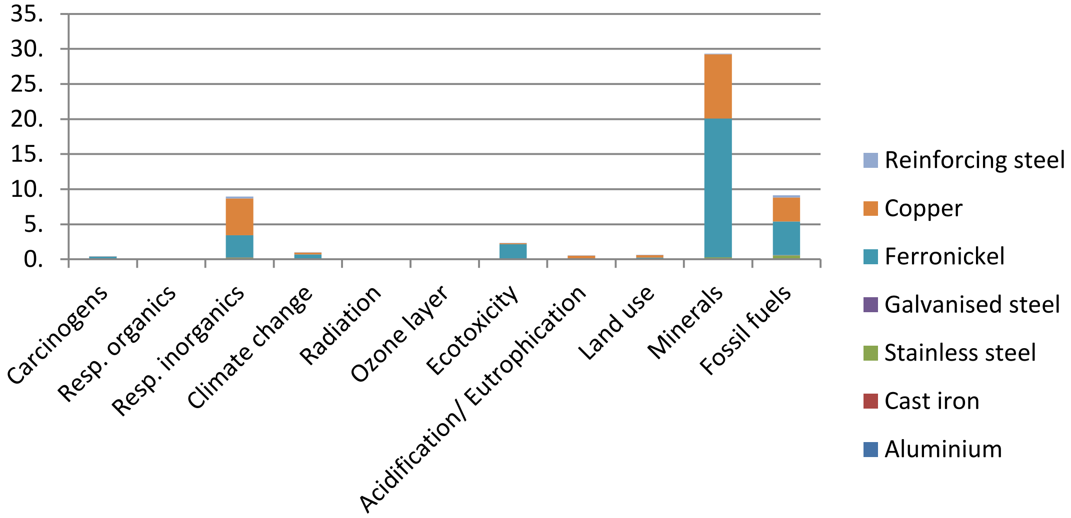
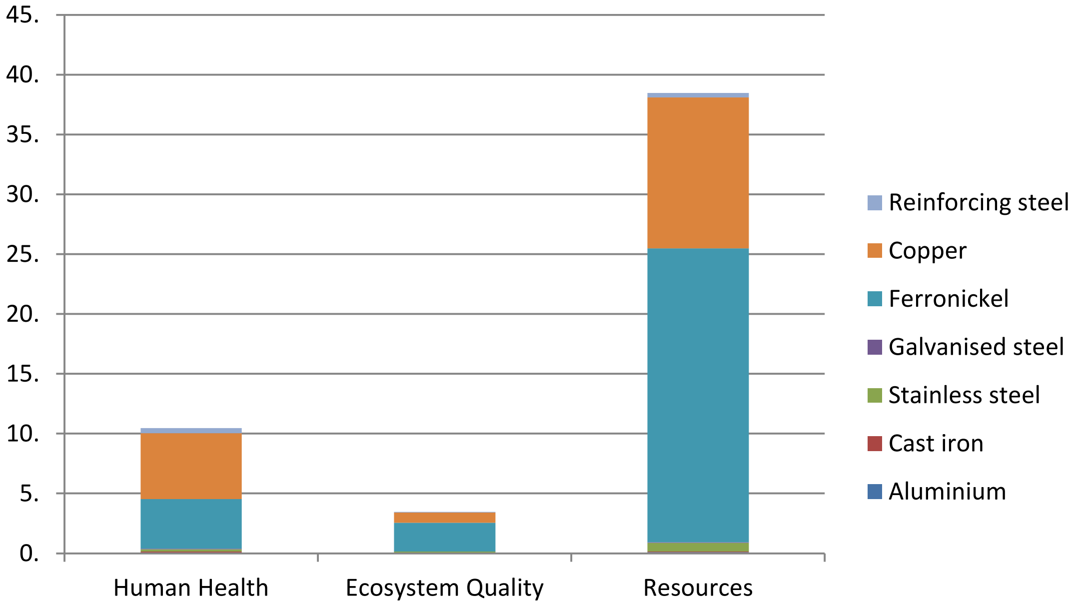


Analyzing 1 p 'Potterrow building_Cooling System_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



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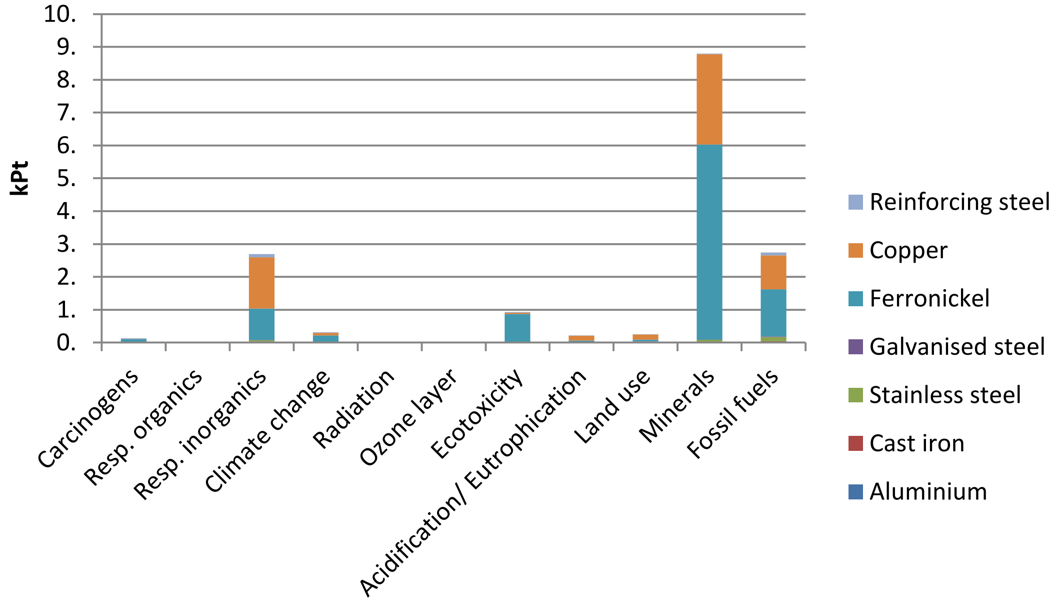
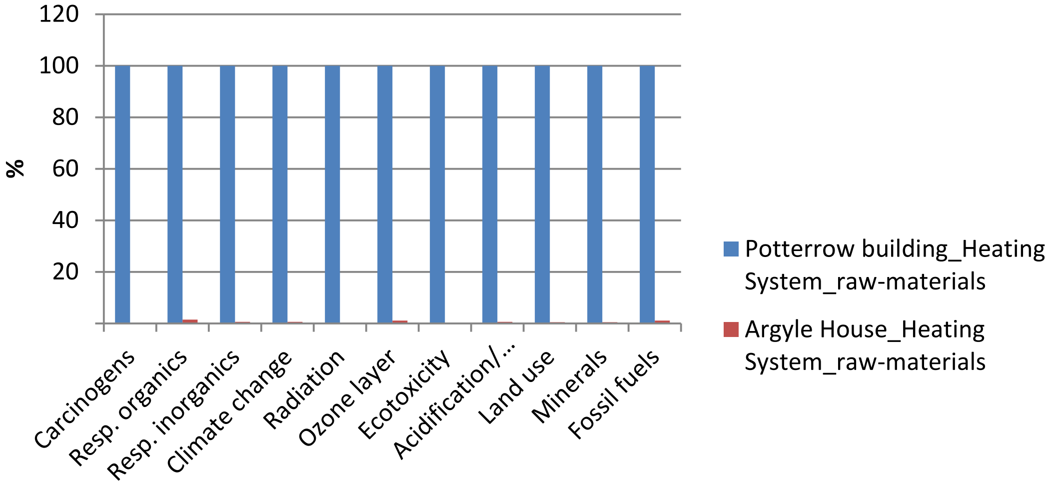
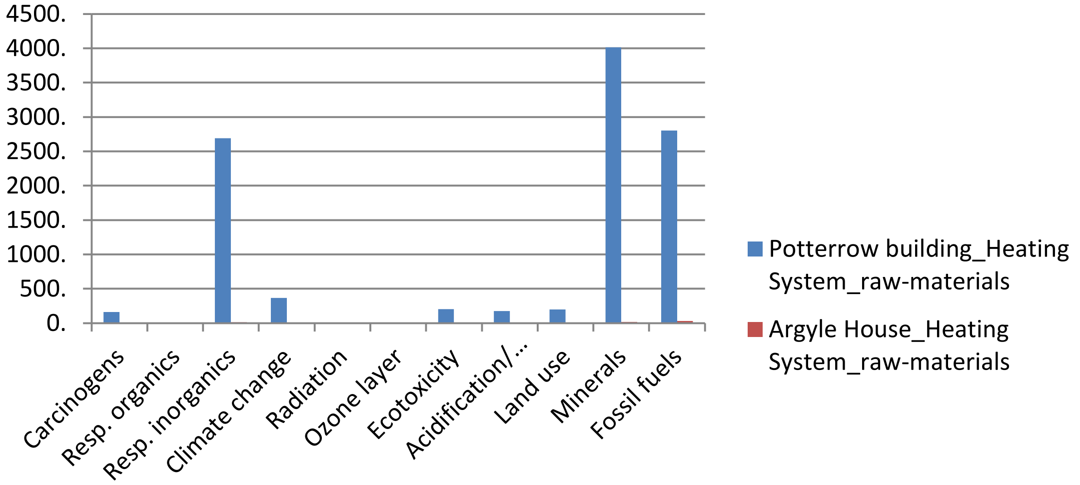


Analyzing 1 p 'Potterrow building_Cooling System_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

LCA comparison evaluation of the raw-materials of the heating system, case study 1



Comparing 1 p 'Potterrow building_Heating System_raw-materials' with 1 p 'Argyle House_Heating System_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



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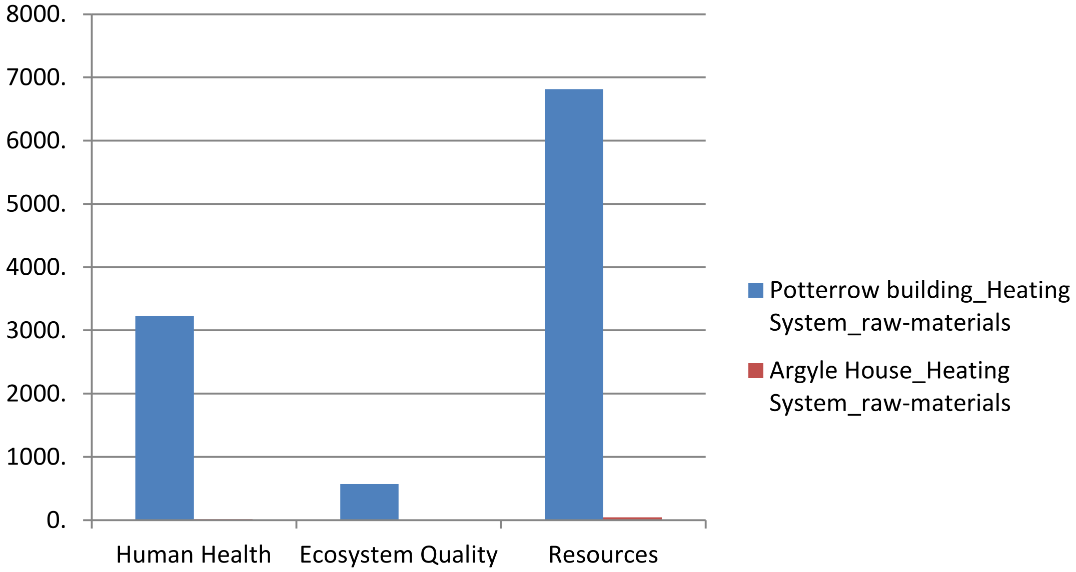

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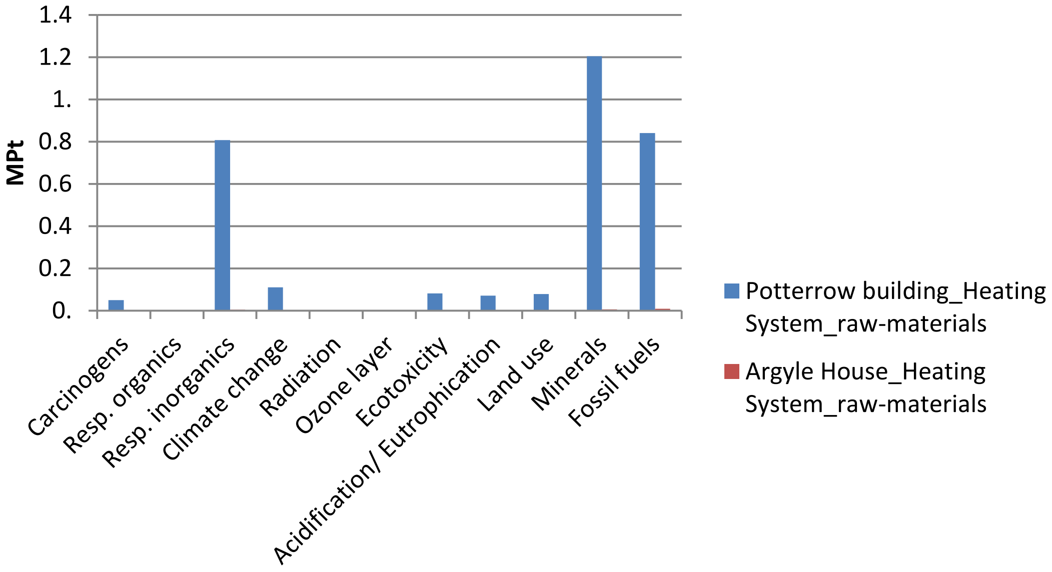
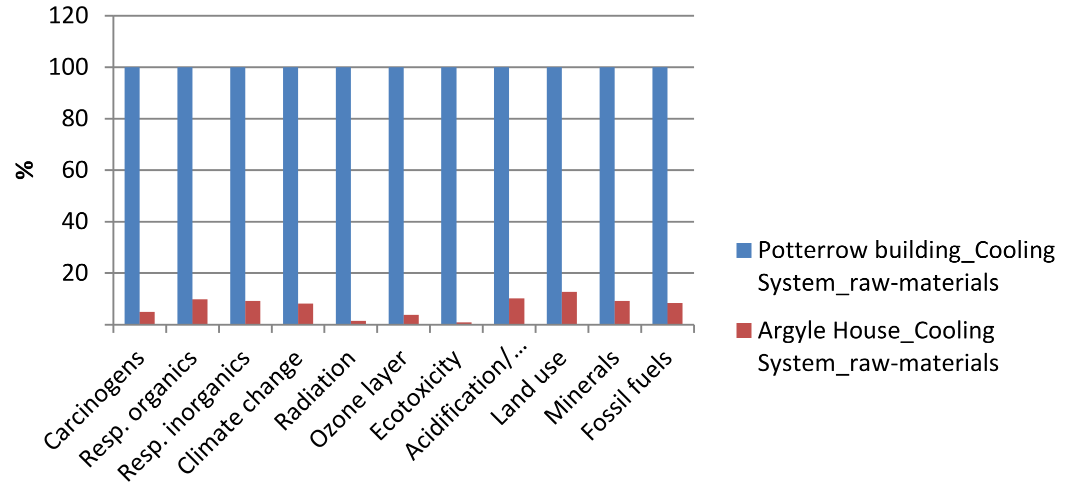


Comparing 1 p 'Potterrow building_Heating System_raw-materials' with 1 p 'Argyle House_Heating System_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

LCA comparison evaluation of the raw-materials of the cooling system, case study 1



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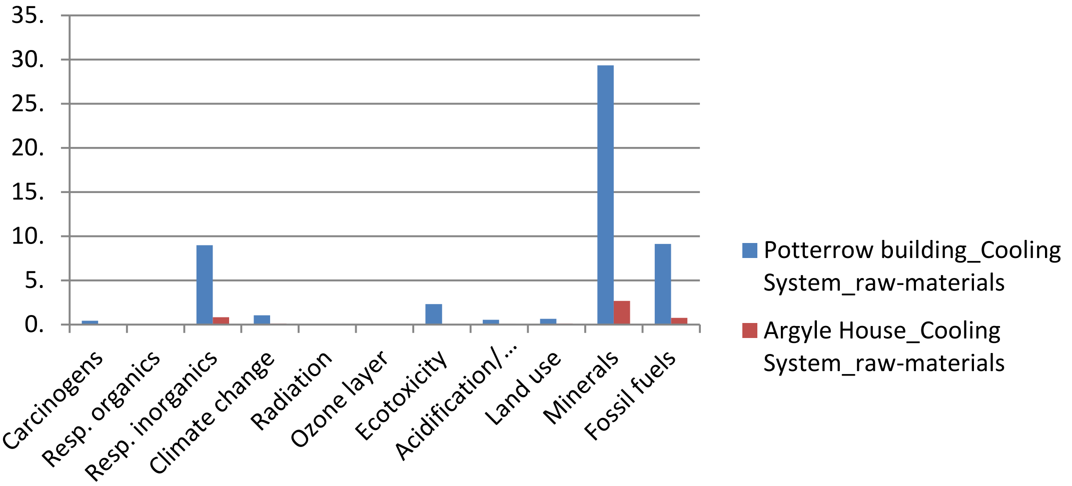
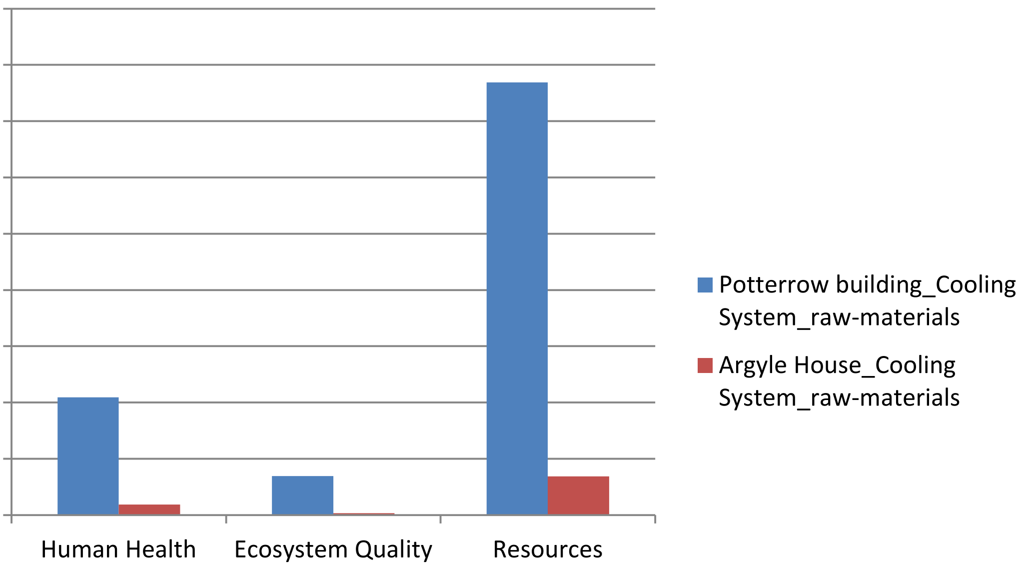


Comparing 1 p 'Potterrow building_Cooling System_raw-materials' with 1 p 'Argyle House_Cooling System_raw-materials'; Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



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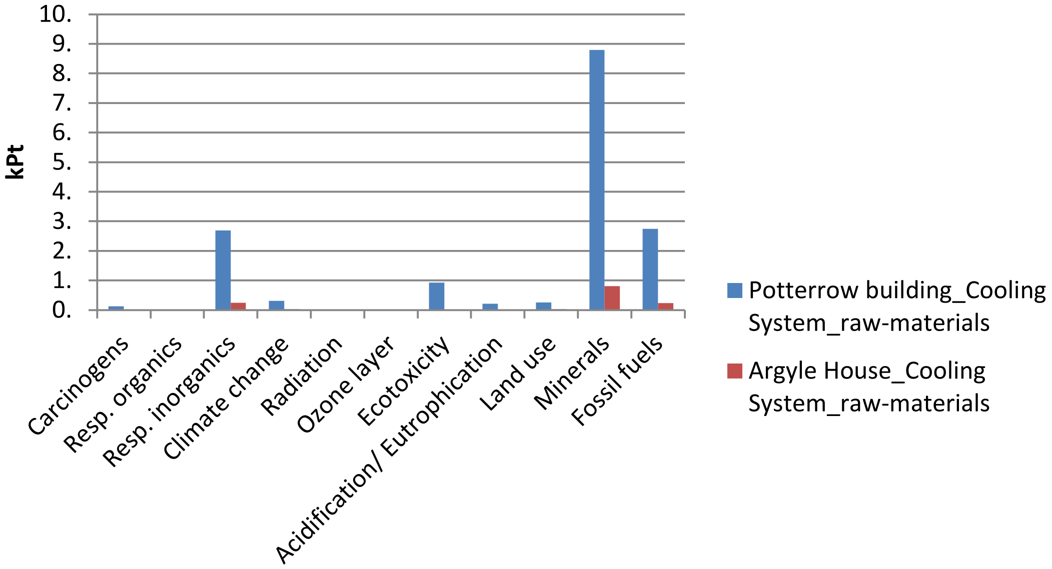

Comparing 1 p 'Potterrow building_Cooling System_raw-materials' with 1 p 'Argyle House_Cooling System_raw-materials';
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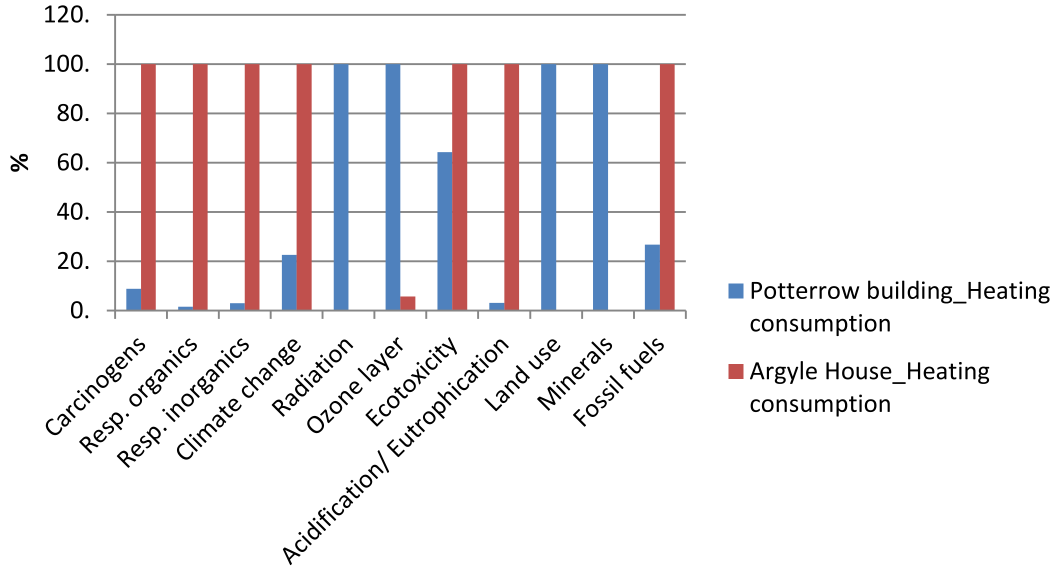
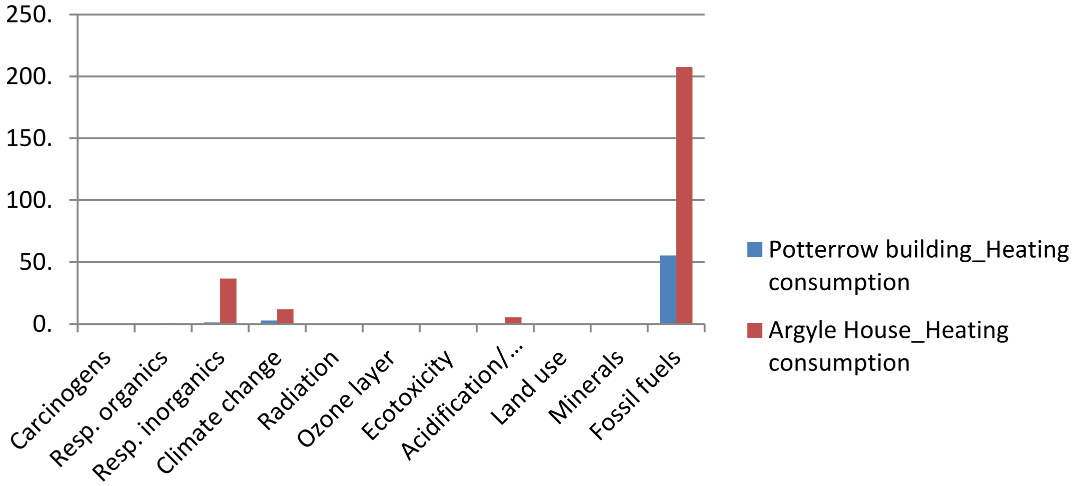
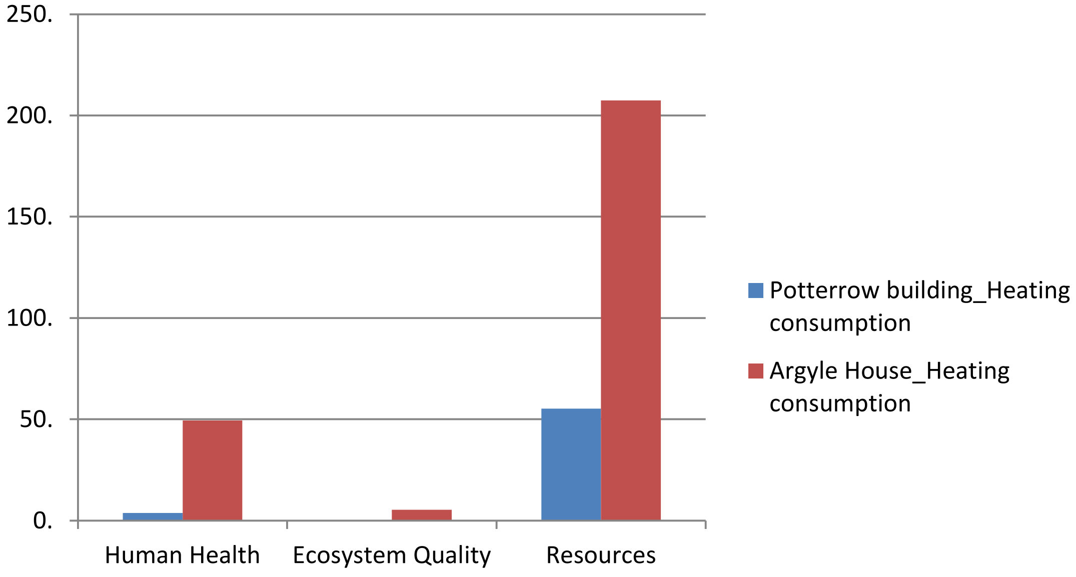
LCA comparison evaluation of the heating consumption, case study 1



Comparing 1 p 'Potterrow building_Heating consumption' with 1 p 'Argyle House_Heating consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Comparing 1 p 'Potterrow building_Heating consumption' with 1 p 'Argyle House_Heating consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



Comparing 1 p 'Potterrow building_Heating consumption' with 1 p 'Argyle House_Heating consumption';
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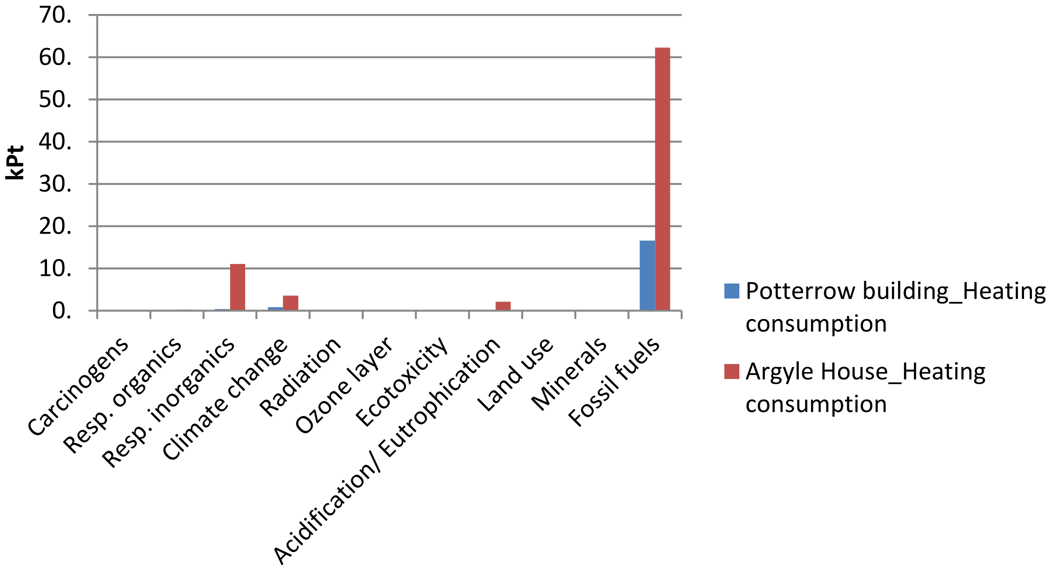
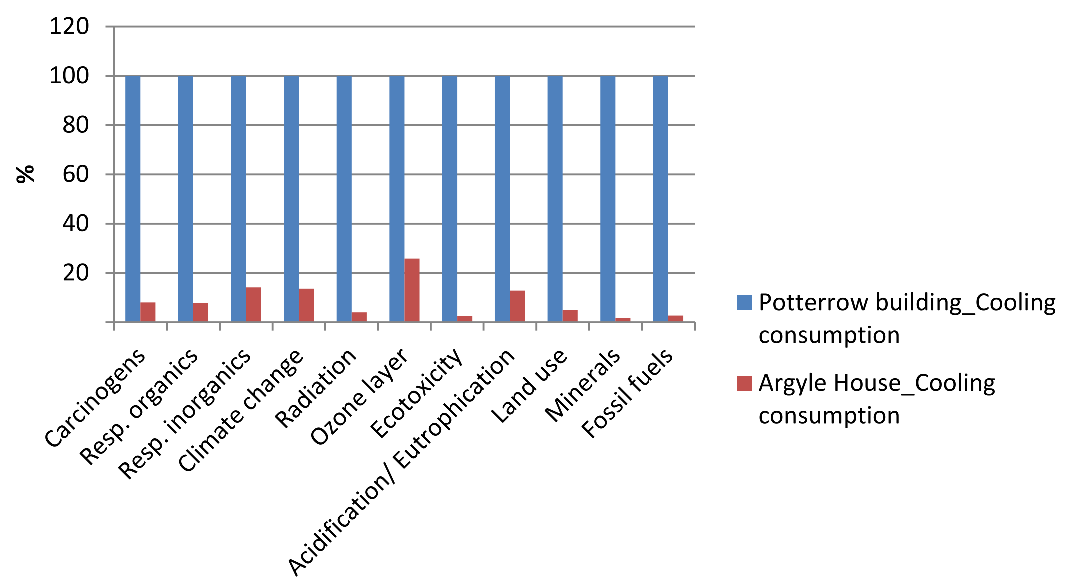
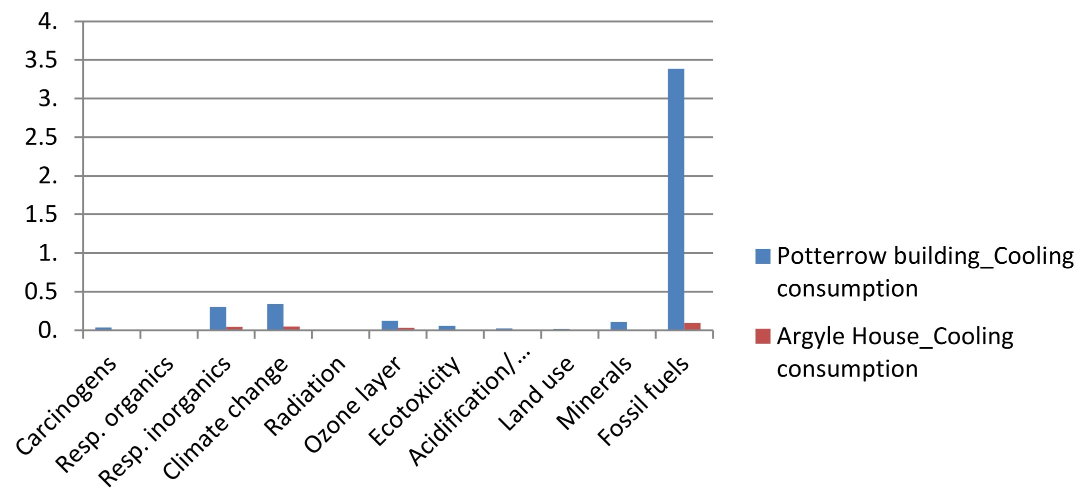


Comparing 1 p 'Potterrow building_Heating consumption' with 1 p 'Argyle House_Heating consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

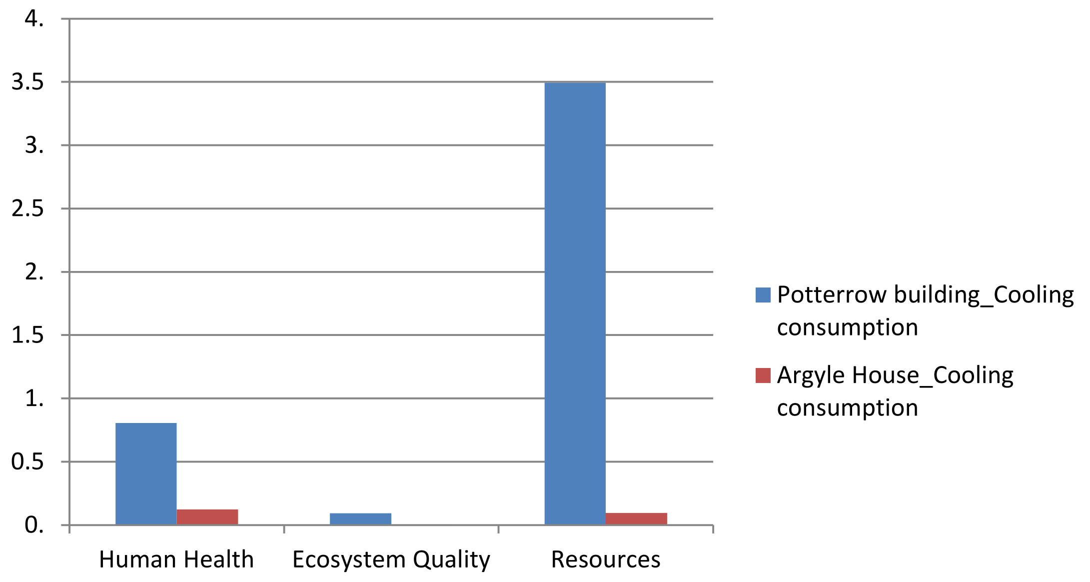
LCA comparison evaluation of the cooling consumption, case study 1



Comparing 1 p 'Potterrow building_Cooling consumption' with 1 p 'Argyle House_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Comparing 1 p 'Potterrow building_Cooling consumption' with 1 p 'Argyle House_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



Comparing 1 p 'Potterrow building_Cooling consumption' with 1 p 'Argyle House_Cooling consumption';
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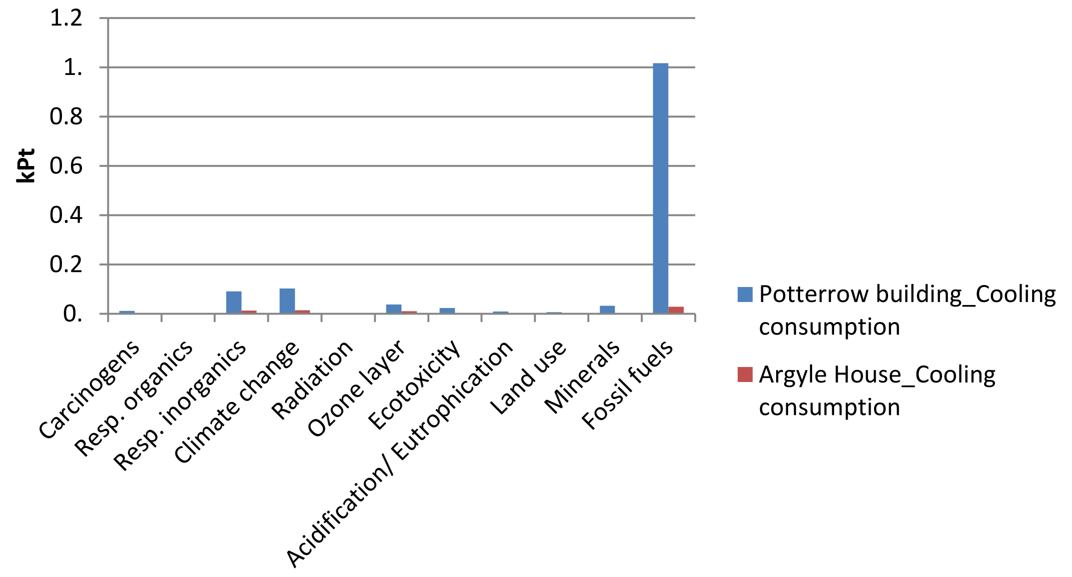
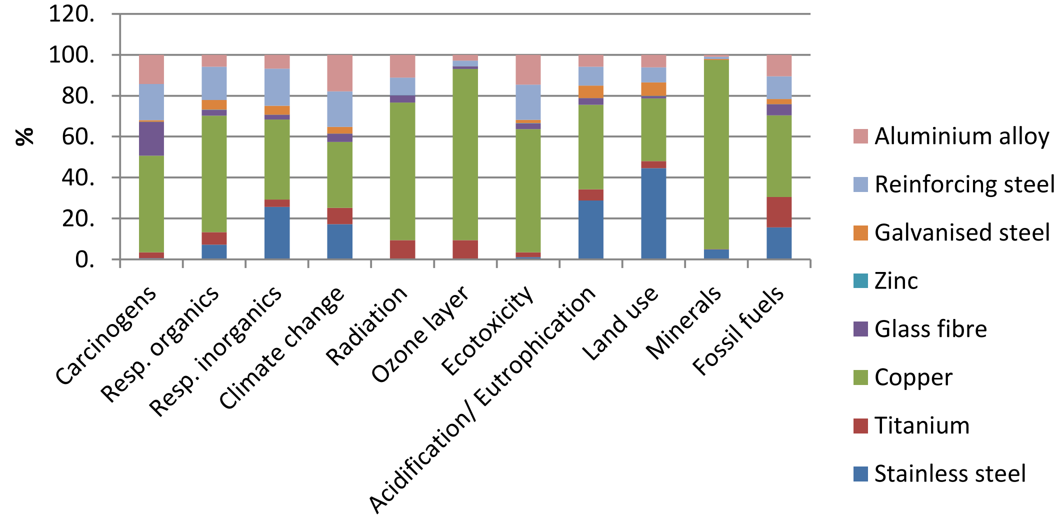
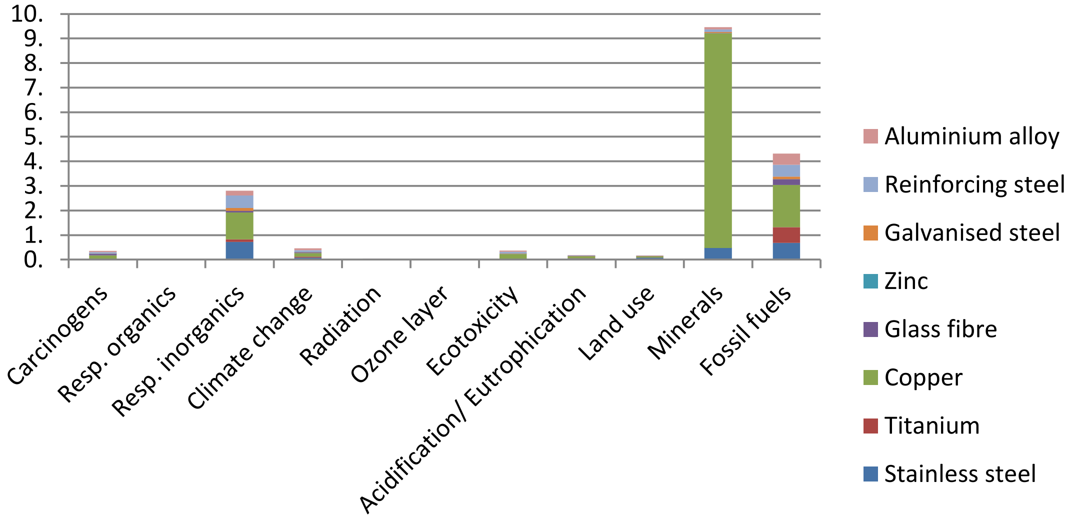


Comparing 1 p 'Potterrow building_Cooling consumption' with 1 p 'Argyle House_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

Raw-materials-heating system-Elizabeth Courts II



Analyzing 1 p 'Elizabeth Courts II_Heating system_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



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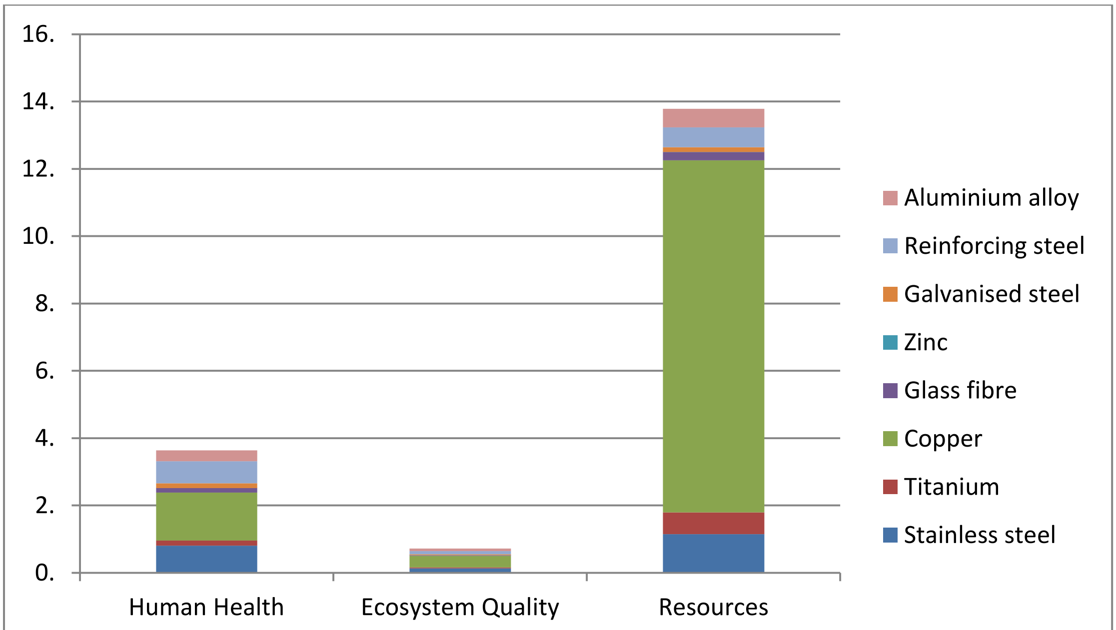

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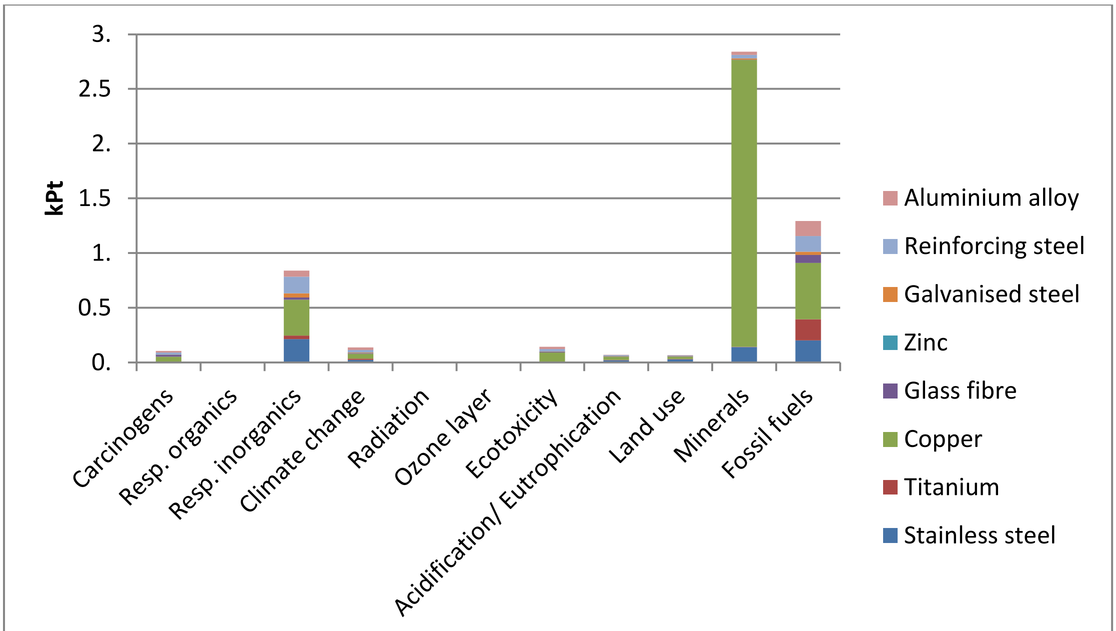
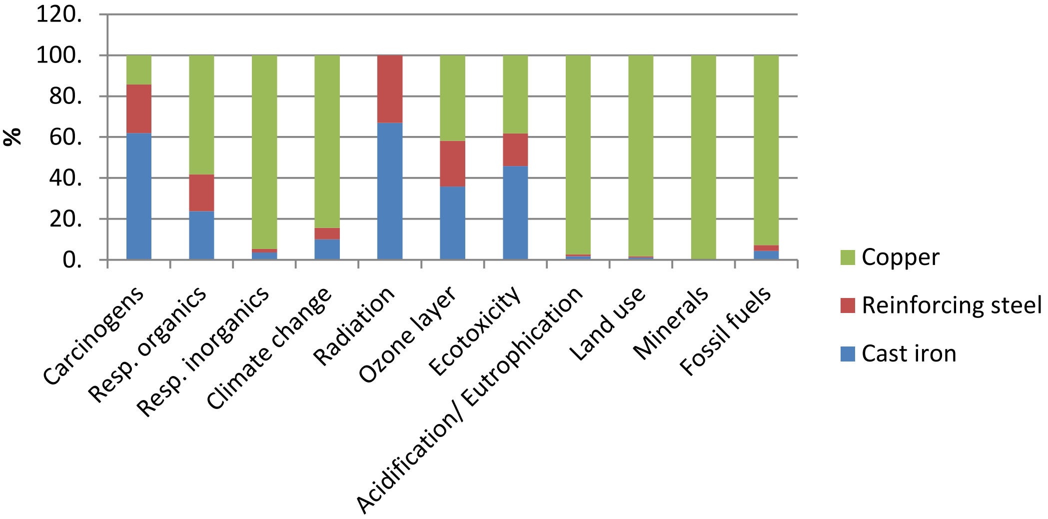


Analyzing 1 p 'Elizabeth Courts II_Heating system_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

Raw-materials-heating system-Five Ways House



Analyzing 1 p 'Five Ways House_Heating system_raw-materials';
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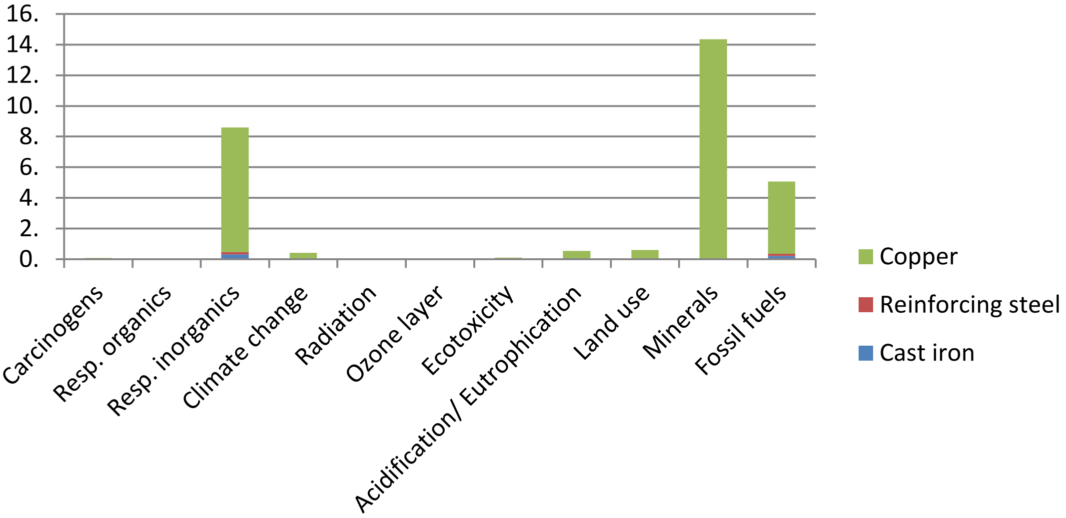

Analyzing 1 p 'Five Ways House_Heating system_raw-materials';
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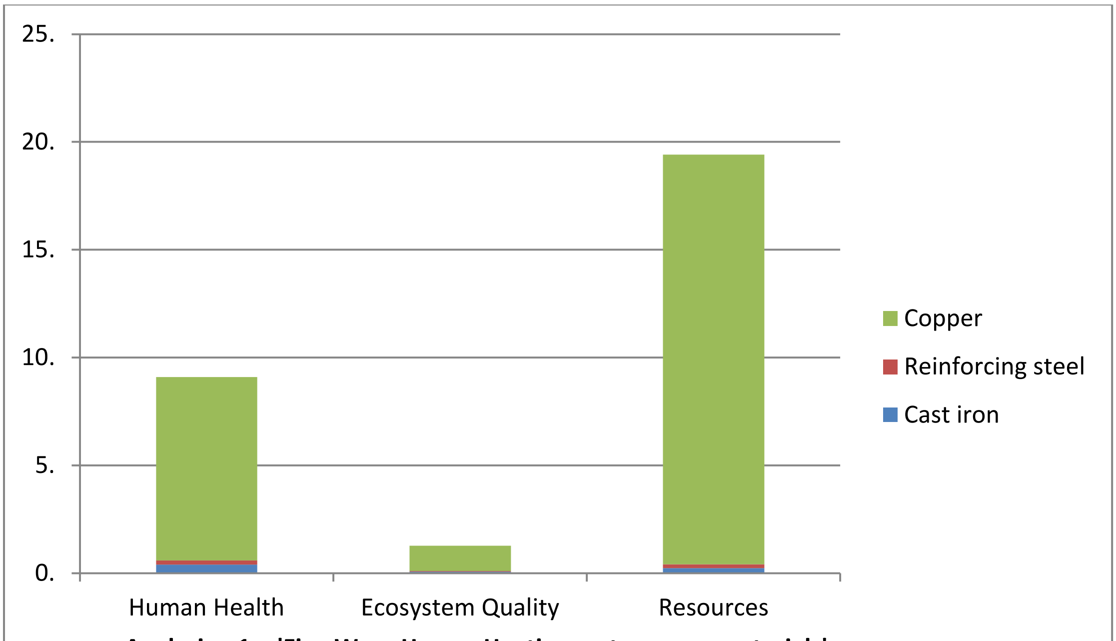

**Analyzing 1 p 'Five Ways House_Heating system_raw-materials';
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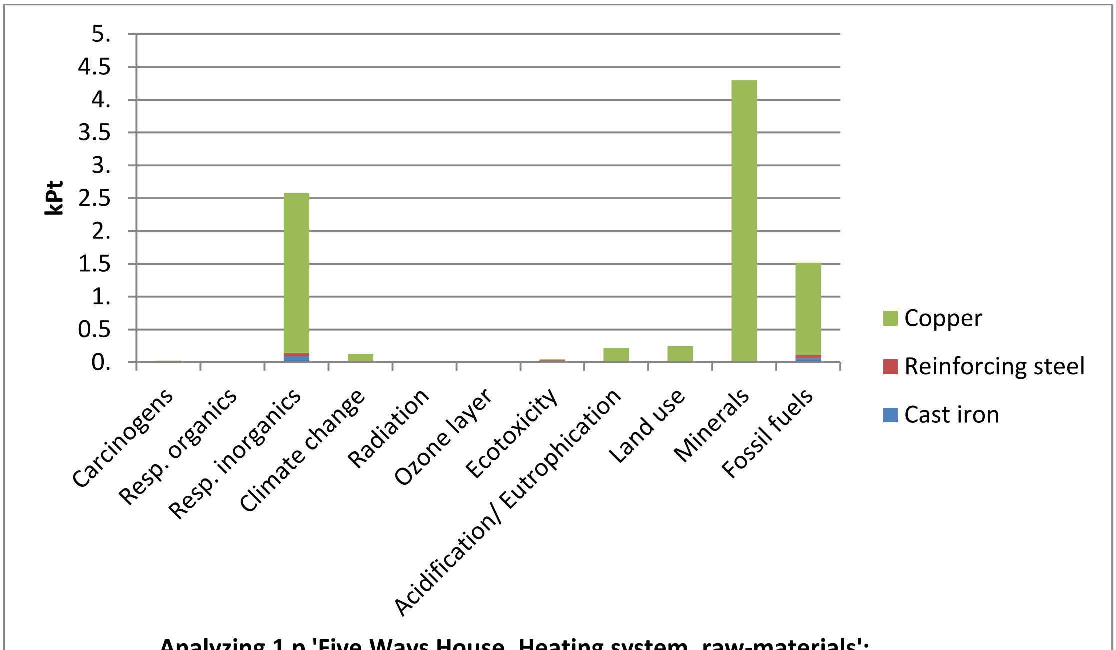
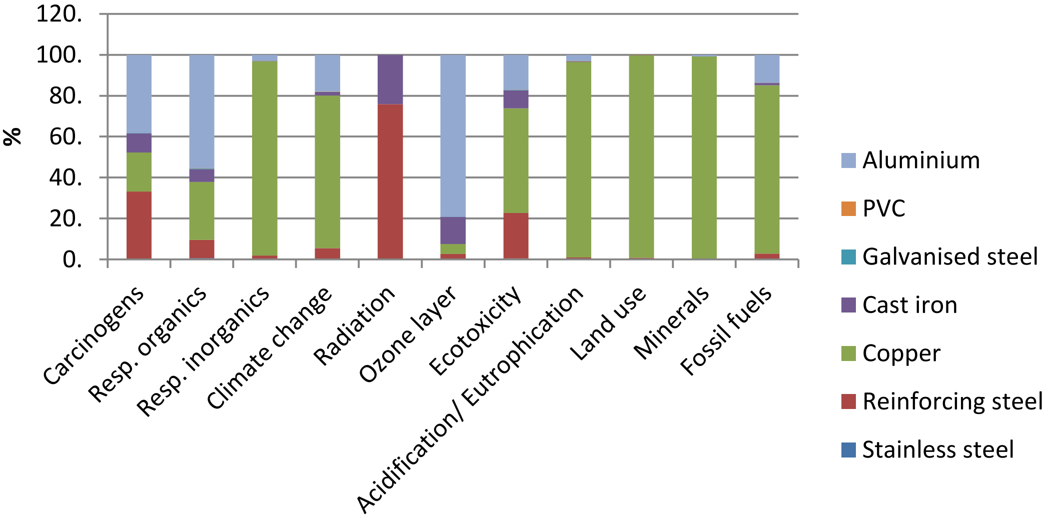


**Analyzing 1 p 'Five Ways House_Heating system_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting**

Raw-materials cooling system Elizabeth Courts



Analyzing 1 p 'Elizabeth Courts II_Cooling system_raw-materials';
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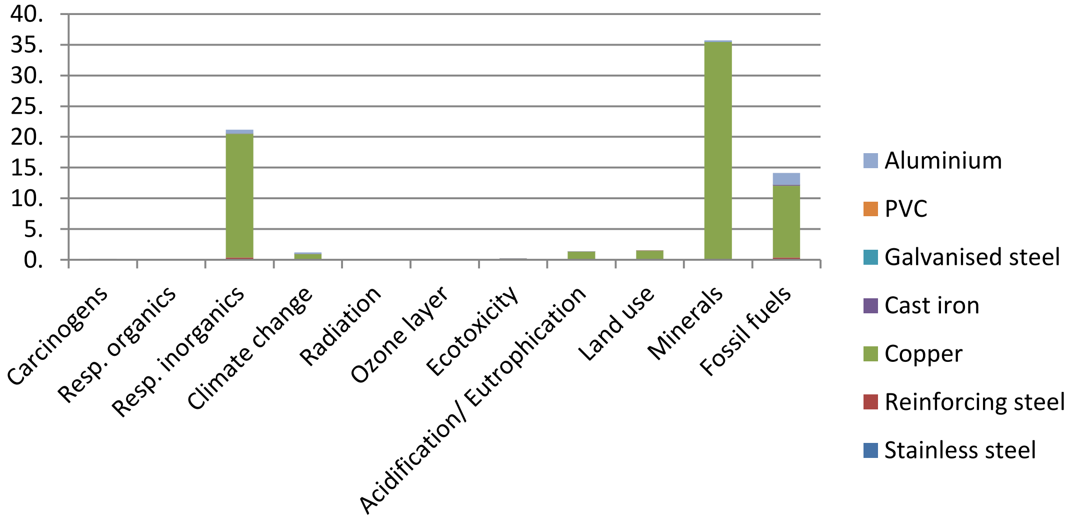

Analyzing 1 p 'Elizabeth Courts II_Cooling system_raw-materials';
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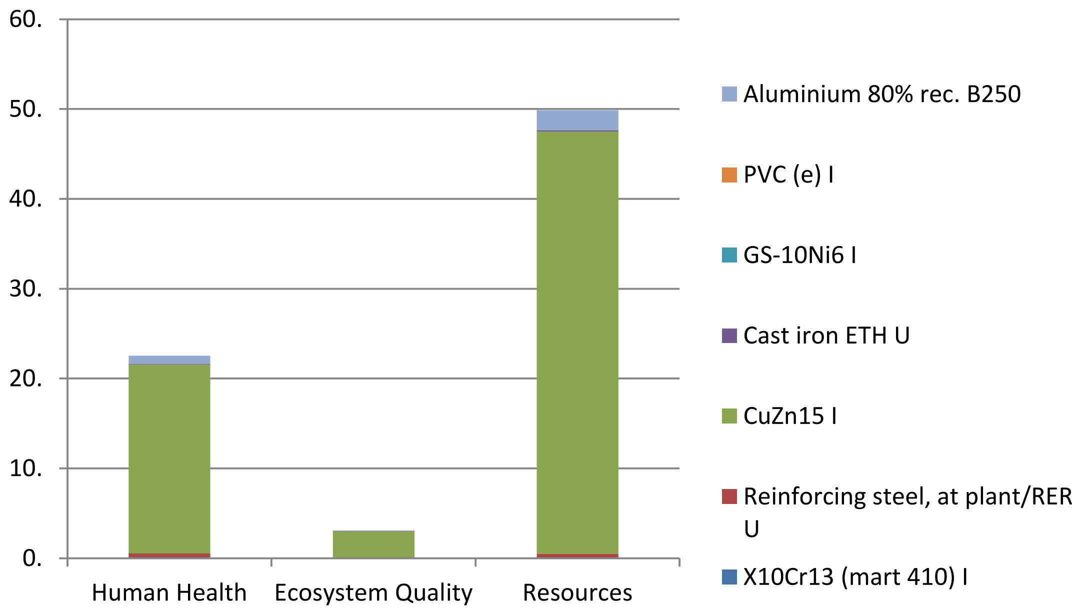

Analyzing 1 p 'Elizabeth Courts II_Cooling system_raw-materials';
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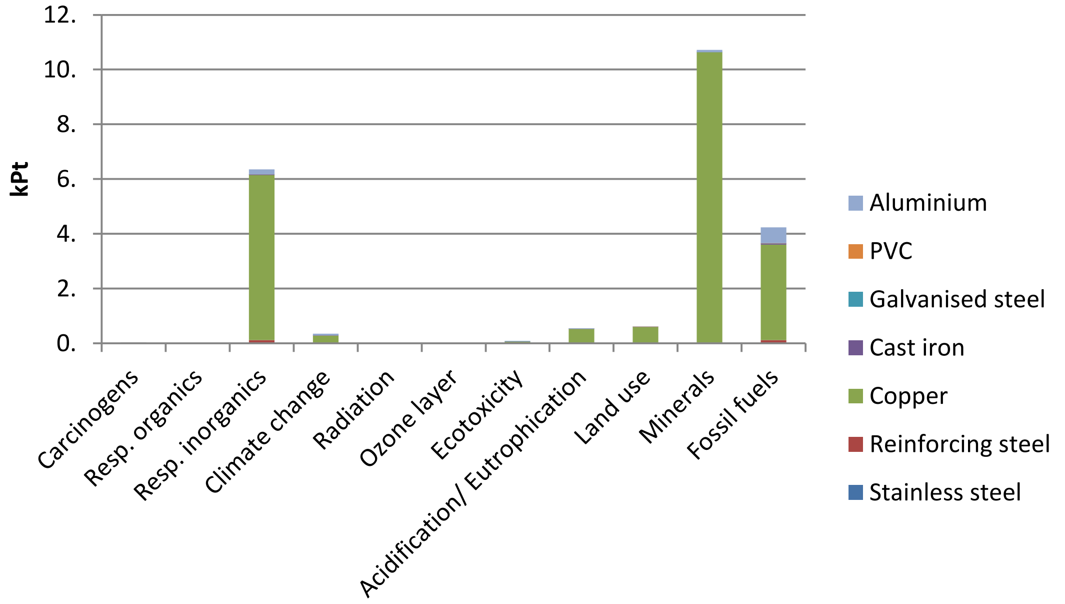

Analyzing 1 p 'Elizabeth Courts II_Cooling system_raw-materials';
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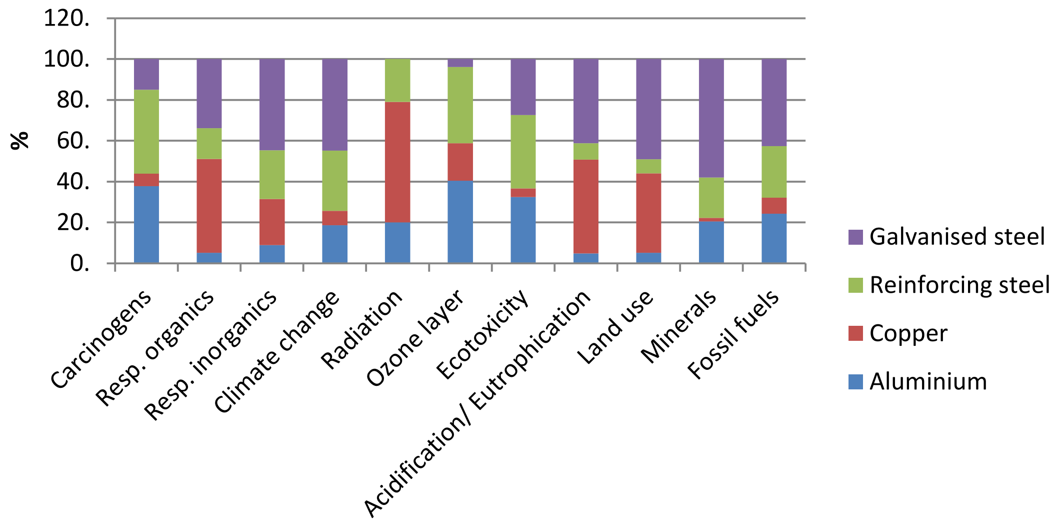
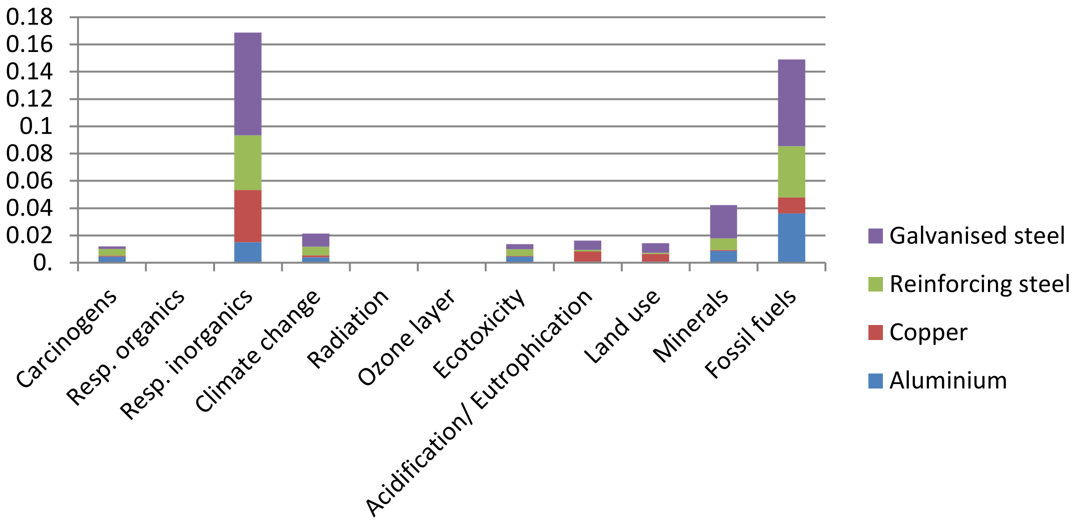
Raw-materials cooling system Five Ways House



Analyzing 1 p 'Five Ways House-raw-material-cooling system';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Analyzing 1 p 'Five Ways House-raw-material-cooling system';
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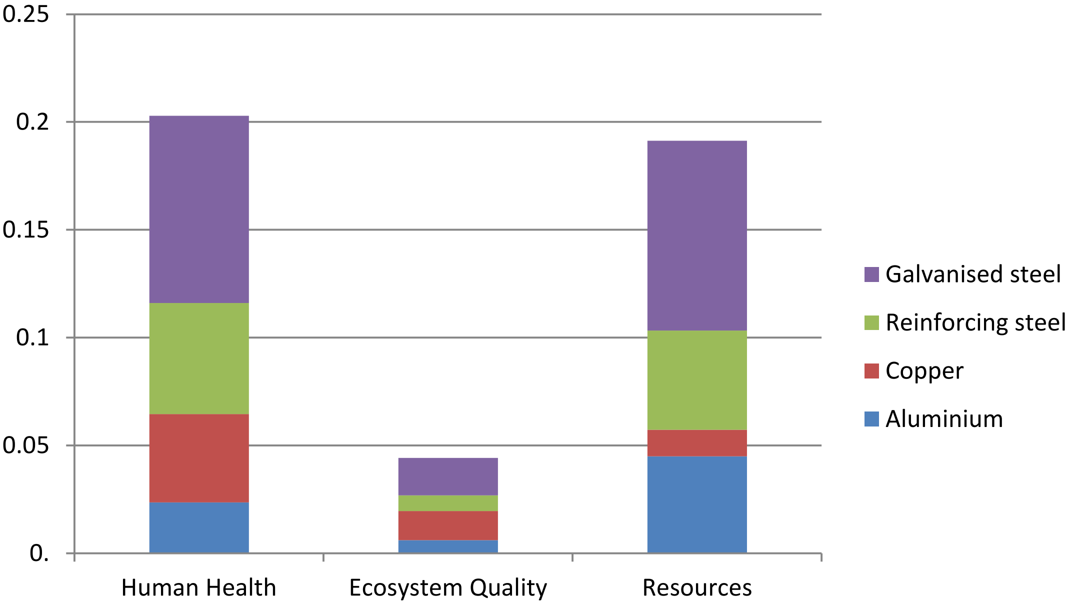

**Analyzing 1 p 'Five Ways House-raw-material-cooling system';
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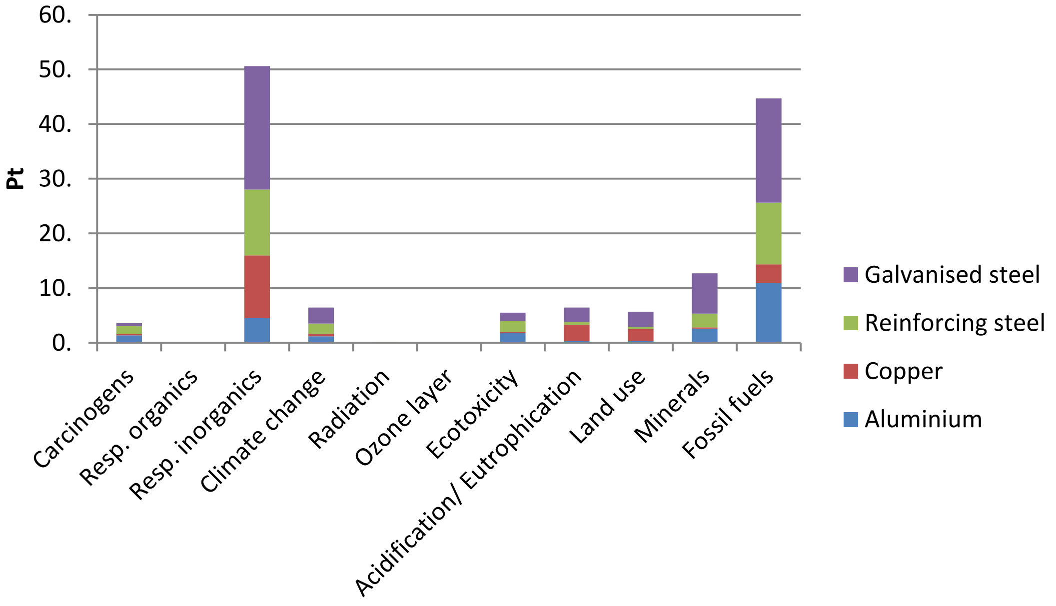
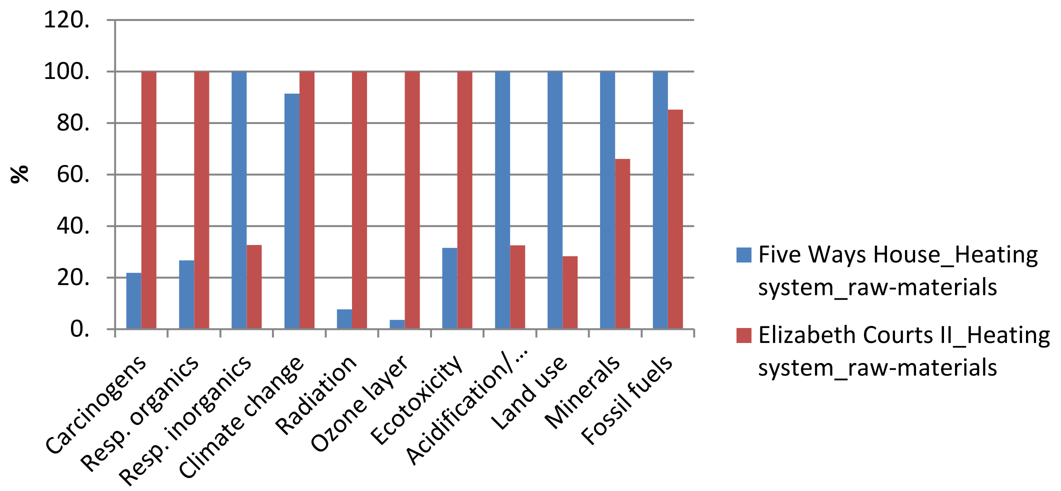
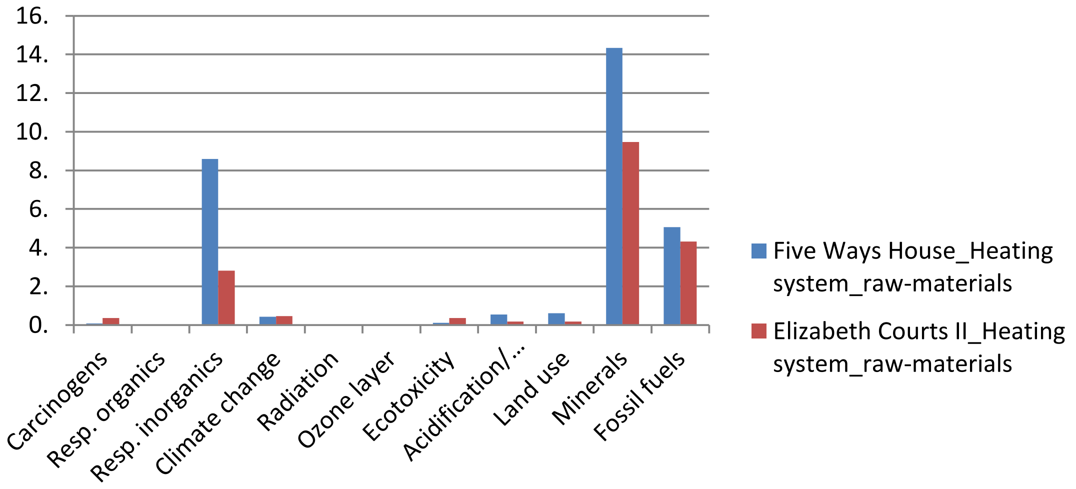


**Analyzing 1 p 'Five Ways House-raw-material-cooling system';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting**

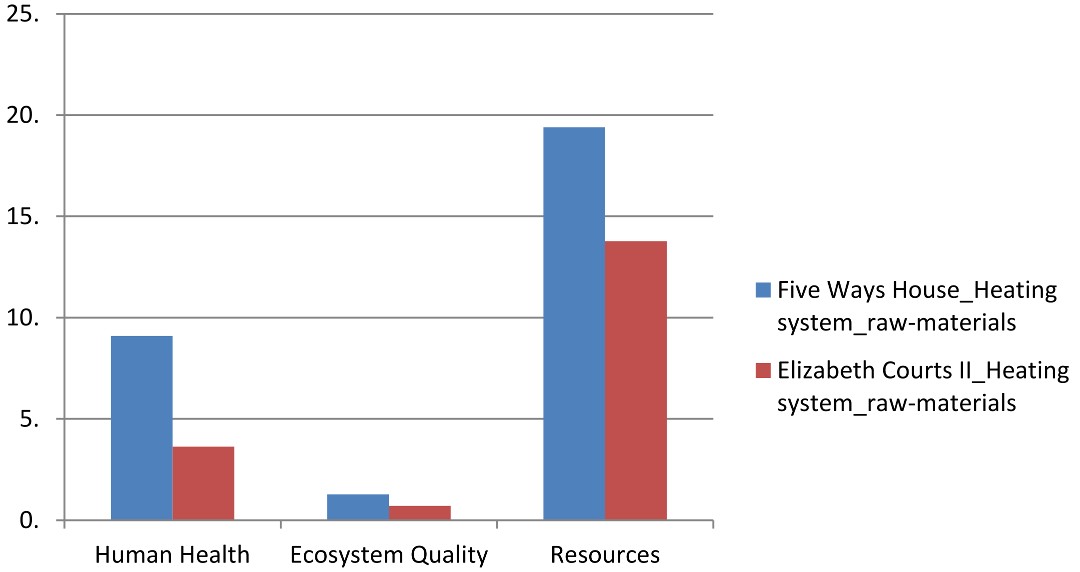
LCA comparison evaluation of the raw-materials of the heating system, case study 2



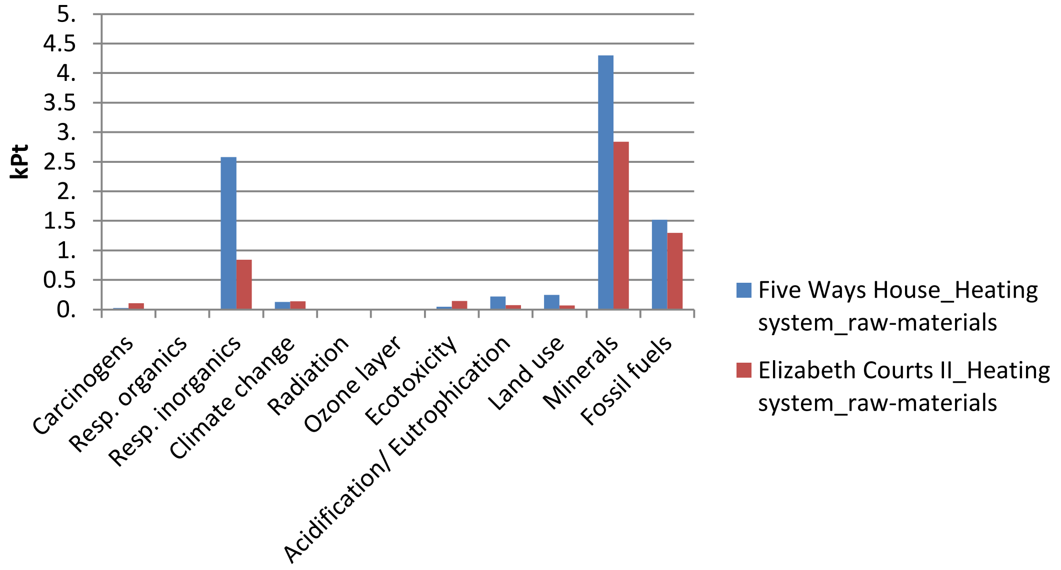
Comparing 1 p 'Five Ways House_Heating system_raw-materials' with 1 p 'Elizabeth Courts II_Heating system_raw-materials'; Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Comparing 1 p 'Five Ways House_Heating system_raw-materials' with 1 p 'Elizabeth Courts II_Heating system_raw-materials'; Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



Comparing 1 p 'Five Ways House_Heating system_raw-materials' with 1 p 'Elizabeth Courts II_Heating system_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



Comparing 1 p 'Five Ways House_Heating system_raw-materials' with 1 p 'Elizabeth Courts II_Heating system_raw-materials';
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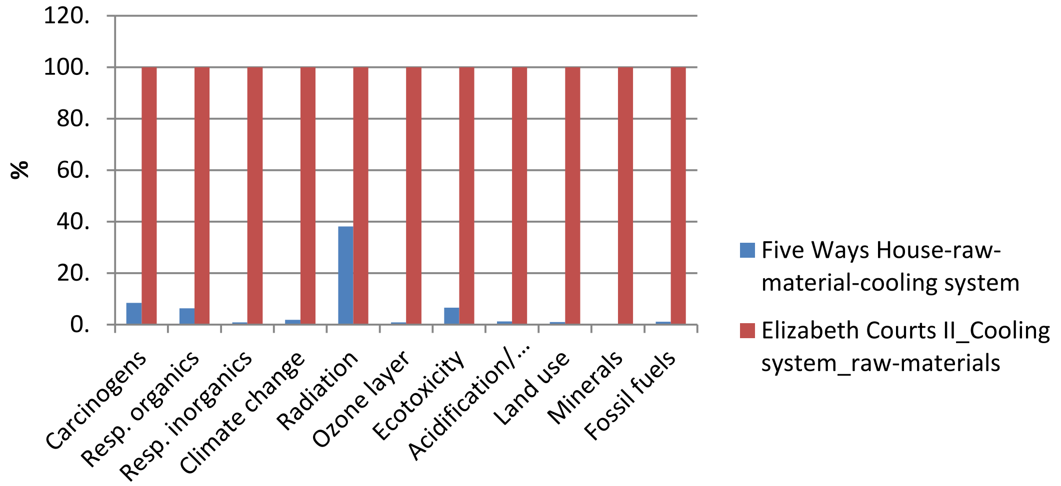
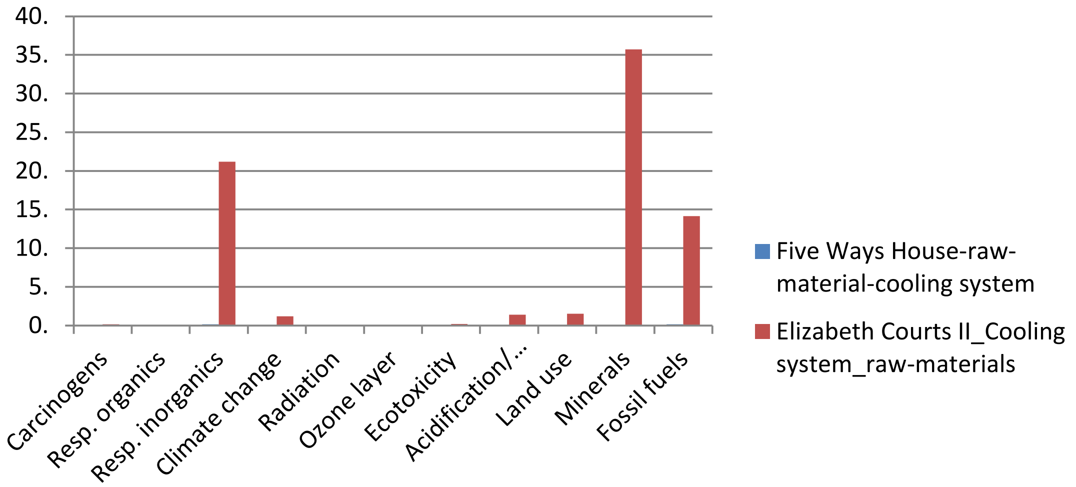
LCA comparison evaluation of the raw-materials of the cooling system, case study 2



Comparing 1 p 'Five Ways House-raw-material-cooling system' with 1 p 'Elizabeth Courts II_Cooling system_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Comparing 1 p 'Five Ways House-raw-material-cooling system' with 1 p 'Elizabeth Courts II_Cooling system_raw-materials';
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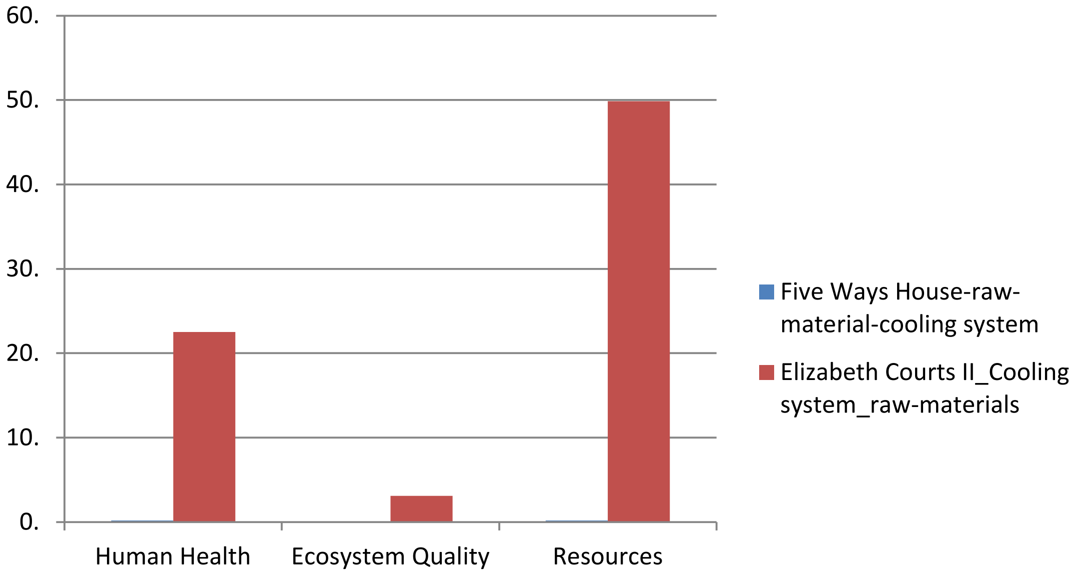
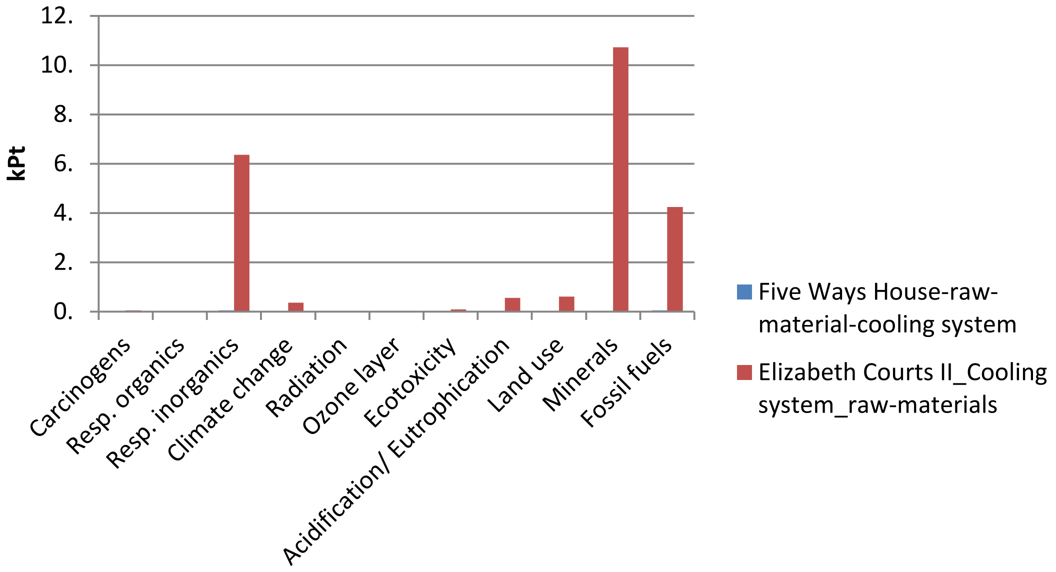
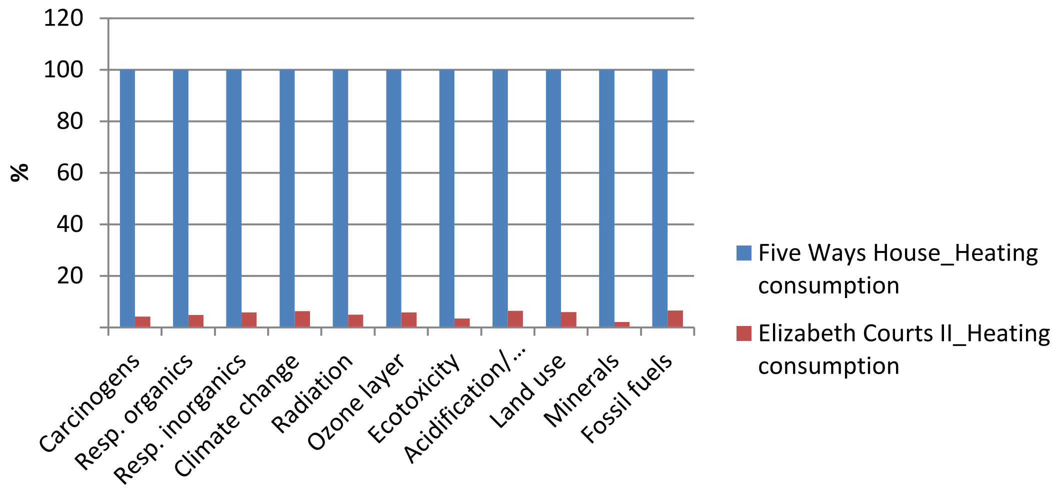


Comparing 1 p 'Five Ways House-raw-material-cooling system' with 1 p 'Elizabeth Courts II_Cooling system_raw-materials'; Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization

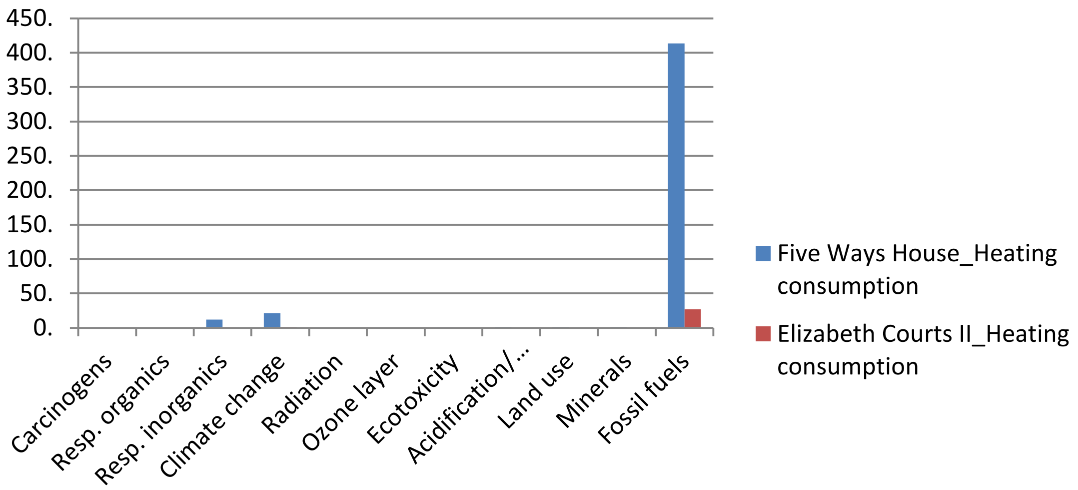


Comparing 1 p 'Five Ways House-raw-material-cooling system' with 1 p 'Elizabeth Courts II_Cooling system_raw-materials'; Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

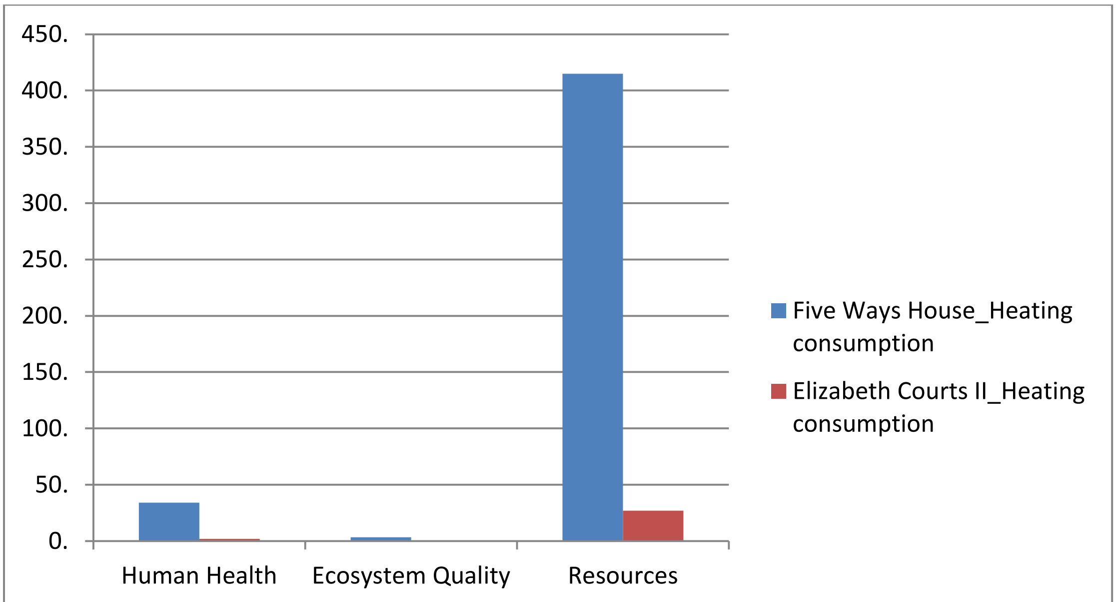
LCA comparison evaluation heating consumption, case study 2



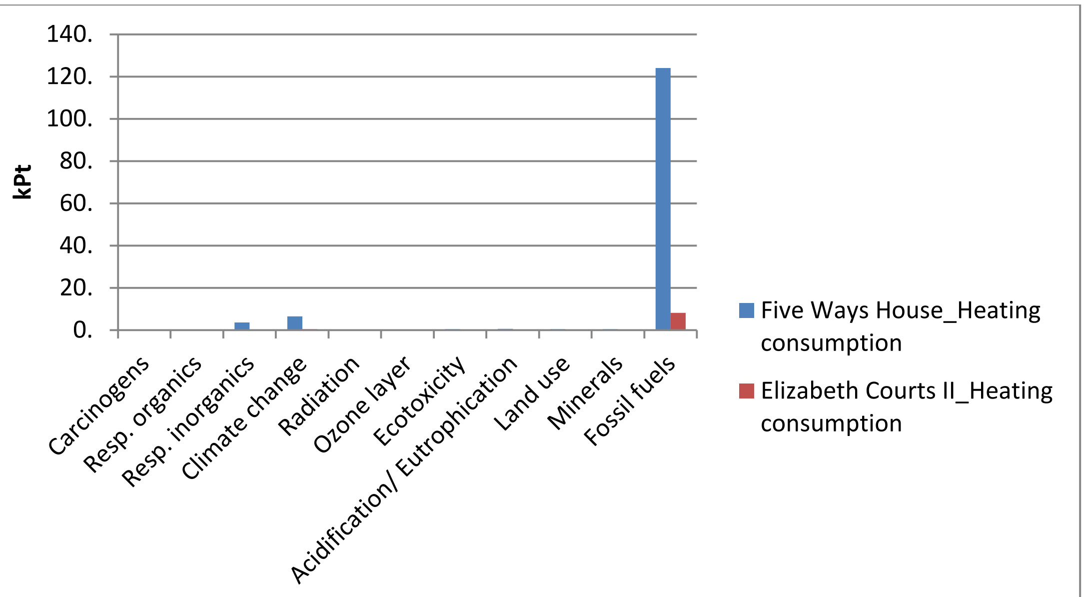
Comparing 1 p 'Five Ways House_Heating consumption' with 1 p 'Elizabeth Courts II_Heating consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Comparing 1 p 'Five Ways House_Heating consumption' with 1 p 'Elizabeth Courts II_Heating consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



Comparing 1 p 'Five Ways House_Heating consumption' with 1 p 'Elizabeth Courts II_Heating consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization



Comparing 1 p 'Five Ways House_Heating consumption' with 1 p 'Elizabeth Courts II_Heating consumption';
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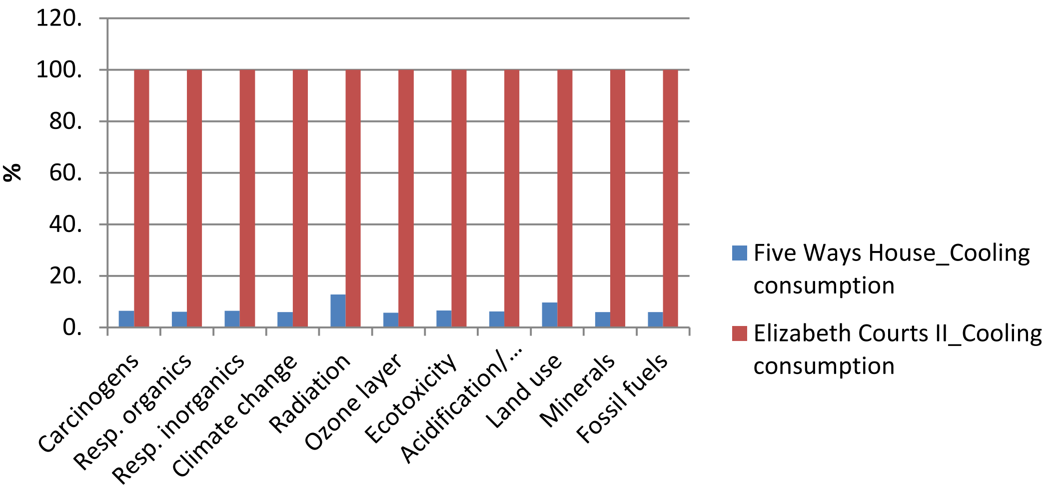
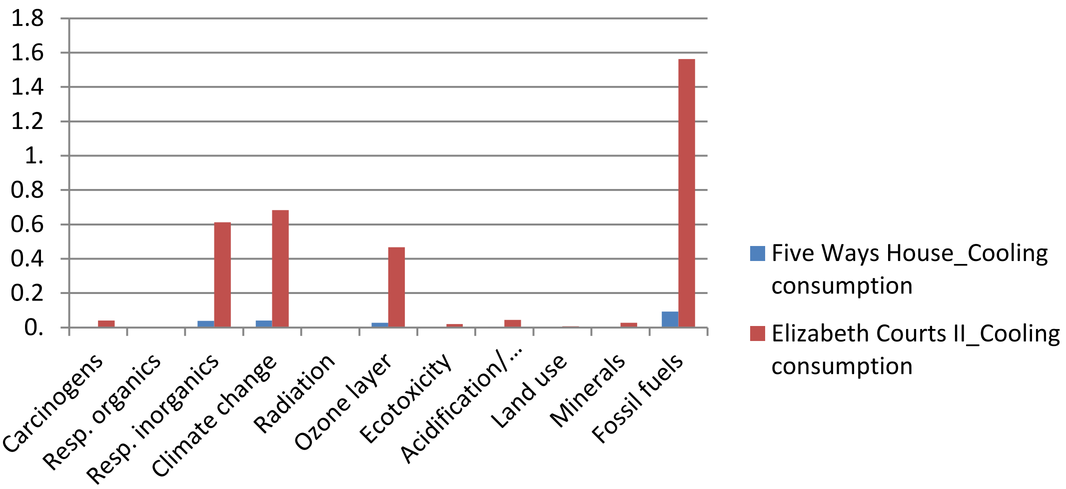
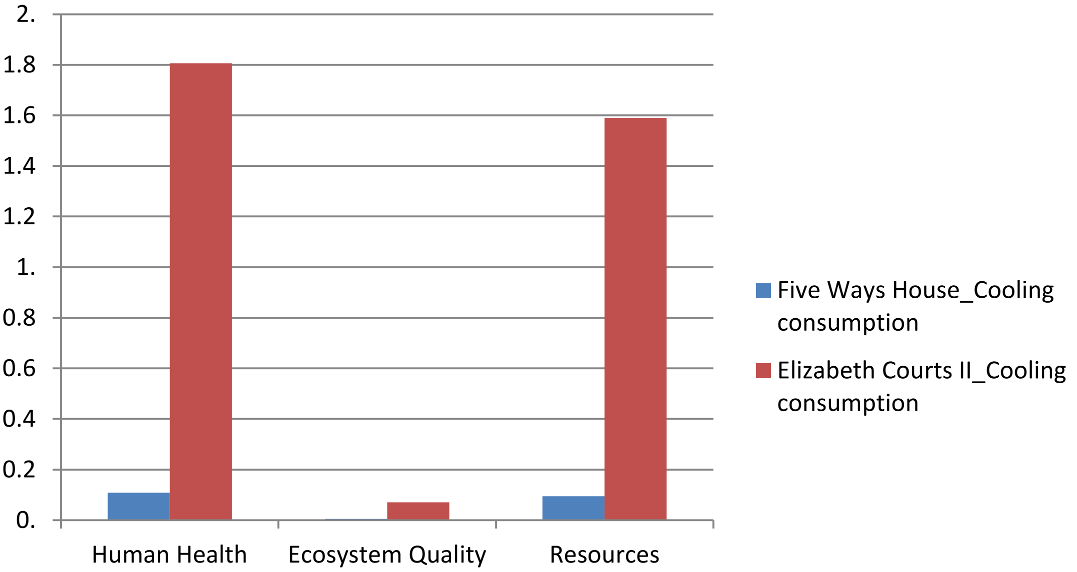
LCA comparison evaluation cooling consumption, case study 2



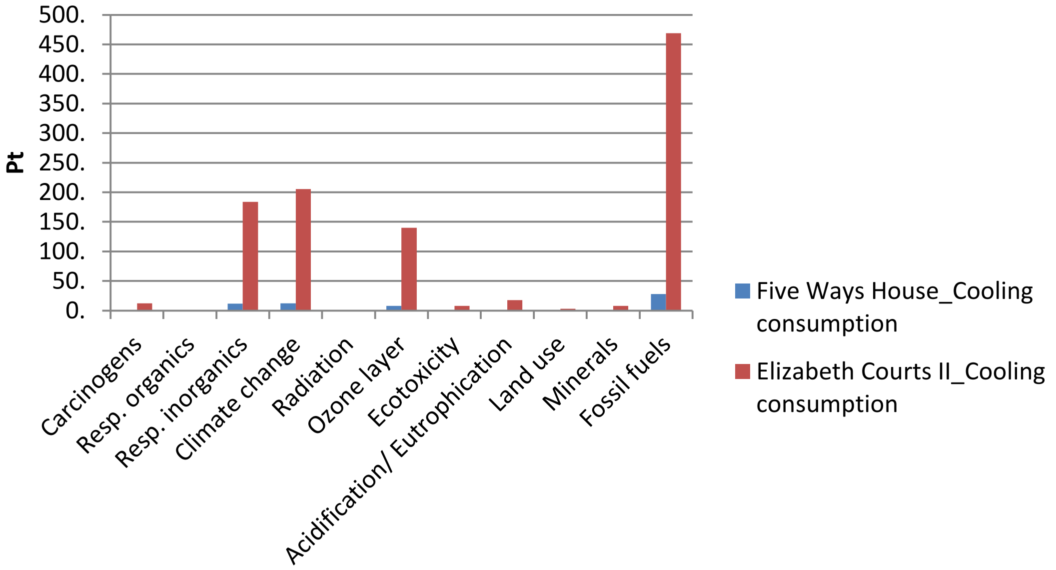
Comparing 1 p 'Five Ways House_Cooling consumption' with 1 p 'Elizabeth Courts II_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



Comparing 1 p 'Five Ways House_Cooling consumption' with 1 p 'Elizabeth Courts II_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization

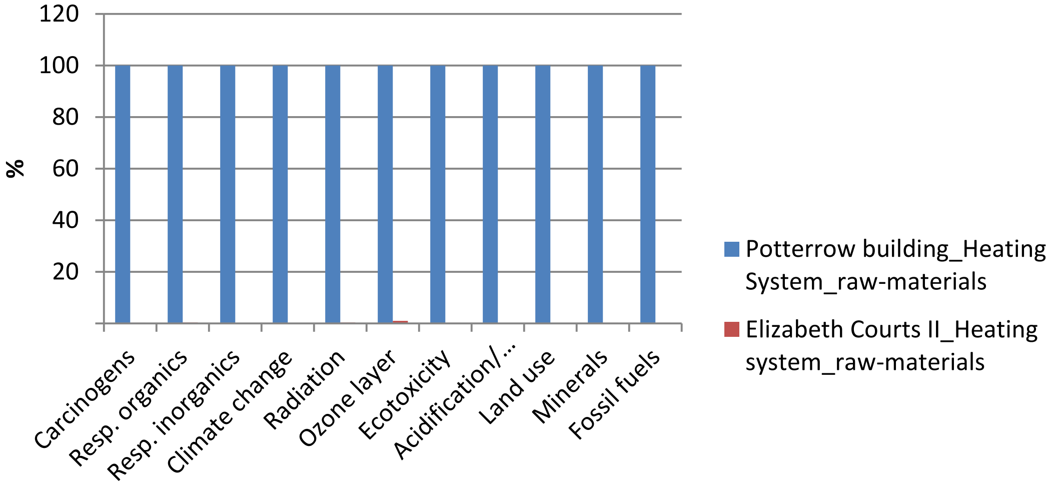


Comparing 1 p 'Five Ways House_Cooling consumption' with 1 p 'Elizabeth Courts II_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Normalization

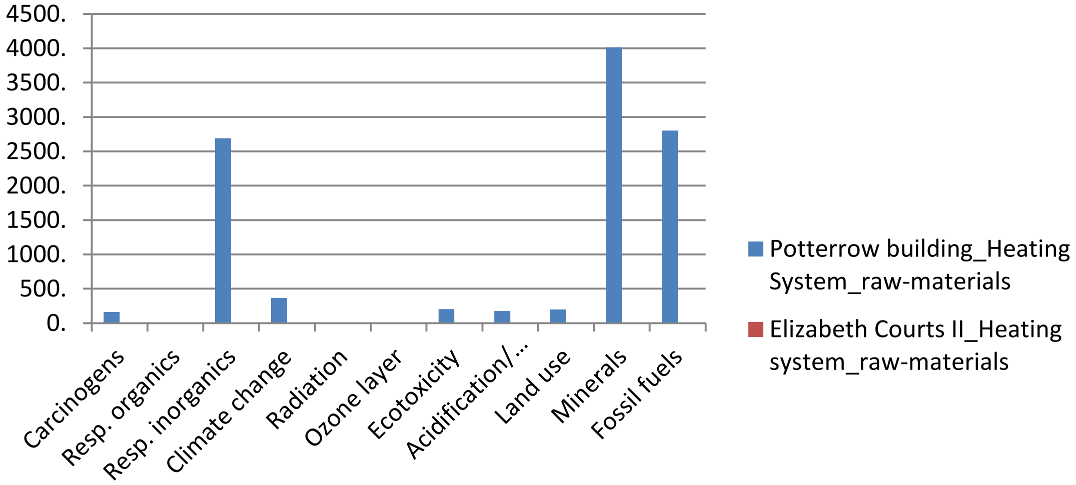


Comparing 1 p 'Five Ways House_Cooling consumption' with 1 p 'Elizabeth Courts II_Cooling consumption';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Weighting

LCA comparison evaluation between the sustainable office case study buildings



Comparing 1 p 'Potterrow building_Heating System_raw-materials' with 1 p 'Elizabeth Courts II_Heating system_raw-materials';
Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



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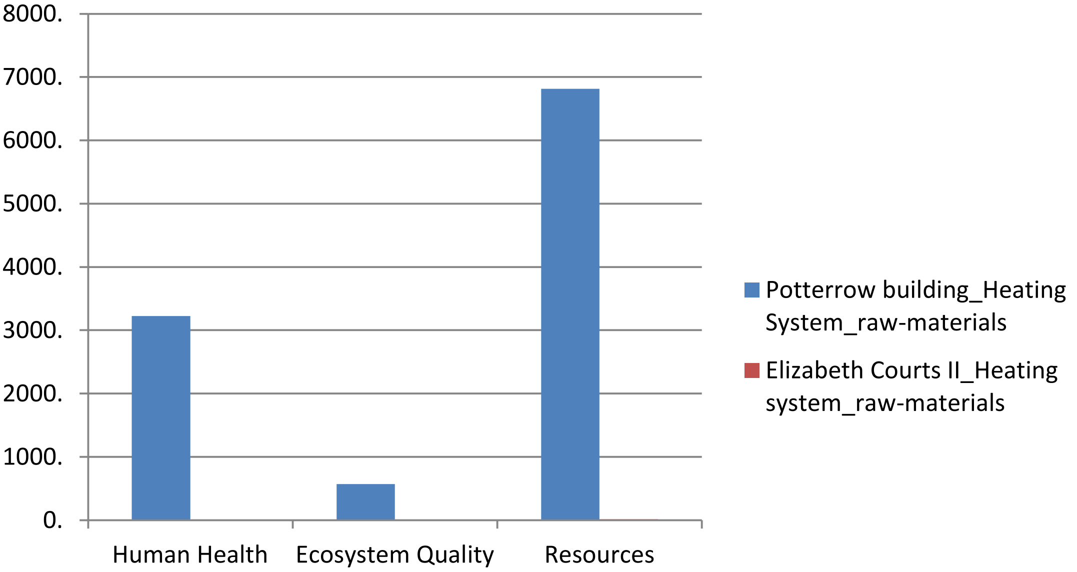

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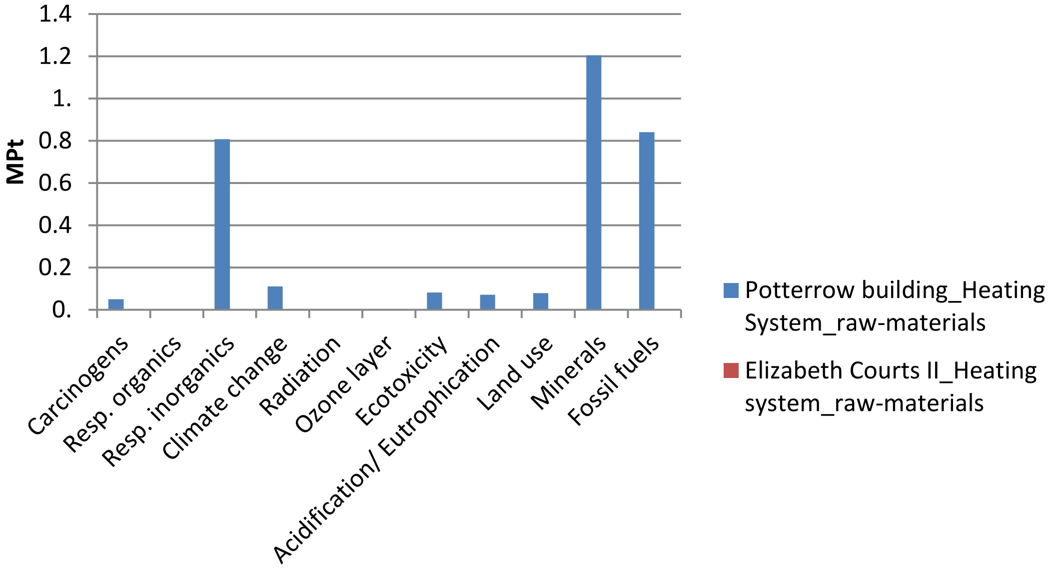

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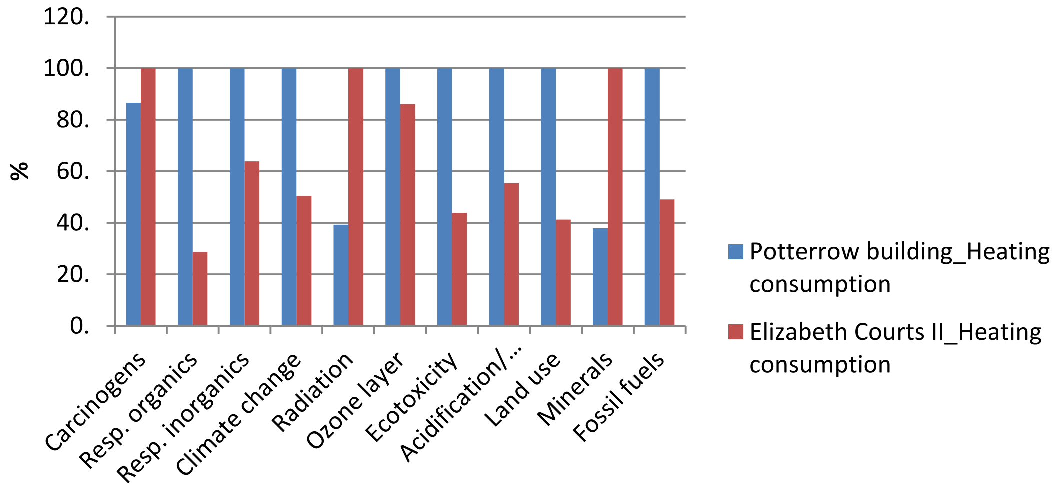

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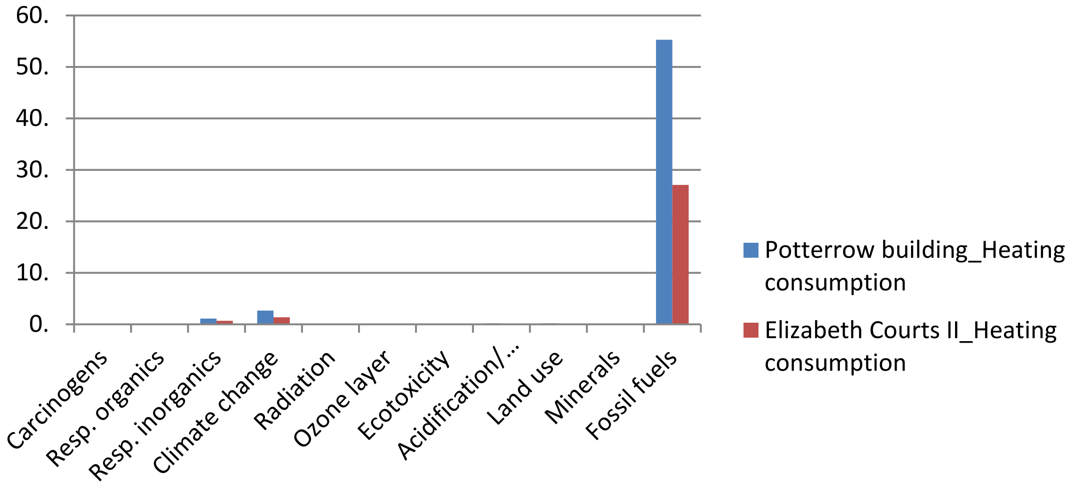

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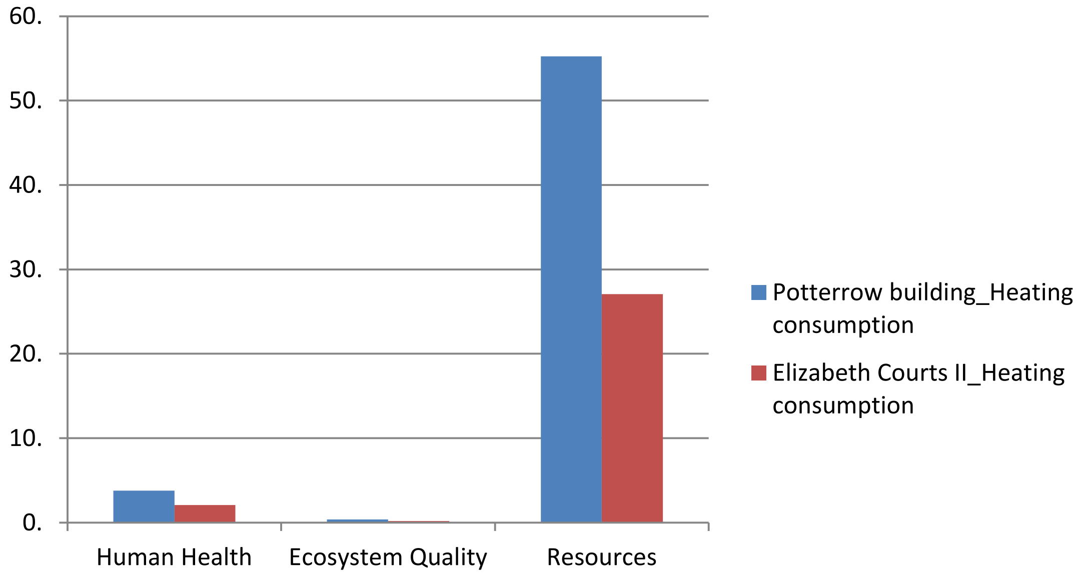

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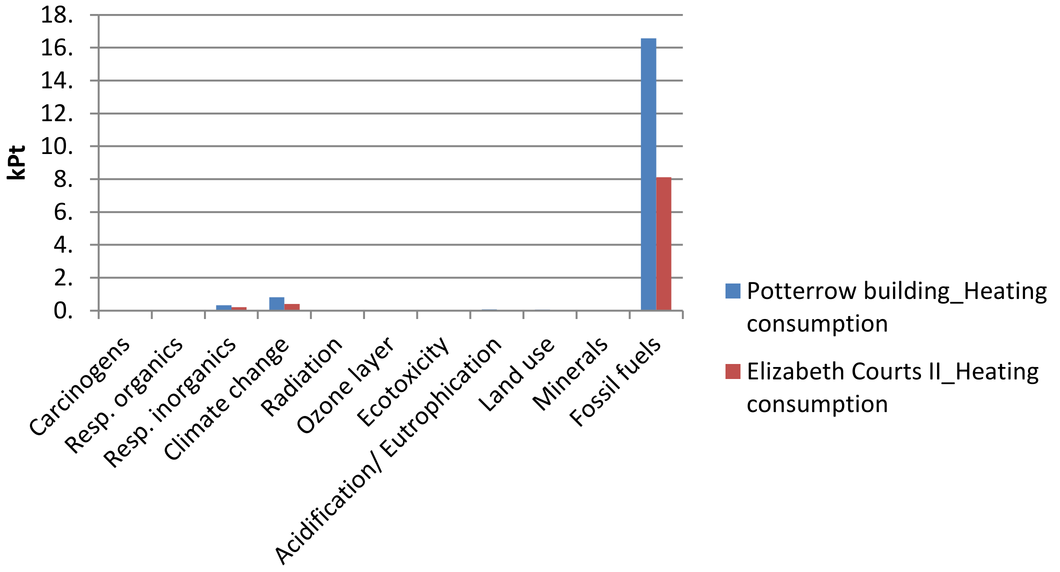

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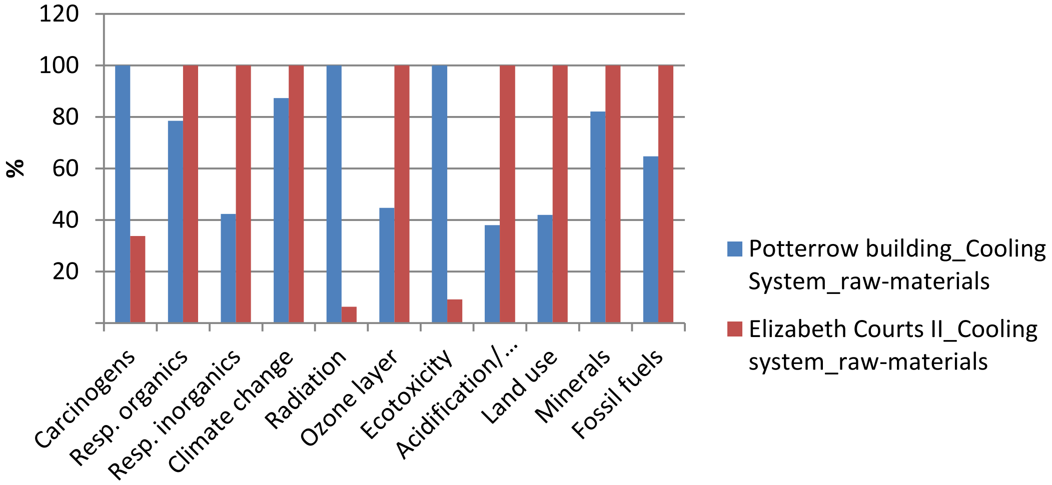
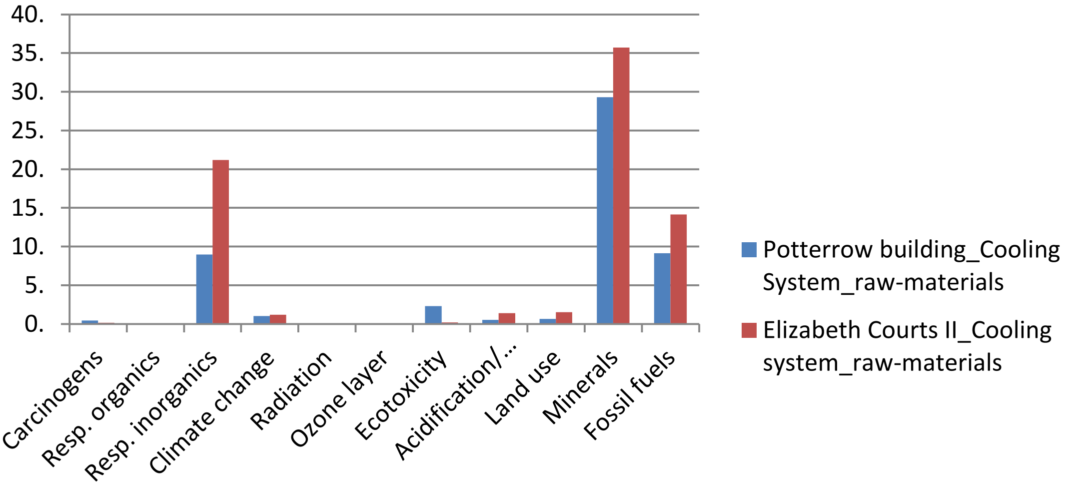


Comparing 1 p 'Potterrow building_Cooling System_raw-materials' with 1 p 'Elizabeth Courts II_Cooling system_raw-materials'; Method: Eco-indicator 99 (H) V2.06 / Europe EI 99 H/H / Characterization



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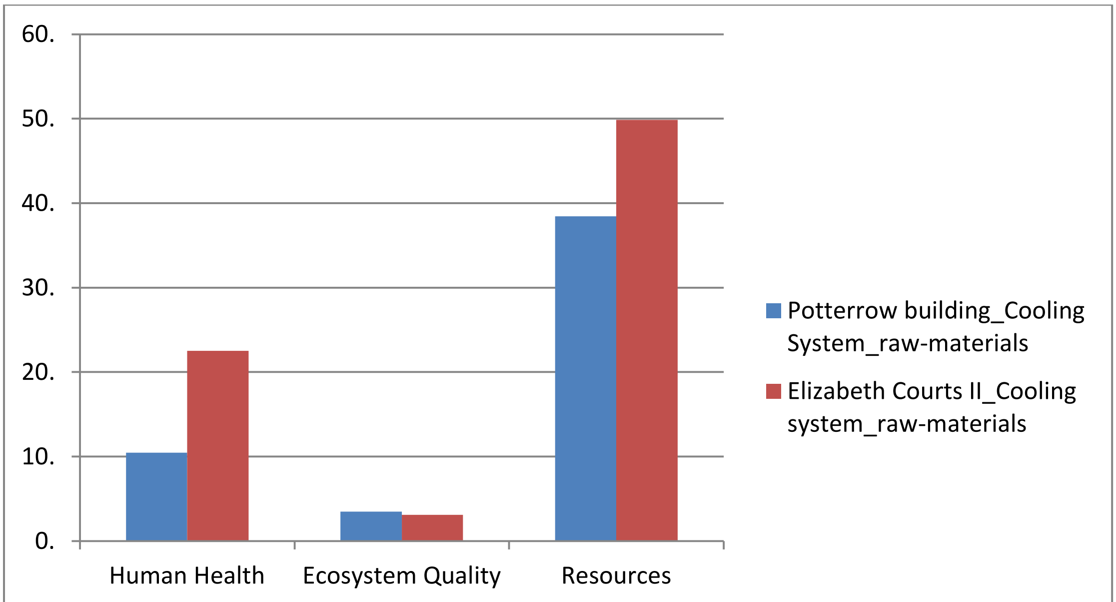

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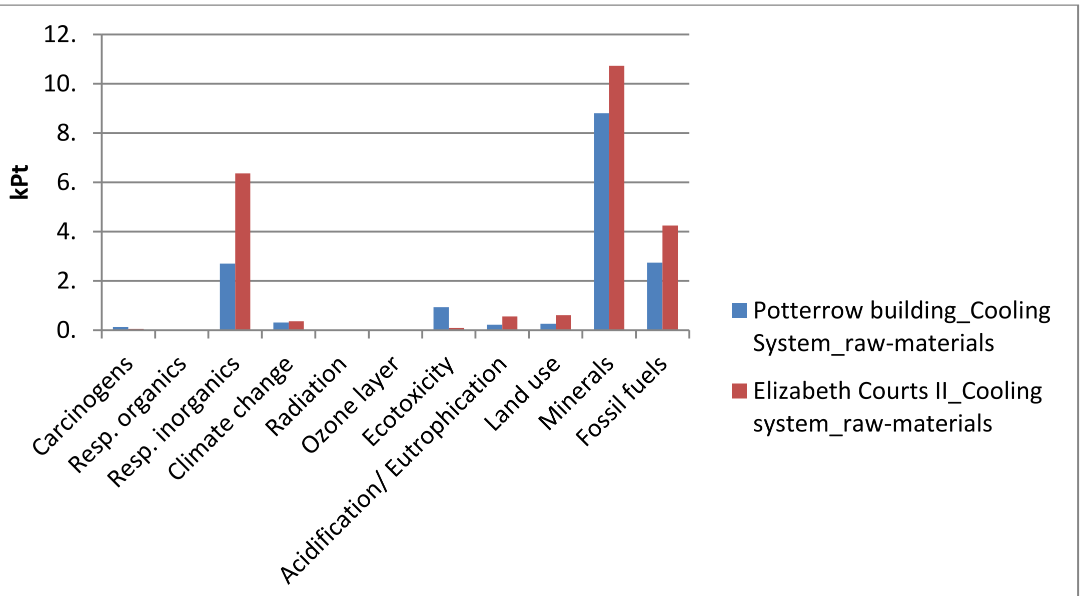

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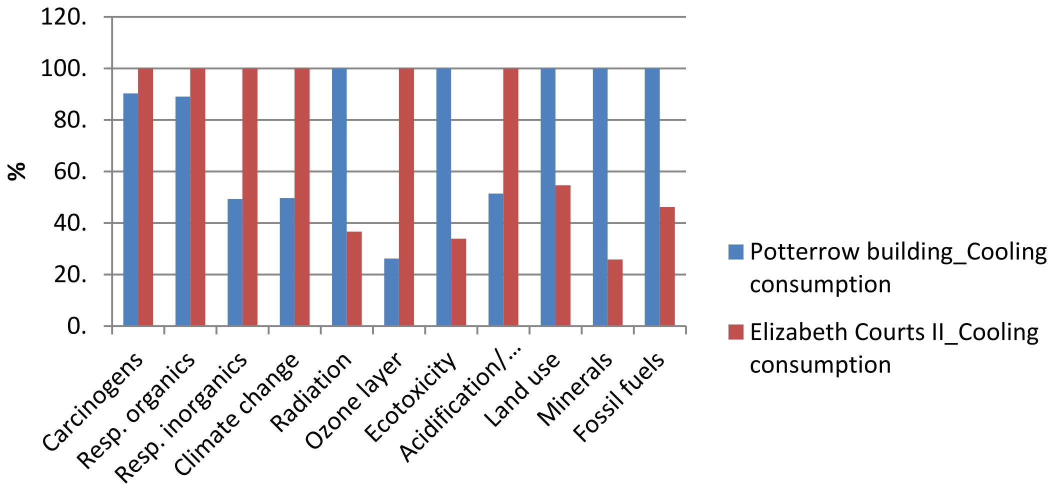

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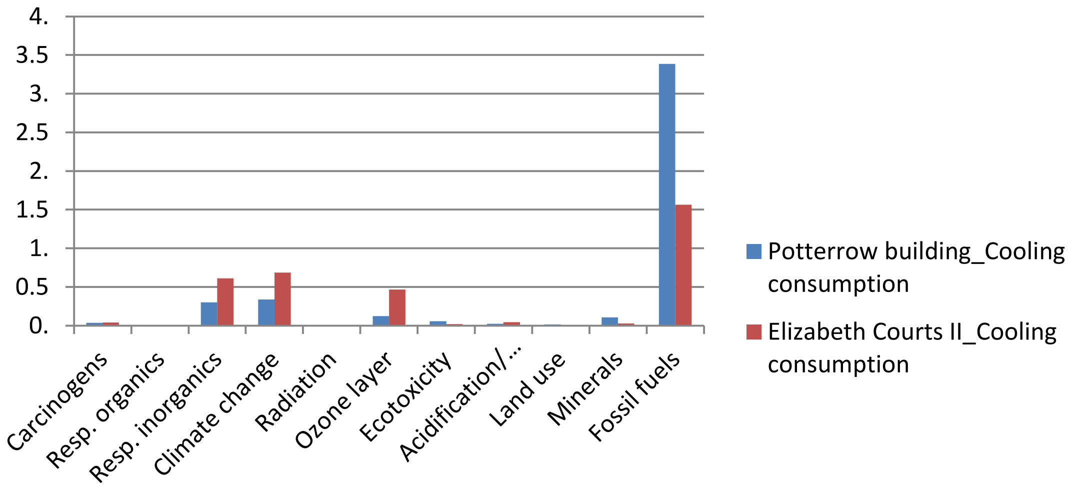

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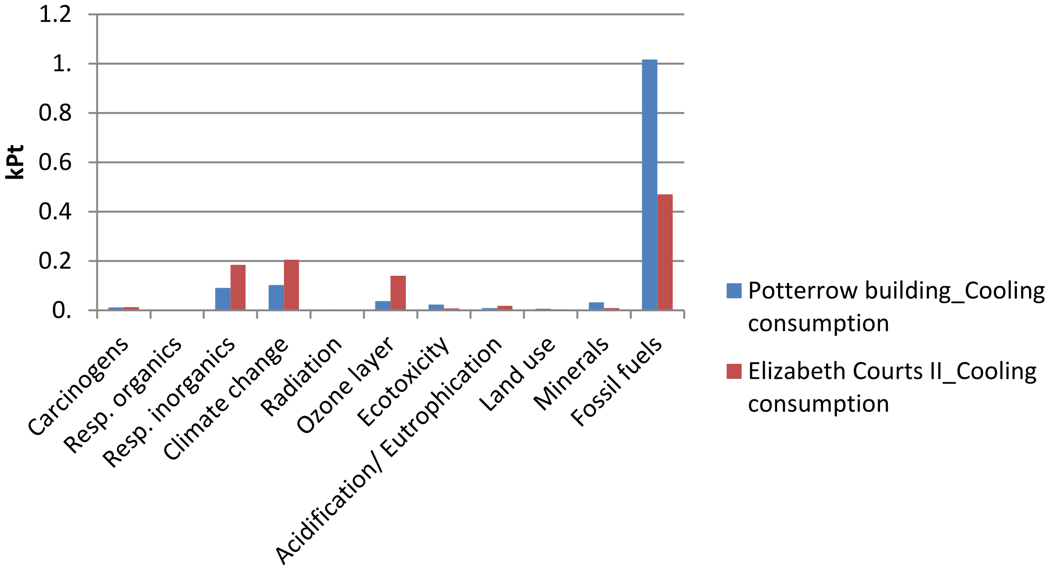

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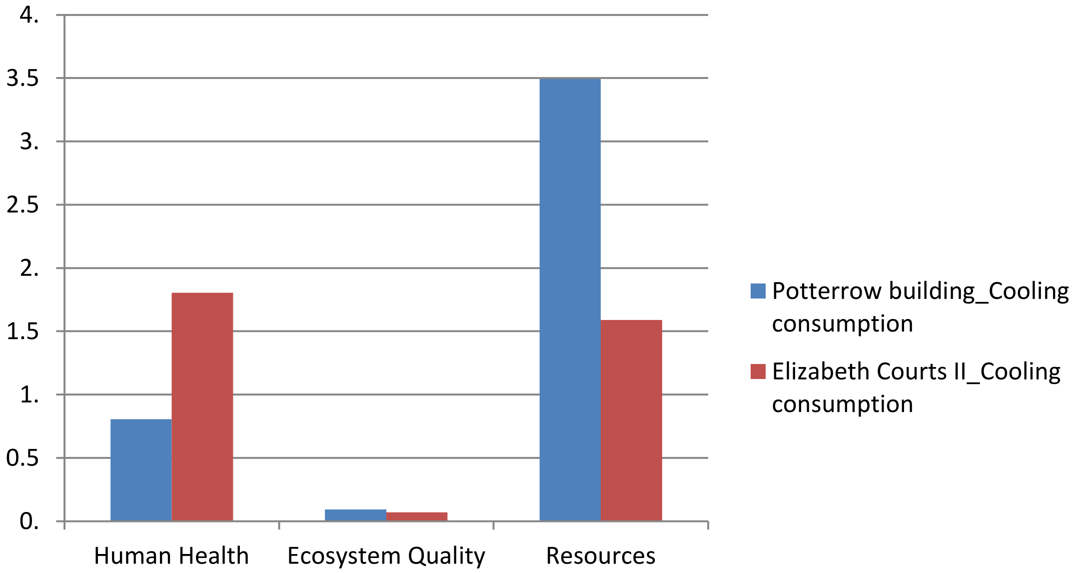

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