Thermal Energy
Modelling, Benchmarking, and Mapping
for University Campus Buildings

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Declaration

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work.

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Salahadin Vaisi

May 2017
Executive Summary

According to the Chartered Institution of Building Services Engineering, CIBSE TM46:2008 University Campus benchmark, a college building needs 240 kWh/m² of thermal energy and proportionally produces 45.6 kg CO₂ per annum. As heat consumption largely depends on the ambient temperature, this fixed-annual benchmark is not suitable because it does not deliver any difference between summer and winter. Firstly, the current research analysed the accuracy of the CIBSE TM46 ‘University Campus’ benchmark against the thermal consumption values presented in Display Energy Certificates (DECs). The DECs of 52 college buildings belonging to four universities in Dublin were assessed and based on the 46% discrepancy between the median of analysed samples and the CIBSE UC (University Campus) benchmark, a new benchmark of 130 kWh/m²/yr was recommended. This new benchmark is 110 kWh/m²/yr lower than the current benchmark which is a substantial improvement. The UC revised benchmark (UCrb, 130 kWh/m²/yr) was validated using Descriptive Statistics (DS). It has been found that the UCrb is a precise description of an up-to-date typical performance of college buildings in Dublin. The benefits of UCrb in terms of fossil energy saving and reduction of CO₂ emissions were calibrated and the results interpreted based on CIBSE UC benchmark and DEC values. Considering the large size of college buildings, applying UCrb could decrease the fossil consumption in Irish universities dramatically because the UCrb is approximately half of the current benchmark.

Secondly, Monthly Thermal Energy Models (MTEMs) which took into account the variations of heat demand during a year were generated using five key factors including mixed use approach, UCrb, activities area, heating degree days, and typical operation hours of heating systems. Two methods for generating the monthly heat models were presented based on the mixed use activities and Display Energy Certificates (DECs). Unlike many studies on energy modelling and benchmarking assuming buildings are single use, in the presented methodology the impact of mixed activities on heat consumption was considered. The results of MTEMs were compared with the CIBSE TM46 methodology and a significant development was obtained. When the absolute error of CIBSE UC benchmark for heat estimation was nearly 98% in summer months, the errors of MTEMs were less than 21%. Moreover, the results of R-squared analyses confirmed the accuracy of models.
Thirdly, the methodology of MTEMs was developed and Monthly Thermal Energy Benchmarks (MTEBs) were generated for the first time in the area. Comparing the fixed-annual CIBSE UC benchmark of 240 kWh/m²/yr, MTEBs altered from 21 kWh/m² in January to 1 and nearly zero kWh/m² in June and July respectively. Comparing the current CIBSE TM46 university campus benchmark, MTEBs are very sensitive and compatible with the real conditions. They also share more information than an annual index.

The MTEMs and MTEBs were used to generate detailed heat energy maps which showed the thermal energy density of buildings in the studied universities. Based on the maps, it was found that the buildings in a campus from viewpoint of thermal energy demand size and pattern could be classified into Periodical Thermal Consumers (PTC) and Continual Thermal Consumers (CTC). A typical college building is an example of the first group, while a swimming pool belongs to the latter group. Based on the data analyses, energy maps, and detailed study of actual thermal consumption, the concept of sharing surplus thermal energy was presented. The concept of sharing surplus heat energy between adjacent buildings in a campus compared with thermal energy storage method and the advantages of sharing surplus thermal energy were discussed.

Finally, the MTEMs and MTEBs methods were validated in Grangegorman developing campus of DIT (Dublin Institute of Technology). The monthly thermal demands of campus were calculated at both the building and campus scale. The detailed information of energy demand especially the energy maps which reflect the scattering model of thermal anchor loads are important for architects, urban planners, energy professionals, and building owners to plan and manage thermal energy more efficiently and smartly at a group of buildings such as a campus rather than an individual building. In addition, the generated 3D energy maps are more user friendly and comprehensible even for public. The developed methodology in this study can be applied to design a thermal efficient campus in future by urban planners and architects.
When writing this page, tears ran down on my cheeks. This thesis is dedicated to my Mum, who I never remember her face, because she passed way when I was just five months.

To my beloved wife, Haleleh, and my lovely two red roses, Amitis and Parmis. My brother, Hamed, and my family.

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Nomenclature

A: Building area ($m^2$)
Ai: Area of the activity i ($m^2$)
A_U: Useable roof area ($m^2$)
c: The specific heat of water (Joule/gram °C)
fi: CIBSE TM46 benchmark belong to the function (i) in a mixed use building (kWh/m²/yr)
KgCO₂e: Carbon dioxide equivalent is a unit to calibrate various greenhouse gases (GHG) in a common unit. For any amount and type of GHGs, CO₂e indicates the quantity of CO₂ which would have the equivalent global warming impact (Kg)
Ktoe: The tonne of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning one tonne of crude oil. It is approximately 42 gigajoules. 1 ktoe = 11,630,000 kWh
M: water volume (litre)
MTEBa: Monthly Thermal Energy Balance (kWh)
R: The amount of solar radiation (kWh/m²/day)
T₁, T₂: Temperature (°C)
TPFER: Total Primary Fossil Energy Required per annum (kWh/m²/yr)
TUFA: Total Useful Floor Area of a building ($m^2$)
AEM: Active Energy Management (Cylon), a website that records the actual thermal energy consumption, mostly gas, in Ireland.
BER: Building Energy Rating
CIBSE: Chartered Institution of Building Services Engineering
CIBSE UC: University Campus energy benchmark defined in CIBSE TM46:2008
CTC: Continual Thermal Consumers buildings
DEC: Display Energy Certificate
DH: District Heating system
DHB tool: District Heat Balance tool, a tool developed in this study to manage thermal energy demand-surplus at a university campus scale.
EBD: Energy Building Database, a database developed in this research including 120,000 data cells.
Eq: Equation such as Eq (1) and Eq (3.6)
EPBD: Energy Performance of Building Directive
EPI: Energy Performance Index
HVAC: Heating, Ventilation and air conditioning system
HDD: Heating Degree Days
HDD month: monthly heating degree days
HDD annual: annual heating degree days
HM: Heat Map
MTEMs: Monthly Thermal Energy models
MTEBs: Monthly Thermal Energy Benchmarks
MTEBa: Monthly Thermal Energy balance
Non-UC: All other CIBSE TM46 building categories except for University Campus (UC)
PTC: Periodical Thermal Consumers buildings
TFC: Total Final Consumption, or actual consumption is the final end use consumption measured by appropriate devices such as metre.
TPER: Total Primary Energy Required
TPFER: Total primary fossil energy required in a building per unit area per annum ($kWh/m^2/yr$)
TUFA: Total Useful Floors Area of a building measured by $m^2$ and comprises the area of conditioned spaces

UC: University Campus as defined in the CIBSE TM46:2008, a category shows the energy benchmark of university buildings

UCrb: Revised benchmark of UC
Chapter 1

Introduction
Chapter 1. Introduction

1.1. Introduction

University buildings are very important in terms of diversity of building function, building size and the large amount of fossil energy consumption. Functions such as library, swimming pool, restaurant, laboratory, fitness, retail, coffee shop, college, entertainment hall, and office can be found on a university campus. Since a university campus includes various building functions, it is a good example of an urban microcosm.

In more than 80% of the buildings on a campus, fossil fuel, especially gas is the main fuel used for producing thermal energy. Therefore, reduction of fossil thermal energy in a university campus results in decreasing of CO₂ emissions and this issue is vital from the global warming perspective.

Due to the importance of study of fossil thermal energy consumption in university buildings, this thesis aims to investigate, assess and analyse the thermal energy consumption in a university campus to discover new methods for reducing the thermal energy consumption.

By law [1] public buildings should provide a Display Energy Certificate (DEC). In Ireland, the energy standard reference (or benchmark) for providing DECs was produced by the Chartered Institution of Buildings Services Engineers, CIBSE TM46:2008 [2]. CIBSE TM46 presented a methodology for energy benchmarking; however, it is a UK based benchmark. First, the accuracy of this benchmark for use in Irish universities was analysed. Then, based on the discrepancy between the CIBSE TM46 benchmark and DEC values, a new benchmark was recommended. Furthermore, a new generation of thermal energy benchmarks was created (Chapter 5) and in other chapters of the thesis a new concept for reducing thermal energy consumption was presented. The thesis also presented a new methodology for sharing surplus thermal energy across a campus thermal network as an alternative for thermal energy storage. By generating the heat maps, the detailed information about heat demand was produced which is crucial for developing a district heating systems. In addition, this information can be used in urban planning to design a thermal energy efficient urban environment. The thesis objectives and outline are presented in the following sections.


1.1.2. The need to reduce fossil fuel consumption

Since the Intergovernmental Panel on Climate Change (IPCC) published the 1st Scientific Assessment Report in 1990 [1], many schemes at national or international scales have been proposed from the viewpoint of improving energy efficiency. UN conference on Environment & Development in Rio in 1992 [2] in which the Rio Declaration was signed by 150 countries; Kyoto Protocol agreed in December 1997 [3]; UN Framework Convention on Climate Change (UNFCCC) in 1999; Durban Conference in December 2011[4]; and a series of other European action plans developed by the European Commission [5] are examples of legislations and action plans being implemented at international scale in order to reduce fossil fuel consumption to mitigate global warming. Reduction of fossil fuel consumption decreases greenhouse gas (GHG) emissions and helps to achieve climate change goals [6] and forms the foundation of many energy action plans at global and national scale.

For the first time COP21 (21st Conference of Parties, Paris, 2015) realised a legally binding global agreement on climate with the objective of keeping global warming below 2 °C [7]. In March 2015 the Irish Government welcomed the EU’s commitment to a binding target of 40% domestic reduction of GHG emissions by 2030 compared to 1990, as set out by the European Council in October 2014 [8].

The fast evolution of energy efficiency in buildings during the last decade has led to an enormous volume of energy modelling methods and assessments. Following this evolution, the trend of research is moving toward creating efficient methods for finding a desired approach to manage energy consumption in a larger number of buildings such as a community or a university campus (UC).

According to Sustainable Energy Authority of Ireland (SEAI), energy demand for heating was 32% of total primary energy supply in 2014 and 39% of final energy demand. Residential energy demand accounted for the largest use of final thermal energy (44%), followed by industry with 35% and services with 16% [9]. The Total Primary Energy Requirement (TPER) of Irish residential and services in 2014 were 3,301 and 1,878 ktoe respectively and resulted in approximately 33 Mt of CO₂ emissions, 85.2% of which being related to fossil fuels [9]. In June 2013 there were approximately 20,000 public sector buildings in Ireland, with a total annual energy cost of €500 M [10]. Offices, third level colleges, schools, and sports centres are main categories of public sector buildings.

Furthermore, space heating and hot water are responsible for a large portion of the energy needs in public buildings; about 80% in Canada [11], 82% in Europe [12]. In educational buildings
including schools and universities more than 80% of thermal energy is used for space heating and the rest used for domestic hot water (DHW) [13].

As almost all of the typical building types such as library, swimming pool, restaurant, gallery, entertainment halls, shops, and laboratories can be found on a university campus (UC), therefore, understanding the energy demand, pattern and efficiency methods in UC buildings are important, where gas has been found to be the main fuel [14]. Since most UCs use fossil fuels (mostly gas) for heating purposes, the reduction of fossil consumption as well as CO₂ emissions in a UC is essential in achieving our energy targets [15, 16].

1.1.3. The Importance of Thermal Energy Assessment in a University Campus

Since several types of public buildings which use a significant amount of fossil energy can be found on a university campus (UC), the study of thermal energy of UC buildings enables an understanding of energy demand, patterns of energy use and energy efficiency methodology. In other words, a UC is a model of an urban context on a smaller scale, hence its thermal energy usage in this research is analysed in detail.

Currently, benchmarking is a predominant methodology developed for evaluating energy efficiency in buildings. Benchmarking is the practice of comparing the measured performance of a building with that of peers (similar function) or established norms. Benchmarking is helpful for state and local governments, building owners, managers, and designers to facilitate energy accounting for quantifying and verifying consumed energy [17].

In Ireland and UK, the Chartered Institution of Building Services Engineers (CIBSE) versions TM46:2008 and TM47:2009 underpin the methodology of benchmarking. The result of end-use energy benchmarking in Ireland presents as a Display Energy Certificate (DEC). DEC indicates the total annual primary energy delivered to a building and it is subdivided in two indices: thermal energy and electricity.

DEC is used to indicate the energy consumption of buildings and it illustrates the efficiency grade of buildings (A–G). CIBSE TM46 is applied in Ireland as a sole benchmark for producing DECs. So, the accuracy of CIBSE TM46 benchmarks is crucial.

Due to the importance of buildings located on a university campus in terms of the large size of buildings as well as the variety of types and functions (activities in the buildings) this PhD research focused on analysis, assessment, and modelling of thermal energy in these types of public buildings as a sample of urban context. The various categories of buildings in UK are presented
in Figure 1.1. As shown the building categories such as ‘General office’, ‘University campus’, ‘Long term residential’, and ‘Cultural activities’, account for significant proportion of the building size (Total floor area) in the analysed dataset [14]. For example, UC (university campus) with area of approximately 8,500,000 $m^2$ is one of the important categories in the dataset.

According to CIBSE TM46:2008, a typical swimming pool needs 1,130 kWh/m$^2$ of thermal energy per year whereas a typical cultural activity building and a restaurant need 420 and 370 kWh/m$^2$/yr of thermal energy respectively. These significant amounts of energy demand per 1 $m^2$ are more crucial when the large size of buildings (area) is also to be considered [18].

In addition, the role of building categories has been analysed from carbon footprint perspective and the results are presented in Figure 1.2, where carbon footprint is defined as kilogram of CO$_2$ emitted from the thermal energy that is consumed by each building category. The categories were arranged in a descending order of CO$_2$ emissions.

Figure 1.1. Comparison of total floor area of building categories, UK [14]
Figure 1.2. CO₂ emissions of categories of buildings [14]

Among the 29 building categories (Figure 1.2) assessed from a CO₂ emissions perspective, UC ranked 4th after schools, hospitals, and offices with an annual emission of 743,526 tonnes per year.

According to CIBSE TM46, a college building needs 240 kWh/m²/yr of fossil thermal energy and accordingly generates 45.6 kg of CO₂ per year. The analysis of DECs in the UK, as shown in Figure 1.3, compared the number of DECs of 29 building categories in which the schools were on top of the list followed by office and UC [14].
Based on the analysis of data that is presented in Figures 1.1-1.3, it can be concluded that UC is one of the most important categories in terms of building area and frequency of buildings. The importance of other building types on a campus such as cultural activities and swimming pools must also be taken into account.

The analysis of heating fuel of 9,540 DECs identified as UC revealed that natural gas was the main heating fuel in 85% of samples as presented in Table 1.1. In this context, the fuel type assessment of 1,150 swimming pools show that natural gas was the main fuel of approximately 96% of analysed samples. In other building types such as cultural activities, general office, entertainment halls, long term residential, and restaurant the percentage fluctuated between 83 and 100% [14]. Since such building types can be found on most UCs, reduction of CO₂ emission by managing thermal energy consumption of all building types on a UC is highly important.

Figure 1.3. *The number of DECs of university campus buildings among 29 building categories* [14]
UC buildings in terms of diversity of building types, scale of thermal energy demand, diversity of consumption pattern, and large area of buildings are very important. Consequently, the energy efficiency and energy saving plans for a campus community is vital.

In addition, the studies of energy modelling and benchmarking show a significant gap between theory and practice [14, 15, 19-23]. In compliance with the requirements of Energy Performance of Building Directive (EPBD), Directive 2002/91/EC, Display Energy Certificate (DEC) is one of the certificates in EU produced to assess the energy efficiency of both domestic and non-domestic buildings.

1.1.4. The Gaps and Problems

A few studies in Ireland have focused on the energy analysis of university buildings at the campus community scale, while significant gaps were found in UK context between CIBSE TM46 benchmarks and in practice. The CIBSE TM46 benchmarking method as well as the accuracy of the method in Irish university communities has not been studied comprehensively.

Despite the crucial role of university buildings from the perspective of thermal energy saving, there are some gaps in the field which need to be addressed. The gaps are summarised as follows:
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i. The paucity of data and datasets in Ireland which comprise both building information (public buildings) and energy consumption values [24, 25]

ii. There is a series of gaps between energy benchmarks and actual energy consumption [14, 21-23]

iii. Lack of flexibility of current energy benchmarking and models [19, 26-28]

iv. Weakness of strategies and methodologies for sharing surplus thermal energy between buildings at the community scale [24, 29]

(i) In Ireland access to a dataset which includes energy and building data of non-domestic buildings is a great barrier for researchers. While, for example, in the United States of America there are a lot of online free access datasets presenting real energy data, census data, graphs, and tools in excel, pdf or other appropriate formats [30-34].

Energy datasets not only are fundamental to facilitate future research but also, are important for community members to access and especially contributing to complete or update it. It is a starting point for participation of citizens in the sustainable development plan.

(ii) Regarding the gaps between theoretical methodology and actual energy performance recently, Bruman et al. [35] reviewed the discrepancies between theoretical and actual energy performance and classified the gaps into 4 main areas. Discovering any gaps between actual measurements and CIBSE TM46 standards in Ireland is necessary.

(iii) The result of recent post-occupancy studies confirmed a gap between theoretical energy prediction and actual figures in educational buildings. The reasons for the discrepancies were classified in the following groups:

- Increasing of installation of IT equipment such as computers (increasing electricity energy demand) [36-39]
- Low accuracy of energy modelling and benchmarking tools [40-43]
- Lack of annual updating of datasets [19, 44]
- Improvement of building quality and heating, ventilation and air conditioning (HVAC) systems (reason for decreasing of thermal energy demand) [45, 46]
- Insufficient accessible (private or public) datasets on energy consumption particularly in non-domestic buildings [45, 47-50]
- Weakness of building construction strategies [39, 51]
- Poor control and management of building systems [35, 39, 52]
(iv) Compared with smart electricity grid, the thermal energy network is not studied in detail. The referenced studies highlighted the problems as well as current and future necessities [24, 29]. For instance, smarter management of supply-demand in a district heating (DH) system is important to increase the efficiency of the system.

1.2. Scope of Research

In order to decrease fossil fuel consumption used for heating and also to reduce CO₂ emissions in university buildings, an accurate modelling method, benchmarks, and renewable energy technologies must be developed further to convert current campuses into green campuses. University buildings have enormous potential to mitigate global warming by reduction of fossil energy consumption. The scope of this PhD study is to reduce fossil thermal energy in a group of buildings located on a university campus (UC) by improving the thermal benchmark and developing a detailed model of thermal energy demand at the campus level. A rich dataset was developed during the PhD research process and using this dataset, the monthly thermal energy models and benchmarks were created to produce the heat maps (HM) at the campus level. Then, ultimately HMs were used to implement the concept of sharing surplus thermal energy between campus buildings.

1.2.1. Thesis Objectives

The objectives of the study are based on the gaps in the field. The thesis main objectives are as follows:

- To discover the accuracy of CIBSE TM46 UC thermal benchmark for Dublin universities
- To improve the UC benchmark reliability for typical college buildings
- To create a new generation of UC thermal benchmarks which are more informative and accurate compared with the current CIBSE UC benchmark
- To understand thermal energy patterns of various building types on a campus. Linking the various thermal patterns to form a larger thermal network demand-surplus model at the campus level
- To develop a new method for managing thermal energy at the campus level
- To assess and validate the advantages of the proposed methods for example revised UC benchmark and monthly benchmarks compared with current annual UC benchmark
- To generate a validated GIS based tool used for smart thermal energy management at the campus level. The tool should link various levels of data and should be useful to match with different sources of energy such as solar and geothermal energy.
1.2.2. Thesis Limitations

The barriers in front of the current research and its limitations are as follows:

- Access to the DEC dataset of public buildings in Ireland was the main barrier in front of this research. Particularly a limited number of DECs of sport centres, restaurants and general accommodations was obtained during the research were limited. Therefore, the thesis did not generate monthly thermal energy models for these types of buildings.

- The thesis focused on the investigation of thermal energy consumption and did not consider electricity consumption. The thermal and electricity consumption were separated because there are key differences between them in terms of efficiency management, drivers, and consumption patterns [53]. For example, heat (thermal energy) is mainly used for space heating in educational buildings and obviously, it is seasonally dependant. In contrast, electricity consumption depends on the devices and their efficiency and less dependent on the building physics such as building envelope quality and area. In other words, the number of pupils and efficiency of electrical equipment impacts on the electricity energy demand, while heat consumption is highly sensitive to the number and size of classes, theatres, coffee shops/restaurants (activity) and outdoor temperature.

- According to Hong et al. [53] and Kyrö et al. [54], in public buildings such as universities the impact of occupant behaviour on thermal energy consumption is not significant. Therefore, in the monthly thermal energy models the number of pupils/staff was not considered as a driver. Further explanation about the weak impact of occupant behaviour on thermal consumption in public buildings is presented in Chapter 2, Section 2.7.

- The limitation of case studies (four campuses) refers to the lack of actual thermal energy consumption. For example, the data of other universities in Ireland such as the University of Limerick was not available.

1.2.3. Thesis Contributions

The thesis has made six important contributions to the field of thermal energy modelling/benchmarking in university buildings. The first contribution is the revision of current CIBSE TM46 UC benchmark and presentation of an alternative which is more accurate. This process is explained comprehensively in Chapter 4. The revised benchmark reduced the threshold of CIBSE UC benchmark by 110 kWh/m²/yr which is a significant amendment. Using the revised benchmark in the future will radically decrease the fossil thermal consumption of typical college buildings. Considering the large size of typical college buildings (506,000 m²), the impact of
revised benchmark on reducing of fossil fuel is substantial. Compared with CIBSE TM46, the revised benchmark can reduce the thermal consumption in typical college buildings by 55,643,000 kWh per year.

The second novel contribution of the thesis is to create a new generation of benchmarks which is called monthly thermal energy benchmarks for typical college buildings. These monthly thermal energy benchmarks are introduced as a useful alternative for the current annual-fixed benchmark developed by CIBSE TM46 in 2008.

Third, two new types of monthly thermal energy models based on the mixed activities and DEC values are developed in the thesis. Comparing with the average monthly estimation of CIBSE TM46 UC benchmark, they are more accurate and useful for energy planning and efficiency action plans.

The fourth contribution is the concept of sharing surplus thermal energy between buildings on a campus which is an alternative for thermal energy storage (TES). The concept of sharing surplus thermal energy across a DH system and smarter management of the system using thermal energy maps can also extrapolate into an urban context. For this purpose, a GIS based tool, District Heat Balance (DHB) tool, has been developed.

Accordingly, the thermal energy balance analysis is also new in the field which refers to the balance between potential solar thermal energy and thermal energy demand in each month at an individual building level as well as campus scale. To do so, the monthly heat maps are generated. The maps share more information about heat demand or potential for generating solar thermal energy.

The last contribution of the research is a valuable Energy Building Database (EBD) which shares a lot of information regarding energy and buildings at four case study universities. It includes 120,000 data cells and shares the information of UC as well as Non-UC buildings.

1.2.3. Thesis Outline

Chapter 2 comprises a literature review focusing on seven key areas including; (1) an overview of energy performance and legislations; (2) mixed use building; (3) energy benchmarking and certification; (4) CIBSE TM46; (5) Display Energy Certificate (DEC); (6) DEC-CIBSE, discrepancies & gaps; and (7) Energy mapping.

Chapter 3 involves the approaches undertaken to create and develop a database and it also includes two methods which have been applied to generate the monthly thermal energy benchmarks and
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models. The chapter finally covers the methodology used to set up the District Heat Balance (DHB) tool.

Chapter 4 provides the process of heat assessment in UC buildings resulting in revising the CIBSE UC Benchmark. The chapter explains what is the situation of current CIBSE TM46 UC benchmark by assessing its accuracy.

Chapter 5 explains two methods for generating monthly heat demand benchmarks/models for typical college buildings. In this chapter a new generation of benchmarks as well as thermal modelling are developed and their accuracy and advantages discussed in detail.

Chapter 6 presents the generated heat maps for case study universities. The chapter focused on the analysis of the current heating systems as well as the assessment of fossil thermal consumption at the campus scale. The monthly heat maps for case study campuses are generated. In addition, the efficiency of the current heating system (individual boilers) at TCD campus is assessed as an example. In addition, two thermal systems including DH (District Heating) and individual boilers systems are compared at TCD.

Chapter 7 includes a novel concept of sharing surplus thermal energy between the campus buildings as a useful, cheaper, efficient and applicable alternative of thermal energy storage. The DHB tool is progressed by adding new information to enable the tool to manage and share thermal energy across a UC.

Chapter 8 includes the validation of monthly thermal energy benchmarks and models in a developing campus. Based on the thesis results, the heat demand for campus buildings is estimated at both the building and campus scale. In addition, heat maps are produced and based on the data analysis some methods for smarter thermal energy management and further energy efficiency are proposed.

Chapter 9 contains the detailed conclusions drawn from the research as well as recommendations for future studies. The supplementary documents, secondary data, tables, and maps are presented in Appendices 1 to 3.
Chapter 2

Literature Review
Chapter 2. Literature Review

2.1. Introduction

In this chapter the recent literature regarding international and national legislations to generate and display energy certificates in public buildings in Europe are reviewed. The recent methodologies that have carried out to generate the certificates are also presented. The aims of the chapter are to understand the current actions and solutions applied to reduce fossil energy consumption in educational buildings. The other aim is to assess the success or weakness aspects of energy benchmarking in the UK and Ireland.

The multidisciplinary nature of this research required a review of literature on energy efficiency legislation, building function, energy benchmarking, certification, and mapping. The recent studies on these themes are presented in this chapter.

2.2. Energy Performance Legislation

Directive 2002/91/EC of European Parliament and Council on the Energy Performance of Buildings Directive (EPBD) defined energy performance of a building as “the amount of energy actually consumed or estimated to meet the different needs associated with a standardised use of the building, which may include, inter alia, heating, hot water, cooling, ventilation, and lighting” [55].

EPBD has led to a fundamental improvement in energy efficiency in buildings. Article 3 which was the foundation of EPBD, required all EU Member States to initiate a methodology for the calculation of building energy performance [55]. The directive came into force in EU States in 2003. In Ireland, the initial methodologies underpinned the energy performance certificate which is called Display Energy Certificate (DEC). Further information about DEC is presented Section 2.6. The recast version of EPBD, i.e. Directive2010/31/EU aimed to expand the scope of the previous version by decreasing the threshold of buildings area so that it is applicable for various types of new and existing public and private buildings [56-58].

In this context, the European Commission 2011c emphasised that more than 75% of CO₂ emissions were generated in cities and consequently the European 20-20-20 strategy was presented. This document aimed to decrease greenhouse gas (GHG) emissions by 20%, to increase energy efficiency by 20% and to increase the renewable energy contribution by 20%, all by 2020 [59]. The current suggestions on low carbon cities [60], post-carbon cities, transition towns [61, 62], and smart cities [63] are among the concepts of how to address these targets.
The concept of ‘Low-Carbon Livable Cities’ was introduced by the World Bank to assist city planners to plan low-carbon and climate-smart cities. It offered a comprehensive set of tools and activities tailored to 300 of the largest cities in developing countries to progress their climate-smart development path. Post-carbon cities aim to reduce GHG by reducing fossil consumption and increasing green technologies. Smart cities apply smart technologies to assess, monitor, visualise and manage fossil fuel consumption creatively. Furthermore, other initiatives were implemented at national level to reduce the energy consumption and boost environmental quality in terms of CO₂ emissions. In Ireland, for example, the third National Energy Efficiency Action Plan (NEEAP3) determined a commitment of saving 20% energy across the whole of the economy by 2020 [60]. Based on NEEAP3, the energy saving target of building sector by 2020 is 10,379 GWh.

In September 2012, the Irish Government introduced a series of measures for instance, (i) Building Energy Rating (BER) should be included in all advertisements for the sale or lease of domestic buildings, (ii) DECs should be displayed in public and privately owned commercial buildings which are frequently visited by the public and above 500 m² in size [64]. By law all public buildings in Europe should display DEC at the main entrance of the building so that it is clearly visible to members of the public [65-67].

The current studies on energy efficiency at the community level emphasise applying upgraded urban policies as well as revolutionizing city management to enhance the performance of a group of buildings rather than an individual one [68, 69]. Renewable energy for example, could sustain the region and have a positive impact on air pollution. To succeed in such programs urban planners, architects and policy makers play a key role. On the other hand, development of techniques, tools, energy modelling methods and IT services are vital to manage a community in a smarter and more efficient way in order to reduce energy consumption.

A significant part of energy legislation refers to public buildings especially university buildings because of their huge size and high level of thermal demand [70, 71]. Educational buildings such as schools and university buildings formed a considerable proportion of building size in the entire public building sector (detailed information is presented in Section 2.7.1). In Ireland for all building categories in the commercial sector, a significant amount of energy was used for the purpose of space heating, hot water and lighting respectively. However, few studies have focused on this field because of the complexity and number of parameters involved. Therefore developing a methodology to control and monitor a daily/monthly thermal energy demand in educational buildings is necessary.
2.2.1. Energy ‘Efficiency Gap’: Discrepancy Between Standards and Practice

Two main reasons for noncompliance of energy consumption with predictions include complexity of operating conditions and human behaviour both of which are difficult to address [51, 72]. The difference between theoretical energy performance and actual performance has been defined as ‘efficiency gap’. Hirst and Brown addressed the topic for the first time in 1990 [73]. EPBD the energy performance framework in the EU [52] is based on theoretical performance. For instance, in the UK, based on standardised building regulations the performance of new buildings should be higher than the minimum acceptable (standard) performance. Currently many studies have revealed the gap between standards and actual measurements. For example, research was conducted on 404 new-build dwellings in the UK and the results revealed only one-third of the analysed buildings were compliant with the energy efficiency codes and standards [74]. Recently, Bruman et al. [35] reviewed the discrepancies between theoretical and actual energy performance and classified the gaps into four main areas as follows:

1. Accuracy and authenticity of modelling of energy performance [35, 72, 75]
2. Insufficiency of modelling methodologies and toolkits [76, 77]
3. Procurement and construction process [38, 39]
4. Building management and operational inefficiencies [36, 38]

Bruman et al. [35] developed a model to assess the compliance of energy use with EPBD as illustrated in Figure 2.1. The authors explained how actual energy performance could be drastically greater than theoretical performance under the EBPD condition. Figure 2.1 shows the drivers such as occupant behaviour, non-regulated end-use, and special function that were not considered in EPBD. The authors, found a significant gap between EPBD and practice. Building special function is one of the drivers that was addressed as a reason of discrepancy between theoretical prediction and actual consumption [35].
In a study in North West England, a secondary school with a total useful area of 10,418 $m^2$ and nominal occupancy of 1,150 pupils was used as a case study [35]. The building was constructed as a low carbon sample based on the UK’s Building Regulation. Using a dynamic simulation (IES Apache software) the annual CO$_2$ emissions of 27.2 kgCO$_2$/m$^2$ was predicted for the school. In contrast, the post-occupancy measurement in 2011-2013 showed approximately 93.6 kgCO$_2$/m$^2$ of CO$_2$ emissions. This measurement accounts for all energy consumer types that was not regulated by EPBD such as all fixed building services, small power appliances, server room load, outdoor lights, lifts and other miscellaneous loads [35]. Due to a significant difference between the standard and measurements, revising of the standards was recommended by the authors [35].

2.3. Mixed Use Buildings

2.3.1. Definition of Mixed Use Building

Heng and Malone-Lee [78] defined mixed use as “places where different activities take place in the same building, street or neighbourhood”. In terms of building, Zhu [79] stated that “Mixed use is multi-functional spatial organization pattern in building design”. According to the definitions the term of mixed use can be used in both urban context as well as individual buildings, however, this research will focus on individual buildings.

Several studies focused on the relationship between energy saving and transportation in mixed use urban development regions [34, 80], however, the role of mixed use buildings in terms of energy saving has not been addressed comprehensively.
Mixing residential with working spaces or other functions such as commercial or office at an urban context has a variety of advantages [81, 82]. For example, mixed urban context reduces travel by car because the residents can do shopping in nearby shops by foot. Walking in such regions is the main method to go to work. Decreasing CO$_2$ emissions and increasing vitality (because of walking/cycling) in the mixed urban contexts have been addressed frequently [83-87]. “Mixed use has become a mantra in contemporary planning” Grant [81]. Mixed use in urban planning contains “integrating segregated uses” by overlapping the boundaries and buffers of various functions because of the inherent characters. Mixing activities/functions in an urban region reduces energy consumption however, the effect of mixed use on energy consumption at the building scale is not clear enough.

2.3.2. Barriers of Analysis of Energy Consumption in Mixed Use Buildings

Typically, buildings were categorized based on their predominant function, i.e. single function. A high proportion of energy analysis methods were improved based on this criterion. For example, in a study developed for energy consumption assessment in commercial buildings the single use of the buildings was taken into account [88]. In addition, to develop a stepwise regression for modelling electricity consumption per square foot, Sharp [48, 49] relied on the single function of the Building Energy Consumption Survey (BECS), which was broadly used by other researchers as an experimental way for energy prediction. BECS is an independent, statistically representative source of national-level data on the characteristics and energy use in buildings in the United States of America.

The studies on energy consumption that presume the buildings as single use are continually increasing both theoretically and empirically [89-92]. For instance, Energy Star has developed a prediction model using the building function categories defined by Commercial Buildings Energy Consumption Survey (CBECS) [93]. In United States of America, CBECS is a survey at the national scale which collects information of commercial buildings including their energy-related building characteristics and energy usage data (consumption and expenditures). In this model, just the principal function of buildings was used instead of real functions which in many cases are mixed functions. Therefore, this limitation had decreased the accuracy of such models. In an actual situation, many non-residential buildings contain several activities such as retail, office, coffee shop, bar, etc. [93]. Providing a sensible predictive energy model for mixed use buildings is a challenge that needs to be addressed comprehensively. All in all, research into the energy assessment in mixed use buildings is infrequent.

Classifying building functions based on a mixed use method is harder than the single function method for two reasons. First, there are a large number of mixed use buildings in an urban context,
especially in large cities. Distinction and recognition of this large number of buildings requires conducting a survey which is hard and expensive from a time-cost perspective. Second, distinguishing and drawing a clear boundary for each function in a mixed use building is difficult which gets harder in large buildings. The mixed use approach of building classification relies upon surveys in order to generate information about all activities in buildings. Obtaining this level of information involves details at floor scale, so few studies have focused on actual mixed functions in buildings.

Kinney and Piette [94] warned about the problems of investigation in mixed use buildings when they defined building categories in an energy survey in 2002. For instance, a building may have 35% of its total area as office, 10% as crèche, 15% as retail and the rest as residential. Therefore, such a building cannot clearly be classified as a single function. Accordingly, the number of building subdivisions may increase/decrease over time. Eventually, the same building may fall into different categories based on assessor judgement. This can lead to an incorrect energy assessment when the single function energy benchmark is used for mixed use buildings [94].

Few studies carried out focus on energy modelling in mixed use buildings due to its complexity. However, a new method for predicting energy demand in mixed use urban regions was proposed at University of Pennsylvania [93]. The researchers developed ‘District Energy Concept Advisor’ tool which had several objectives. It helps urban planners, construction companies, local policy makers and developers at the early stage of urban planning to calculate energy use at the urban district scale to design an energy efficient neighbourhood. However, the tool does not provide detailed information of individual buildings. It considers the urban context as a set of mixed buildings, hence, it divides the buildings into two main types; residential and non-residential. The tool has also classified non-residential buildings into eight sub-types such as school, sport hall, nursery school, office, workshop, hotel, library, and supermarket.

The tool helps users to compare the energy consumption of a case study with the national benchmark. The heat benchmark suggested by this tool for non-residential buildings is 167.3 kWh/m²/yr. This benchmark for non-residential buildings is close to the CIBSE TM46 benchmark for ‘School & seasonal public buildings’, i.e. 150 kWh/m²/yr [18].

In spite of advantages of District Energy Concept Advisor tool, there are some limitations and gaps which were not addressed in the software. The number of non-residential types of buildings is very limited so that it does not cover university or college buildings. In addition, the tool presents a benchmark (167.3 kWh/m²/yr) for all eight non-residential buildings, while there is a significant difference between the amounts of heat demand of these types of buildings [18, 93]. Eight non-residential categories reduced the accuracy of tool comparing with 237 building types.
proposed by CIBSE TM46:2008 [18]. In addition, the tool is not useful to assess energy demand in mixed use buildings.

2.4. Energy Benchmarking & Certification

In this section of the literature review, the energy standards, classification, and benchmarking methods are reviewed. The section focused on the CIBSE TM46:2008 (Chartered Institution of Building Services Engineers) standard which is a touchstone of energy certification in Europe, particularly in the UK and Ireland. In this section, the origin of certification schemes, its definition, aims and implementation aspects is reviewed. In addition, DEC (Display Energy Certificate) is reviewed in detail as it forms the basis of the monthly thermal energy demand models generated in this research.

2.4.1. Building Energy Certification

In the early 1990s energy certification was presented as a fundamental methodology in order to improve the energy efficiency of buildings. Building energy certification was defined by the European Council Directive 93/76/CEE [95] as a cornerstone to increase energy efficiency and decrease CO₂ emissions in buildings. The European Standard EN 15217 [96] not only explains the methods for analysing and assessing energy efficiency but also describes the process of producing building energy certificates.

According to the Council Directive 93/76/CEE an energy certificate “shall consist of a description of their energy characteristics and must provide information for prospective users concerning a building’s energy efficiency” as well as “include options for the improvement of these energy characteristics” [95]. In this context, the European Parliament of the Council on 16 December 2002 revised the previous version. In the revised version energy performance certificate mentioned clearly as “a certificate recognised by the Member State which includes the energy performance of a building calculated according to a methodology ...” [97].

Energy Performance Certificate, known in Ireland and UK as Display Energy Certificate (DEC), was developed based on the European certification scheme presented in Figure 2.2 [28]. DEC contains at least (1) an overall fossil and electricity performance index, i.e. Energy Performance Index (EPI) presented in terms of energy consumption and (2) the amount of CO₂ emissions per kg per unit area (m²) of conditioned spaces. A conditioned space is “an enclosed space within a building where there is intentional control of the space thermal conditions within defined limits using natural, electrical, or mechanical means. Spaces that do not have heating or cooling systems, but rely on natural or mechanical flow of thermal energy from adjacent spaces to
maintain thermal conditions within defined limits are considered conditioned spaces” [98]. The methodology of calculating the total useful floor area (TUFA) relies upon the conditioned space definition.

Comparing the energy consumption of a building with the consumption of typical buildings is a fundamental approach of certification. Generally, in practice the EPI standard efficiency is established by authorised organizations such as CIBSE. This standard (benchmark) was calculated using the consumption of 50% of peer (similar function) buildings. Other relevant variables and correlations such as weather parameters can be suggested by authorised organisations.

![Figure 2.2. The scheme of European building energy certification [28]](image)

On a DEC, an alphabetical coloured band of A-G shows the efficiency rank of buildings. A sample of an Irish DEC is presented in Figure 2.5. More information about DEC and energy efficiency grades is presented in Section 2.6. The building energy performance of the previous three years is also presented on DECs in order to allow the building users to assess the impact of any implemented energy efficiency action plans.

Other important information displayed on DECs is the building category which indicates the main function of the building. The Irish DEC method based on CIBSE TM46:2008 [99] uses 29 building categories. To generate DECs the assessors conduct a survey at floor scale and inspect all building parts, maps, and energy bills. Failure to provide the mixed activities of the building
on DEC is a weakness of the method. Regarding the building types and categories a detailed explanation is presented in Section 2.5.

Measuring primary energy delivered to the boundary of the building and calculating the total useful floor area (TUFA) of the building require a high level detail. For example, DEC assessors should meticulously check all energy bills, date of bills, all bulk energy delivered to the building such as oil and coal. They are also required to survey the buildings at floor scale to calculate the TUFA. It only calculates for buildings with walls and covered by a roof in which the energy is used heating, cooling, and ventilation purposes. Therefore, if no energy is used the space should not be considered in TUFA calculation [100]. The main function of the building and TUFA are presented in DEC database. The process of building benchmarking and generation of DECs is presented in Figure 2.3.

Matson and Piette prepared a report in 2005 in which they explained four phases of energy benchmarking [88] as shown in Figure 2.3. Development of database is the first phase which comprises data of various building types. Categorisation of data is a key objective in this phase, thus building type and size are essential. The second phase involves the collection of information to generate an EPI (energy performance index). The third phase includes the analysis process and mathematical calculation of energy performance of the applicant building versus the performance of typical buildings in the database, e.g. comparing with peer buildings, which quantifies the quality of buildings in terms of energy consumption. The final phase is to present recommendations to improve the building’s energy efficiency in the future [88].
2.4.2. Energy Benchmarking

In the 1970s, several manufacturing industries applied benchmarking tools in production lines which enabled them to assess and improve the efficiency of the manufacturing process. In buildings, the ‘energy benchmarking’ term was used nearly 20 years later to compare the energy performance of a building with the performance of a similar building type [28]. Energy benchmarking compares the annual Energy Performance Index (EPI) per unit area of a building with the median comparison of peer buildings. However, other types of units such as energy per workers, energy per capita and energy per seats (for example, in entertainment halls) may also be used. Initial energy audits, compare EPI with benchmarks of typical buildings.

The technique of benchmarking not only elevates the accuracy of energy monitoring, but also the public displaying of certificate (DEC) raises motivation to improve the energy efficiency. Benchmarking also impacts on the market price if buildings are presented for sale or rent. According to the S.I. No. 243 (Statutory Instruments) [101], generating a building energy rating (BER) is obligatory under the following conditions:

- The building owner must obtain a BER before a new building is occupied for the first time regardless of whether it is offered for sale or rent.
- When a new or existing building is offered for sale or rent the seller/renter must provide a BER to prospective buyers or tenants. BER details must be included in advertisements when a building is offered for sale or rent.

From an energy benchmarking perspective, the quality and quantity of the database are fundamental. A few countries have established a comprehensive dataset up to now. The US Energy Information Administration (EIA) is a good example of establishing such a dataset particularly two recent surveys, i.e. Residential Energy Consumption Survey (RECS) [102] and Commercial Buildings Energy Consumption Survey (CBECS) [103]. In UK many studies were carried out about benchmarking [104]. In Ireland, up to now the DEC dataset for public buildings is unavailable and consequently only a small amount of research on accuracy of benchmarks has been published.

2.4.2.1. Energy Benchmarking Approaches

Benchmarking plays a key role in the development of energy efficiency in buildings. Benchmarking is usually used as a practical approach for energy management in both existing and developing buildings to analyse and enhance the efficiency of buildings. Based on the granularity of data, benchmarking methods have been classified into two approaches top-down and bottom-up. The bottom-up approach refers to techniques in which whole-building energy
determinants are calculated and simulated by the aggregation of detailed data obtained from sub-systems. The bottom-up approach can be classified into two main groups; building physics and end-use [20].

The top-down method is applied as a valuable way to understand how similar buildings (peers) perform. Calculating the energy performance of a building and then comparing the result with the performance of that of its peers indicates the situation of that building among the group. In other words, instead of an absolute value resulting from the bottom-up method, the relative performance shows the quality of building in terms of energy efficiency hence, the index pushes for more improvement and this is a powerful motivator. Descriptive Statistics (DS) and Artificial Neural Network (ANN), Carbon Trust, and CIBSE are examples of the top-down approach. Released in 2008, CIBSE TM46 benchmarking methodology, a top-down method, immediately underpinned the UK’s Display Energy Certificate scheme [15].

The robustness of the top-down method depends on the richness, quantity, and quality of DEC dataset. Acquiring sufficient and useful data were recognised as limitations of the top-down approach particularly in benchmarking of non-domestic buildings [105]. Regarding the top-down approach, the earliest studies were conducted in 1982 [106] in which multiple linear regression models were used to recognize key energy determinants, the approach was developed further by Sharp [48, 49]. These methods formed the basis of US Environment Protection Agency (EPA) Energy Star structure [107]. Accordingly, in 2006 the similar method was applied in Hong Kong [44, 108] for benchmarking of energy efficiency of commercial buildings. Recently in the UK [23] and US [43, 109] the capability of artificial neural network (ANN) for energy benchmarking has been developed as well as the use of the Data Envelopment Analysis (DEA) [42, 110-112].

The top-down method refers to a structure in which an overview is formulated and the main character of the system is taken into account instead of details of the system. In contrast, a bottom-up method relies upon sub-system details and uses them based on a defined methodology. Top-down approach refines further subjects to avoid using detailed information. A bottom-up method, on the other hand, engages with detailed data to develop a more specified overview [105]. In terms of benchmarking, a top-down approach concerns techniques in which benchmarks are calculated based on building-level energy performance. The top-down approach is broadly used in the UK to assess energy benchmarks using descriptive statistics, for instance, 25th and 50th percentiles of the distribution of energy performance of same type buildings [18, 45, 99, 105, 113]. In addition, similar approaches in Argentina [114] and Greece [106] were also applied for analysing the energy performance of school buildings.
Hong et al. [105] carried out research combining two top-down techniques e.g., Descriptive Statistics (DS) and Artificial Neural Network (ANN) to explore the purpose of benchmarking energy performance of schools in UK. The researchers used a dataset previously developed by Bruhns et al. [15] and Godoy-Shimizu et al. [16]. The authors also used the results of the research carried out by the Carbon Trust, i.e. 80% of fossil thermal energy is usually consumed for space heating [13], as a baseline case in the analysis. The results were compared with the CIBSE Guide F [115] and CIBSE TM46 [99] benchmarks for School & seasonal public buildings.

The comparison of results with both versions of CIBSE, i.e., Guide F and TM46, showed that schools in the UK in 2010-2012 consumed more electricity and less heat than outlined by CIBSE. According to Table 2.1, primary and secondary schools consumed 121 and 111 kWh/m² of energy for heating respectively between February 2010 and June 2012 while CIBSE TM46 predicted 150 kWh/m² and CIBSE Guide F predicted 164 kWh/m²/yr for Primary schools and 144 kWh/m²/yr for secondary schools. The discrepancy between actual consumption and CIBSE benchmarks is significant [105].

**Table 2.1. Energy demand analysis for schools in the UK [105]**

<table>
<thead>
<tr>
<th>Phase of education</th>
<th>N</th>
<th>%</th>
<th>Electrical EUI (kWh/m²)</th>
<th>Weather-corrected fossil-thermal EUI (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10th%</td>
<td>25th%</td>
</tr>
<tr>
<td>Latest data (2010-2012)</td>
<td></td>
<td></td>
<td>67</td>
<td>73</td>
</tr>
<tr>
<td>Primary</td>
<td>7455</td>
<td>85</td>
<td>29</td>
<td>35</td>
</tr>
<tr>
<td>Secondary</td>
<td>1277</td>
<td>15</td>
<td>32</td>
<td>41</td>
</tr>
<tr>
<td>CIBSE TM46</td>
<td></td>
<td></td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>CIBSE Guide F</td>
<td></td>
<td></td>
<td>40</td>
<td>55</td>
</tr>
</tbody>
</table>

The reason for the observed discrepancies refers to the basis of CIBSE TM46:2008 which is mostly obtained from earlier investigations undertaken in 1990s. Since this, equipment particularly IT has grown in use increasing electrical load. The efficiency of Heating, Ventilation and Air Conditioning (HVAC) systems and building material quality such as double-glazing and thermal insulation have been developed and these measurements reduced thermal energy consumption in schools.

The authors [105] argued that evaluating energy efficiency in schools using current CIBSE TM46 benchmarks does not provide useful feedback for building operators because it is not a precise indicator of how schools perform. Therefore, a dynamic dataset as a basis for benchmarking would deliver more accurate data than TM46. Continuous updating as well as refining of the dataset in a top-down model is crucial and this moves toward systematic monitoring/updating and collection of a comprehensive database.
Furthermore, the authors [105] found that the compactness (the ratio of surface area to volume) is the strongest parameter that affects heat demand followed by year of building construction, floor area, heating degree day and surface exposure. The result of ANN (Artificial Neural Network) assessment presented in Figure 2.4 shows schools with larger perimeter related to the building size and larger external wall area lose more thermal energy than compact buildings so they required higher levels of energy for heating. The occupant density (number of the pupils) has a considerable impact on electricity demand, but its impact on heat demand was only 10%.

![Figure 2.4. Effect of building parameters on heat consumption][105]

### 2.5. CIBSE TM46:2008

Based on chapter 20 of original CIBSE Guide F i.e., ‘Energy Efficiency in Buildings’ and ‘Energy Consumption Guide 19’ (ECG19) i.e., Energy Efficiency in Offices; the CIBSE TM46 [99] energy benchmark was published by Chartered Institution of Building Services Engineers (CIBSE) in 2008. CIBSE TM46 explained the statutory building energy benchmark methodology which is used as a reference in the UK and Ireland. Display Energy Certificate (DEC), a document that shows an annual energy performance of buildings relies on the CIBSE TM46 methodology.

CIBSE TM46:2008 relies on the collected energy consumption data of various types of buildings from 1995 to 2007 [116]. The median of data (heat consumed) for each type of buildings was calculated by CIBSE and published in TM46. CIBSE on behalf of the Department of the Environment, Transport and the Regions in UK was responsible to conduct the research. Further
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Explanation about the benchmarks was presented in CIBSE TM47:2009 [18]. Other European countries are using the similar methodology for energy benchmarking in buildings.

2.5.1. TM46 Energy Benchmarking Approach

CIBSE TM 46:2008 is the latest version of the benchmarking methodology published in the UK. CIBSE is the responsible authority for providing the energy standards. CIBSE TM46 has specified 237 building types and then based on similarity of functions classified them into 29 benchmark categories as set out in Table 2.2. A larger table is presented in Appendix 1. The 29 functional categories, the electricity and fossil-thermal typical benchmarks as well as their relevant CO\(_2\) emissions are presented in the table. Each building category represents a major functional group of buildings; therefore, the benchmarks indicate how a building performs in relation to the group [18, 99].

Table 2.2. CIBSE TM46 building categories & energy benchmarks [99]

<table>
<thead>
<tr>
<th>Category</th>
<th>Name</th>
<th>Electricity typical benchmark kWh/m(^2)/yr</th>
<th>Fossil_thermal typical benchmark kWh/m(^2)/yr</th>
<th>Total Energy benchmark kWh/m(^2)/yr</th>
<th>Illustrative Electricity typical benchmark kgCO(_2)/m(^2)/yr</th>
<th>Illustrative Fossil_thermal typical benchmark kgCO(_2)/m(^2)/yr</th>
<th>Illustrative Total typical benchmark kgCO(_2)/m(^2)/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row 1</td>
<td>Office</td>
<td>70</td>
<td>120</td>
<td>212</td>
<td>36.3</td>
<td>22.8</td>
<td>59.1</td>
</tr>
<tr>
<td>Row 2</td>
<td>High Street agency</td>
<td>140</td>
<td>140</td>
<td>274</td>
<td>49.5</td>
<td>32.8</td>
<td>82.3</td>
</tr>
<tr>
<td>Row 3</td>
<td>General Retail</td>
<td>105</td>
<td>105</td>
<td>210</td>
<td>36.3</td>
<td>22.8</td>
<td>59.1</td>
</tr>
<tr>
<td>Row 4</td>
<td>Large Retail</td>
<td>70</td>
<td>170</td>
<td>240</td>
<td>41.5</td>
<td>27.3</td>
<td>68.8</td>
</tr>
<tr>
<td>Row 5</td>
<td>Small Retail</td>
<td>310</td>
<td>310</td>
<td>620</td>
<td>106.0</td>
<td>68.8</td>
<td>174.8</td>
</tr>
<tr>
<td>Row 6</td>
<td>Large retail</td>
<td>100</td>
<td>150</td>
<td>250</td>
<td>42.0</td>
<td>27.3</td>
<td>69.3</td>
</tr>
<tr>
<td>Row 7</td>
<td>Restarant</td>
<td>90</td>
<td>370</td>
<td>460</td>
<td>80.5</td>
<td>52.3</td>
<td>132.8</td>
</tr>
<tr>
<td>Row 8</td>
<td>Bar, Pubs, Leisure</td>
<td>150</td>
<td>350</td>
<td>500</td>
<td>87.5</td>
<td>55.5</td>
<td>143.0</td>
</tr>
<tr>
<td>Row 9</td>
<td>Hotel</td>
<td>105</td>
<td>210</td>
<td>325</td>
<td>56.3</td>
<td>34.2</td>
<td>90.5</td>
</tr>
<tr>
<td>Row 10</td>
<td>Cultural activities</td>
<td>70</td>
<td>280</td>
<td>350</td>
<td>60.5</td>
<td>38.4</td>
<td>98.9</td>
</tr>
<tr>
<td>Row 11</td>
<td>Entertainment hall</td>
<td>150</td>
<td>420</td>
<td>570</td>
<td>97.5</td>
<td>62.3</td>
<td>159.8</td>
</tr>
<tr>
<td>Row 12</td>
<td>Swimming Pool Centre</td>
<td>245</td>
<td>1350</td>
<td>1595</td>
<td>214.5</td>
<td>135.1</td>
<td>349.6</td>
</tr>
<tr>
<td>Row 13</td>
<td>Fitness &amp; Health Centre</td>
<td>150</td>
<td>440</td>
<td>600</td>
<td>88.0</td>
<td>55.5</td>
<td>143.5</td>
</tr>
<tr>
<td>Row 14</td>
<td>Dry sports &amp; leisure facility</td>
<td>45</td>
<td>350</td>
<td>415</td>
<td>75.3</td>
<td>47.2</td>
<td>122.5</td>
</tr>
<tr>
<td>Row 15</td>
<td>Covered car parks</td>
<td>15</td>
<td>90</td>
<td>105</td>
<td>18.3</td>
<td>11.4</td>
<td>30.4</td>
</tr>
<tr>
<td>Row 16</td>
<td>Public building with tight energy</td>
<td>40</td>
<td>195</td>
<td>235</td>
<td>41.3</td>
<td>26.8</td>
<td>68.1</td>
</tr>
<tr>
<td>Row 17</td>
<td>Schools &amp; public buildings</td>
<td>40</td>
<td>150</td>
<td>290</td>
<td>51.5</td>
<td>32.5</td>
<td>84.0</td>
</tr>
<tr>
<td>Row 18</td>
<td>University campus</td>
<td>150</td>
<td>195</td>
<td>300</td>
<td>53.8</td>
<td>33.1</td>
<td>86.9</td>
</tr>
</tbody>
</table>

In Table 2.2, the energy benchmarks are presented in kWh/m\(^2\)/yr and they show the typical amount of total primary energy demand in each category in terms of electricity and fossil-thermal. Accordingly, the carbon dioxide benchmark is presented in kgCO\(_2\)/m\(^2\)/yr. The illustrative fossil thermal benchmark (kgCO\(_2\)/m\(^2\)/yr) is expressed for two fuel types (fossil and electricity) and the total fuel consumption. The illustrative fossil thermal typical benchmark shows the amount of emitted CO\(_2\) (kg) from fossil fuel consumed to generate 1 kWh of energy. 0.19 kg of CO\(_2\) per 1 kWh was considered as illustrative benchmark. The literature reviewed in this PhD project mainly...
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focused on the category of University Campus (UC) and further detail is presented in Table 2.3. Other educational buildings such Secondary/Primary schools were also reviewed to understand the thermal energy consumption in other types of educational buildings.

According to the CIBSE TM46 a UC category, incorporates four building types (sub-categories) including: Lecture hall, Sixth form college, Classroom, and University (Table 2.3). An issue which causes confusion is the meaning of UC which could cover various types of buildings on and off campus even though the building could be a sports centre. Moreover, the category title e.g., university campus and its sub-category e.g., university are very similar. The general meaning of UC and its sub-category have caused a series of problems in practice. This gap will be reviewed in further detail in the following sections.

Table 2.3. Sub-categories of UC [99]

<table>
<thead>
<tr>
<th>Building type</th>
<th>Benchmark category</th>
<th>Category name</th>
<th>Building type (Sub-category)</th>
</tr>
</thead>
<tbody>
<tr>
<td>153</td>
<td>18</td>
<td>University campus</td>
<td>Classroom</td>
</tr>
<tr>
<td>154</td>
<td>18</td>
<td>University campus</td>
<td>Lecture hall</td>
</tr>
<tr>
<td>155</td>
<td>18</td>
<td>University campus</td>
<td>Sixth form college</td>
</tr>
<tr>
<td>156</td>
<td>18</td>
<td>University campus</td>
<td>University</td>
</tr>
</tbody>
</table>

There is a wide range of building types on a university campus, however, CIBSE does not explain how to reference these types of buildings on a DEC. This is especially problematic in mixed use buildings which are more complicated. On the other hand, it is not clear which types of buildings on a campus the subcategory of ‘university’ refers to. This gap has misled DEC assessors, for example the Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) & Sports Centre at Trinity College Dublin (TCD) was categorised as UC while it is a mixed use building with swimming pool, fitness, café, research labs, office, and gallery (Figure 2.5). CRANN is also known as Naughton Institute.

CIBSE TM46 suggested only four sub-categories for UC. Comparing 26 sub-categories dedicated to the category of Schools & seasonal public buildings, the limited number of sub-categories of UC needs to be expanded. Due to the variety of university building types comparing with few types of schools in one hand, and a greater amount of energy demand of university buildings, on the other hand, it is expected that CIBSE TM46 will take this gap into account in future revisions of the benchmark. The number of sub-categories in the dataset impacts on the accurate selection of building type by DEC assessors. Filtering unrelated buildings to select the most similar type in the dataset is called Comparison Scenario [28] and the accuracy of the Comparison Scenario is crucial in the top-down benchmarking approach.
2.5.1.1. Annual Consumption Period

Display Energy Certificate (DEC) relies upon the primary delivered energy to a building; therefore, the method of calculating delivered energy is a key factor. Ideally, the delivered energy is measured over a period of one year. The metered or calculated (in case of oil and coal) energy used (kWh) in a course of 365 days is taken into account, however ±31 days are permitted. If delivered energy is not possible to meter directly it is the responsibility of the assessor to inspect delivery records and inventory levels to calculate the annual energy.

2.5.1.2. Separable Energy Uses

If there are significant energy consumers within a building which are metered separately, CIBSE states that these separable energy consumers must be calculated separately from the main building consumption in order to calculate an accurate energy performance. For example, some activities such as supercomputer server rooms or high energy-intensity laboratories, if individually metered, their energy consumption can be subtracted from the overall energy use of the building. These high energy density areas [47] may occupy a small percentage of Total Useful Floor Area (TUFA) of the building which radically affects the Building Energy Rating (BER). Obviously, by separating these parts of the building, the accuracy, relevance and value of BER will improve significantly. Thus, separate DECs for separate energy use areas in the building may be produced. If the separable energy use is subtracted from the total energy consumption of the building the associated area should be subtracted from TUFA [18, 99].

2.5.1.3. Mixed Use Assessment and Composite Benchmark

CIBSE TM47 [18] presented an approach for the calculation of a composite benchmark for mixed use buildings, for example, a library within a public entertainment centre or an office with an integral leisure centre. “Where each activity area exceeds 1000 m² and is separately metered, then it may be appropriate to assess each area separately and produce a separate DEC for each area” [18]. If separate activities are not metered individually an overall DEC may be provided using a composite benchmark method based the weighted area (percentage of area) of each activity. For instance, in a mixed school/swimming pool building, the part of the building that includes classrooms, the category of school and seasonal public buildings could be assigned, category 17; and the part of the building that includes a swimming pool, category 12 could be assigned. Hence, the composite benchmark (CB) is calculated as follows:

\[
CB = \frac{(BM_{school} \times A_{school}) + (BM_{pool} \times A_{pool})}{(A_{school} + A_{pool})} \tag{Equation 2.1}
\]

where A is area (m²) and BM is benchmark.
The composite benchmark concept was used in this work to calculate the heat demand in mixed use college buildings (outlined in Chapter 5).

2.5.1.4. DEC and CIBSE TM46 correlation

The CIBSE TM46 developed methodologies in terms of data collection, data assessment, descriptive statistics (median and mean of data, consumption of 50% of peer buildings) analysis, which were applied in Ireland and many European countries to calculate the typical performance of buildings as well as to generate DECs. Applying weather and occupancy adjustments, neglecting very little difference, similar TM46 benchmarks are used in Ireland. Lack of data collection (fossil, electricity and building information) in Ireland is the main reason for using the CIBSE TM46 benchmarks.

2.6. Display Energy Certificate

In Europe, the Display Energy Certificate (DEC) is a fundamental document adopted to present the energy performance of buildings. In 2008 DECs were introduced in the EU under the Energy Performance of Building Directive (EPBD) regulation as discussed in Section 2.4.1. The feature of DEC is somewhat different among EU member states; however, the alphabetical scale, Building Energy Rating (BER), annual fossil & electricity consumption (kWh/m²), building & assessor information, and carbon footprint are common information. From 9th January 2013 providing a DEC is obligatory for all Irish public buildings over 500m² [67]. Exempted categories of buildings were listed in S.I.243 of 2012. Nevertheless, Sustainable Energy Authority of Ireland (SEAI) requires public bodies to produce and display a DEC for all buildings [67]. In S.I.243 the public body was defined and includes “any public body or public authority/institution set up by Government enactment”, For example, Health Service Executive (HSE), Department of Environment, and Department of State, hospitals, and colleges [67].

SEAI [101] was selected as a responsible authority for managing, supervising, assessing and issuing DECs. Simplified Building Energy Model (SBEM) software generates an energy rating to show how to properly operate a building using a benchmarking methodology which was originally developed in the UK. Obviously, the original methodology has been adjusted to include Irish conditions.

DEC displays the Total Primary Fossil Energy Requirement (TPFER) of a building per year. TPFER is a quantity of all the energy types delivered to the building for the purpose of space heating and hot water and includes all the energy that is used or lost beyond the boundary of the building during the transformation, transmission and distribution processes. Usually, TPFER includes gas, but if other types of bulk energy such as electricity (for heating), oil and coal are
used the amount should be converted into kWh of energy. TPFER is not equal with the Total Final Consumption (TFC), which is the amount of consumed energy as recorded or measured at the end use boundary of the organisation. TFC is measured by a meter and it is the quantity shown on bills [67]. Due to the losses of TPFER at the boundary of buildings, there is about 20% difference between TFC and TPFER, where TPFER is usually greater than the measured energy [104].

Figure 2.5. DEC of CRANN & Sports Centre, TCD
Carbon benchmark, kg of CO₂ emissions of both energy sources (fossil and electricity), was derived using specific coefficients. The Department for Communities and Local Government (CLG) defined the coefficients separately for both energy sources. The coefficients of 0.550 and 0.190 kgCO₂ per 1 kWh of electricity and fossil-thermal respectively were suggested by CIBSE TM 46 [99].

1. UHDB CV Total Primary Fossil Energy Required (TPFER) = 294 kWh/m²/yr
2. Total Primary Electricity Energy Required (TPEER) = 904 kWh/m²/yr
3. Total Primary Energy Required (TPER) = TPFER + TPEER = 294 + 904 = 1198 kWh/m²/yr

The total energy (fossil and electricity) delivered to the building is divided by the typical consumption of peer buildings (similar function) and the result multiplied by 100 to calculate the Building Energy Rating (BER).

\[
\text{BER} = \frac{1198 \text{ kWh/m}^2/\text{yr}}{(610 + 415) \text{ kWh/m}^2/\text{yr}} \times 100 = \frac{569}{1025} \times 100 = 117
\]

To facilitate the understanding of these numbers, especially BER for the people visiting public buildings, the BER was converted into alphabetical (A-G) grades, which shows the building efficiency as illustrated in Figure 2.5. They indicate the best and worst energy performance. There are 15 alphabetical grades on Irish DECs.

The large number of DECs lodged in the DEC database over the years and the breadth of building categories (29 category) allow to the collation of useful information about non-domestic building stock in terms of the overall buildings size, the amount of energy consumption and building performance which is impossible to find from other sources. In addition, long term monitoring and the systematic analysis has caused a movement toward the targets of applicable energy action plans as a result of the annual renewing of DECs [16]. These advantages would be more valuable if the database could be updated annually when new DECs are lodged.

### 2.7. DEC-CIBSE; Discrepancies and Gaps

“For our case study projects, the operational energy use was up to five times higher than estimates during design. There is an opportunity to close this gap and save money and carbon” Carbon Trust [13].

The gap between energy standards and actual measurements can be divided into two main parts; (i) the gap between energy predictions at the design/construction stage and post-occupancy, and (ii) the gap between benchmarks and actual consumption of existing buildings. In (i) the reasons for discrepancy refer to the poor calculation method of performance prediction during the design
stage, weak construction strategies, poor design of building systems, or a combination of all. The studies on the non-domestic sector in European States revealed a 30% discrepancy between actual performance and energy performance estimation using EPBD compliance software [35, 51, 52]. This PhD study focused on (ii), the discrepancies between benchmark and actual measurements.

Regarding the gap between energy benchmarks and actual consumption, the trend of energy consumption over 13 years (1995-2008) showed approximately 21-24% reduction of fossil energy in UK schools due to an increase in performance of building insulation as well as increasing internal heat produced by IT equipment [89]. In the context of European energy certification, Pe´rez-Lombard et al. [28] reviewed benchmarking concepts of energy certification schemes and found that the energy certification faced seven critical issues as follows:

a) Energy performance index definition
b) Ability of tools used for calculation of energy performance
c) Defining an accurate threshold value for performance index
d) Detection of potential energy efficiency measures
e) Comparison scenario selection
f) Determination of scale for energy labelling
g) Energy database quality, quantity, upgrading & development

In this PhD thesis, the first four issues are addressed. Therefore, understanding the current situation of CIBSE TM46 UC benchmarks as well as gaps in this field were reviewed.

Since the thermal energy modelling methodology was influenced by actual conditions, simulation of actual situation increases the accuracy of modelling methodology. Nonetheless, the actual situation alters over time. For instance, the heating set point for classrooms (school and seasonal public buildings category) according to the CIBSE TM46 is 18°C. This temperature in educational buildings did not remain constant during the night and holidays. Moreover, the operation of the heating system is normally defined between 6:00 and 17:00 over weekdays which may alter for a preheating period in winter or overtime activities. Post-occupancy studies showed regular actual operating hours are less than 10% of nominal operating hours. In addition, all spaces were not used during overtime activities, so isolation of conditioned zones that were occupied during overtime can reduce heat consumption [20]. All these changes plus the local HVAC strategies are not considered in standards. As an example, the HVAC strategy and operating schedule of UK schools is shown in Table 2.4.
Using the comparison method the result of actual consumption vs. modelling prediction at four new schools in the UK, constructed under the Building Regulation 2006, was assessed [20]. The authors found that there were significant discrepancies between predicted and measured performance. The difference between calculated (at building design stage using building physics) and measured (post-occupancy) data in some cases was more than 50% as shown in Figure 2.6. The research also found that increasing energy consumption for ventilation purposes, inappropriate operating schedule of heating systems, and the weakness of strategies of demand-control had negative impacts on the heating efficiency and these factors increased the heating energy demand in the studied buildings.

Table 2.4. Timetable and HVAC strategy of UK schools [20]

<table>
<thead>
<tr>
<th>Building type/location, and nominal occupancy</th>
<th>Year built</th>
<th>Gross internal area (m²)</th>
<th>HVAC strategy</th>
<th>Term time operating schedule for heating systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Academy, North West England, 1250 occupants (pupils and staff)</td>
<td>2008</td>
<td>10,418</td>
<td>Mechanically ventilated, Ground Source Heat Pumps supplemented by gas-fired condensing boilers for heating, limited cooling to ICT enhanced spaces is provided by chilled beams served by GSHP</td>
<td>Monday, Wednesday, Thursday: 6:00-18:00</td>
</tr>
<tr>
<td>B. Sixth Form, North West England, 350 occupants</td>
<td>2010</td>
<td>2843</td>
<td>Mechanically ventilated, gas-fired condensing boilers for heating, variable refrigerant flow system for ICT enhanced spaces, solar thermal panels for domestic hot water</td>
<td>Monday, Wednesday, Thursday: Pre-heating: 4:00-6:00, heating: 7:00-20:30</td>
</tr>
<tr>
<td>C. Academy, North East England, 1200 occupants</td>
<td>2009</td>
<td>10,172</td>
<td>Mixed-mode ventilation (natural ventilation boosted by extract fans), biomass-boiler supplemented by gas-fired condensing boilers for heating, cooling and mechanical ventilation provided to ICT enhanced spaces and core areas</td>
<td>Monday to Friday: 7:00-17:00</td>
</tr>
<tr>
<td>D. Secondary School, East London, 2000 occupants</td>
<td>2010</td>
<td>14,610</td>
<td>Natural ventilation, ground source heat pumps supplemented by gas-fired condensing boilers for heating, cooling and mechanical ventilation provided to ICT enhanced spaces and core areas</td>
<td>Monday to Friday: 8:00-17:00</td>
</tr>
</tbody>
</table>

Figure 2.6. Comparison of design prediction and actual consumed heating energy [20]
The research confirmed that the operating schedule of a heating system is a key driver in terms of thermal energy efficiency. This driver was referred to as ‘occupant behaviour’ [117-121]. In these studies, both heat and electrical energy consumption were not assessed separately while the effect of occupant behaviour on heat and electricity consumption is radically different. A lot of studies confirmed that the impact of occupant behaviour on the electricity consumption in public and commercial buildings is greater than the impact of occupant behaviour on heat consumption [122]. The role of occupant behaviour in public buildings in terms of heat consumption is limited to the control of overheating of indoor spaces, whereas this is the outcome of water temperature (boiler systems), heating degree day, and heating operation schedule as shown in Figure 2.7. In fact, these factors are controlled by the Building Services Engineering in non-residential buildings. Therefore, the studies that split the occupant impact on electricity and heat consumption addressed the impact more accurately [123, 124].

Figure 2.7. Role of occupant behaviour on heat energy consumption [117]. (a). % of occupant role in opening windows, (b). % of occupant role in using fans, % of occupant role in turning on the heating systems

“Occupants have little influence on the overall energy consumption in district heated apartment buildings” Kyrö et al.,[54] where data obtained from seven housing companies was used to assess how occupant behaviour in a neutral environment affects the energy consumption in multi-family apartments in Helsinki. The research confirmed that practices and policies of building managers have a direct influence on heating consumption rather than resident’s behaviour. Such results
were also highlighted by Baumann [125] and Brunklaus [126]. The role of the occupant to control indoor conditions in office buildings were also studied and similar results were found [127].

### 2.7.1. DEC Evaluation

In December 2013, research was carried out to assess the accuracy of DEC data collected by Landmark Information Group [128] on behalf of Department for Communities and Local Government (DCLG) in the UK. All the DECs lodged until June 2012 were used in the research. The file contained 120,253 records related to 46,441 various buildings in the UK [14]. To finalise appropriate datasets several rectifications were done including filtering of duplicate data, cleaning of uncertain records, and deleting of pro-rated DECs. After elimination of weak data, 73,160 records belonging to 31,802 buildings were approved [14].

Among the final dataset, the category of UC (University Campus) formed 7% of the approved DECs which belonged to 1,442 buildings as shown in Table 2.5. UC accounted for 8,433,431 m² of the total floor area and emitting more than 743,000 tonnes of CO₂ per year.

<table>
<thead>
<tr>
<th>Benchmark Category</th>
<th>Number of buildings</th>
<th>% of all</th>
<th>% of all</th>
</tr>
</thead>
<tbody>
<tr>
<td>General office</td>
<td>2,911</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>Cultural activities</td>
<td>554</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Entertainment halls</td>
<td>203</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>School and seasonal public buildings</td>
<td>12,563</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td>University campus</td>
<td>1,442</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>Hospital, Clinical &amp; research</td>
<td>573</td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>

The analysis of UC DECs between 2009 and 2011 revealed that about 50% of the buildings have acquired efficiency grades of D, E, F, and G, as presented in Figure 2.8. This means the efficiency of half of the existing university buildings was lower than the CIBSE standard [14]. Thus, taking the high level of thermal energy demand of university buildings i.e. 240 kWh/m²/yr [99] into consideration, the improvement of fossil energy consumption of this type of buildings is crucial and should be addressed.
In Figure 2.9 the distribution of DECs (number of buildings, percentage) by type of HVAC systems is presented. According to the presented data, 50% of buildings (721 building) used heating and natural ventilation system followed by 21% (303 building) of heating & mechanical ventilation.

According to Table 2.6, 85% of thermal energy of analysed UC buildings was provided by natural gas followed by 7% district heating, 3% oil, 3% grid-supplied electricity, and 1% other types of fuel. Other building categories known for a high level of thermal energy demand such as swimming pools with thermal energy benchmark of 1,130 kWh/m²/yr [99] which completely rely upon natural gas. The fuel type assessment of 1,150 of swimming pools in the UK showed that natural gas was the main fuel type of approximately 96% of them. Since most university campuses are equipped with such facilities, the reduction of CO₂ emissions by applying a smart management methodology is highly recommended.
2.7.2. University Occupier Buildings

Hawkins et al. [23] conducted a study to determine the energy drivers in higher education buildings in the UK. The authors classified the energy use drivers in two classes, activity and non-activity drivers. So, for energy benchmarking at the design stage similar to the methodology of CIBSE TM46, the activity was used as a fundamental driver. From the viewpoint of non-activity drivers, the quality of the internal environment is considered as an energy driver. Architectural factors such as building physics played a key role in this class.

A series of problems in the listing of sub-categories of CIBSE TM46 UC was highlighted such as missing of several activities. Hawkins et al. [23] have investigated this gap in more detail and suggested a new category instead of UC. UC category reflects a site-based, complex of buildings, rather than an individual building. To fill the gap, a more pragmatic and demonstrative category called University Occupier Buildings (UOB) was defined instead of the UC. UOB comprised all sub-categories of CIBSE UC which includes four building types, i.e. Lecture hall, Sixth form college, Classroom, and University; plus, other building types that can be identified on a campus such as office, library, auditorium, and laboratory. The authors believed that adding four new building types under the category of UOB (Table 2.7) increased its accuracy.
On the right side of Table 2.7 four building types suggesting by CIBSE under the title of UC are presented. The research team enhanced the list by adding four new building types and collated all eight types under the name of UOB.

The distribution of energy consumption of 1,872 UOBs in terms of electricity and heat energy were compared against CIBSE TM46 benchmark and the results are illustrated in Figure 2.10.

**Figure 2.10. Comparison of energy consumption of UOB samples against CIBSE TM46 [23]**

The results of UOB study are as follows:

- Approximately 78% of the UOB samples were below 240 kWh/m² the heating fuel benchmark suggested by CIBSE TM46 (Figure 2.10).
- Approximately 70% of the UOB samples were below the lowest university campus adjusted heating fuel benchmark of 216 kWh/m² (Figure 2.10).
• The median of electricity consumption was above CIBSE benchmark; in contrast, the median of heating consumption was below the benchmark. Altogether, the actual measured heating consumption for all buildings was 180 kWh/m² (Figure 2.1).

The red dash-dotted line in the Figure 2.11 shows 240 kWh/m² the threshold of CIBSE benchmark. Only the mean of the academic lab was above the CIBSE heat benchmark; while the mean of academic non-lab (17 buildings), administration, medical research, and residential were under heating benchmark line [23].

![Figure 2.11. Medians and interquartile ranges of electricity and heating energy by building activity](image)

The weakness of UOB benchmarking refers to the merging of irrelevant building functions such as cultural activities, entertainment halls, and laboratories with typical college buildings. For example, according to the CIBSE TM46, an entertainment hall needs 420 kWh/m²/yr. So, merging these four suggested categories has a negative impact on the accuracy of benchmarking.

Several studies were carried out to assess the correlation between specific building factors and actual energy consumption to measure the strength of energy use determinants. Raslan and Davies discovered a significant amount of alterability in Part L2a based on forecasted energy performance between various software tools [77].

Various building simulation methods were applied to assess the impact of energy determinants [129-131]. Furthermore, research has been undertaken on university buildings in the UK using DECs to analyse activity and non-activity energy consumption determinants. In the context of
UK, most of the DEC studies have used a dataset compiled by Landmark Information Group [132].

The key drivers affecting the energy performance in non-domestic buildings are architectural aspects, energy systems, and regional conditions [133]. In the school sector, the space heating accounted for about 73% of fossil thermal consumption and the rest was used for hot water and catering. The percentage showed a major portion of fossil energy demand fluctuated with outdoor temperature [133]. Accordingly, other scholars found that there was a direct relationship between fossil thermal consumption and outdoor temperature [134-137].

Building parameters including building activity, building environment, heating fuel type, building age, geometry data, adjacency shading data, adjacency sheltering factor, orientation, glazing, and weather data were assessed using Artificial Neural Network (ANN) energy modelling [23]. In Figure 2.12, the result of assessments of the causal strengths of heat energy determinants is presented. The authors found that the most effective parameters were heating fuel type, activity, building material, and environment respectively. The strength of glazing type and building height was between 10% and 25% however the impact of the other parameters such as glazing ratio, shading factor, orientation, winter/summer sun hours, and aspect ratio was less than 10%. Surprisingly, the authors found that the average winter temperature was not a strong factor and explained that the degree-day was a relevant parameter, but no data was presented to confirm this [23].

![Figure 2.12. Causal strengths of various parameters affect the heat consumption [23]](image-url)
2.7.3. DEC Dataset Review

A review of CIBSE TM46 benchmarks was conducted to assess the robustness of the benchmarking method which underpins the DEC scheme [15]. DEC dataset review shows a series of gaps that justifies further research in the field. By February 2010, almost 45,000 DECs were lodged into the DEC database in the UK. After data cleaning the number of DECs reduced to 29,320. Building Energy Rating (BER) was used as a basis of investigation. Among approved data the schools and seasonal public buildings category formed nearly 50% of the database with 15,335 samples followed by general office and UC with 3,230 and 2,637 samples respectively. The number of analysed buildings and mean floor area of each category are shown in Figure 2.1.

The mean floor area of UC was approximately 3,600 m². By multiplying the number of buildings by the mean of the floor area, the overall area of UC buildings equals 9,493,200 m². The large area plus the high level of thermal energy demand showed the importance of study of energy efficiency in university buildings. The study has proved that the benchmarks are no longer accurately explaining the pattern of energy use of various types of public buildings.

Figure 2.13. (a) Number of buildings. (b) building size in the dataset [15]
The authors suggested a series of recommendations for future DECs including a need to expand the difference between classification types and building activity, a need to regroup building sectors into well-defined categories, and a need to reassess current classifications. Furthermore, they proposed to stop issuing of site-based DECs and recommended to split the site-based DECs into individual buildings [15].

The distribution of efficiency grades of UC category is indicated in Table 2.8. Regarding the category of UC, among 2,637 of the assessed DECs, 797 buildings obtained efficiency grades of E, F, and G which account for 24% of college buildings. Merely 0.3% of DECs (153 buildings) used the option of separable energy use. Based on the assessments, the authors recommended that it is better that CIBSE in the future allows higher consuming electrical equipment to be considered as a separable energy use to make the benchmark more accurate principally in hospitals, universities, laboratories, operating theatres, and workshops.

<table>
<thead>
<tr>
<th>Benchmark category</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>All</th>
<th>BER median</th>
<th>TUFA median</th>
</tr>
</thead>
<tbody>
<tr>
<td>University Campus</td>
<td>8</td>
<td>193</td>
<td>784</td>
<td>855</td>
<td>418</td>
<td>208</td>
<td>171</td>
<td>2,637</td>
<td>84</td>
<td>3,621</td>
</tr>
</tbody>
</table>

Table 2.9 shows the median Energy Use Intensities (Eui) in terms of heat and electricity. The table displays how much the medians deviate from the TM46 benchmarks. For example, a value of 150 indicates the median was 50% above the CIBSE benchmark. In addition, the deviation of value of 61 kWh/m² (for university heating) means it was 39% lower than the benchmark.
Table 2.9. Energy Use Intensities [15]

<table>
<thead>
<tr>
<th>Category</th>
<th>Building Type</th>
<th>No. of Sites</th>
<th>Mean Floor Area</th>
<th>DEC EuBlkR Median</th>
<th>DEC EuHgR Median</th>
<th>DEC Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>General office</td>
<td>3,230</td>
<td>2,762</td>
<td>94</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>High street agency</td>
<td>289</td>
<td>2,310</td>
<td>58</td>
<td>59</td>
<td>85</td>
</tr>
<tr>
<td>3</td>
<td>General retail</td>
<td>37</td>
<td>4,010</td>
<td>57</td>
<td>245</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>Large non-food shop</td>
<td>3</td>
<td>5,905</td>
<td>118</td>
<td>61</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>Small food store</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Large food store</td>
<td>1</td>
<td>6,495</td>
<td>136</td>
<td>119</td>
<td>138</td>
</tr>
<tr>
<td>7</td>
<td>Restaurant</td>
<td>71</td>
<td>1,574</td>
<td>127</td>
<td>59</td>
<td>94</td>
</tr>
<tr>
<td>8</td>
<td>Bar, pub or licensed club</td>
<td>23</td>
<td>2,850</td>
<td>101</td>
<td>55</td>
<td>85</td>
</tr>
<tr>
<td>9</td>
<td>Hotel</td>
<td>34</td>
<td>4,350</td>
<td>83</td>
<td>80</td>
<td>88</td>
</tr>
<tr>
<td>10</td>
<td>Cultural activities</td>
<td>676</td>
<td>2,245</td>
<td>97</td>
<td>24</td>
<td>85</td>
</tr>
<tr>
<td>11</td>
<td>Entertainment halls</td>
<td>266</td>
<td>2,380</td>
<td>224</td>
<td>33</td>
<td>51</td>
</tr>
<tr>
<td>12</td>
<td>Swimming pool centre</td>
<td>588</td>
<td>2,673</td>
<td>79</td>
<td>72</td>
<td>79</td>
</tr>
<tr>
<td>13</td>
<td>Fitness and health centre</td>
<td>107</td>
<td>3,600</td>
<td>108</td>
<td>76</td>
<td>79</td>
</tr>
<tr>
<td>14</td>
<td>Dry sports and leisure facility</td>
<td>895</td>
<td>2,450</td>
<td>78</td>
<td>38</td>
<td>84</td>
</tr>
<tr>
<td>15</td>
<td>Covered car park</td>
<td>2</td>
<td>12,648</td>
<td>43</td>
<td>144</td>
<td>84</td>
</tr>
<tr>
<td>16</td>
<td>Public buildings with light use</td>
<td>7</td>
<td>1,127</td>
<td>210</td>
<td>111</td>
<td>172</td>
</tr>
<tr>
<td>17</td>
<td>Schools and seasonal public buildings</td>
<td>44,454</td>
<td>2,724</td>
<td>5,200</td>
<td>82</td>
<td>46</td>
</tr>
<tr>
<td>18</td>
<td>University campus</td>
<td>2,037</td>
<td>3,011</td>
<td>106</td>
<td>53</td>
<td>81</td>
</tr>
<tr>
<td>19</td>
<td>Clinic</td>
<td>657</td>
<td>1,452</td>
<td>101</td>
<td>87</td>
<td>95</td>
</tr>
<tr>
<td>20</td>
<td>Hospital - clinical and research</td>
<td>1,117</td>
<td>9,219</td>
<td>123</td>
<td>89</td>
<td>104</td>
</tr>
<tr>
<td>21</td>
<td>Long term residential</td>
<td>1,467</td>
<td>1,922</td>
<td>123</td>
<td>79</td>
<td>96</td>
</tr>
<tr>
<td>22</td>
<td>General accommodation</td>
<td>361</td>
<td>2,136</td>
<td>90</td>
<td>55</td>
<td>70</td>
</tr>
<tr>
<td>23</td>
<td>Emergency services</td>
<td>802</td>
<td>1,877</td>
<td>92</td>
<td>76</td>
<td>97</td>
</tr>
<tr>
<td>24</td>
<td>Laboratory or operating theatre</td>
<td>165</td>
<td>3,269</td>
<td>124</td>
<td>131</td>
<td>127</td>
</tr>
<tr>
<td>25</td>
<td>Public waiting or circulation</td>
<td>9</td>
<td>2,276</td>
<td>143</td>
<td>64</td>
<td>225</td>
</tr>
<tr>
<td>26</td>
<td>Terminal</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>Workshop</td>
<td>444</td>
<td>1,651</td>
<td>182</td>
<td>85</td>
<td>139</td>
</tr>
<tr>
<td>28</td>
<td>Storage facility</td>
<td>84</td>
<td>2,545</td>
<td>113</td>
<td>78</td>
<td>94</td>
</tr>
<tr>
<td>29</td>
<td>Cold storage</td>
<td>1</td>
<td>5,161</td>
<td>292</td>
<td>215</td>
<td>259</td>
</tr>
</tbody>
</table>

**Table 2.9. Energy Use Intensities [15]**

- **DEC** - more than 25% out OR more than one grade out
- **AMBER** - a sample too small
- **GREEN** - within 25%

2.7.4. Quantifying Energy Consumption in UK Schools Using DECs

Schools are a type of educational buildings with classrooms, laboratories, coffee shops, fitness and other activities that can be found on a university campus. The occupant behaviour of school pupils is similar to the college students. Due to the similarity in function, activities and occupant behaviour, school buildings were investigated in terms of thermal energy consumption.

Schools accounted for 1.32% of the UK’s total carbon dioxide according to the Sustainable Development Commission report which the amount equalled 7% of emissions of non-domestic buildings [138]. Primary, secondary, and academy (a type of school) building types formed over 80% of 24,600 school stock in the UK. In research carried out by Godoy-Shimizu et al. [16] they used a top-down model of analysis, using DEC data lodged into a dataset under the category of ‘schools and seasonal public buildings’. More than 12,000 school DECs were added to the dataset between 2008 and 2009 which represents a large proportion of the total school building stock. The research aimed to assess key parameters impacted on the energy use such as location, HVAC system, and building size. Comparing the current performance with relevant benchmark was the other aim of the research [16].
Approximately 50% of the all DEC data lodged into the dataset belonged to the category of ‘schools and seasonal buildings’. In the data cleaning process, all duplicate data was removed from the analysis and extra information such as building age, number of pupils, and school type obtained from Ofsted Inspection Reports dataset was added. Around 8,500 DECs matched with the Ofsted dataset. The majority of the matched data was identified as either secondary or primary schools while a few identified as academy. The revised dataset represents 40% of overall public stock for each of these three school types in the UK. Multi-use buildings were removed from the analysis.

Figure 2.14 compares university buildings with other public buildings in terms of number of buildings and annual CO₂ emissions. From CO₂ emission perspective, hospitals generated more than 3.5 Mt of CO₂ per annum, followed by schools, offices and university campuses with 1.80, 1.15, 0.90 Mt respectively [16].

Figure 2.14. Number of building & CO₂ emissions per year [16]

The cumulative frequency distributions of annual energy consumption for the three types of schools i.e., primary, secondary, and academy is shown in Figure 2.15. The dissemination of the curves signifies the range of energy consumption while the median consumption can be observed at 50% of the cumulative frequency for each type. The cumulative frequency was compared with CIBSE TM46 benchmark of ‘Schools and seasonal public buildings’. Approximately 60% of primary schools, 65% of secondary schools, and 75% of academies consumed less thermal energy than TM46 benchmark (150 kWh/m²/yr). The analysis showed that there was not a meaningful difference between fossil thermal energy consumption of these three types of schools. For instance, the difference between the median consumption of primary and secondary was almost 3% and the difference of median of secondary and academies was almost 4%. In analysed schools, the electrical consumption was less than one-third of fossil thermal consumption. Considering kWh/pupil and kWh/m² together, is an effective approach to understand and interpret the energy performance of schools [16].
Table 2.10 presents the percentile statistics of electricity and fossil thermal energy consumption and relevant CO₂ emissions [16]. The average of the medians of heat consumption of 3 types of schools was about 132 kWh/m²/yr which showed a 12% gap with CIBSE TM46 benchmark.

Table 2.10. Energy & CO₂ analysis for schools [16]

<table>
<thead>
<tr>
<th>Building type</th>
<th>Parameter</th>
<th>10%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary schools</td>
<td>Electrical energy (kWh/m²)</td>
<td>27</td>
<td>34</td>
<td>42</td>
<td>53</td>
<td>64</td>
<td>44</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Fossil–Thermal energy (kWh/m²)</td>
<td>81</td>
<td>107</td>
<td>136</td>
<td>170</td>
<td>204</td>
<td>140</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Total energy (kWh/m²)</td>
<td>122</td>
<td>149</td>
<td>180</td>
<td>216</td>
<td>253</td>
<td>184</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>CO₂ emissions (kg CO₂/m²)</td>
<td>36</td>
<td>43</td>
<td>51</td>
<td>61</td>
<td>70</td>
<td>52</td>
<td>14</td>
</tr>
<tr>
<td>Secondary schools</td>
<td>Electrical energy (kWh/m²)</td>
<td>32</td>
<td>40</td>
<td>49</td>
<td>58</td>
<td>70</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Fossil–Thermal energy (kWh/m²)</td>
<td>82</td>
<td>104</td>
<td>132</td>
<td>165</td>
<td>201</td>
<td>138</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Total energy (kWh/m²)</td>
<td>126</td>
<td>151</td>
<td>183</td>
<td>217</td>
<td>257</td>
<td>188</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>CO₂ emissions (kg CO₂/m²)</td>
<td>39</td>
<td>46</td>
<td>54</td>
<td>63</td>
<td>73</td>
<td>55</td>
<td>14</td>
</tr>
<tr>
<td>Academies</td>
<td>Electrical energy (kWh/m²)</td>
<td>39</td>
<td>54</td>
<td>64</td>
<td>99</td>
<td>121</td>
<td>73</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Fossil–Thermal energy (kWh/m²)</td>
<td>75</td>
<td>96</td>
<td>127</td>
<td>153</td>
<td>222</td>
<td>132</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Total energy (kWh/m²)</td>
<td>143</td>
<td>159</td>
<td>183</td>
<td>233</td>
<td>284</td>
<td>205</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>CO₂ emissions (kg CO₂/m²)</td>
<td>45</td>
<td>53</td>
<td>65</td>
<td>77</td>
<td>95</td>
<td>68</td>
<td>20</td>
</tr>
</tbody>
</table>

Research [53] was carried out in 2014 to assess energy consumption of schools in the UK to improve the benchmarking method. The authors used the Landmark dataset which comprised 120,253 DECs in June 2012. The supplementary information such as the number of students in each school obtained from the Department for Education’s EduBase Public portal which contained 39,604 records. Using unique postcodes the supplementary data merged with Landmark dataset. The variation of seasonal difference based on the weather was considered to assess the thermal fossil consumption. After data cleaning, 465 schools were used in the analysis [53].

The cumulative frequency as presented in Figure 2.16 showed that there was no considerable difference in the quantity of fossil thermal energy of primary and secondary schools, with median
values of 121 and $122 \text{kWh/m}^2/\text{yr}$ respectively. These figures of heat energy demand were compared with benchmark of $150 \text{kWh/m}^2/\text{yr}$ suggested by CIBSE TM46 for ‘School and seasonal public buildings.

![Cumulative frequency distribution of energy use index by school types](image)

Figure 2.16. *Cumulative frequency distribution of energy use index by school types* [53]

Parameters which impacted on the heat demand in school buildings are shown in Figure 2.17. The compactness of the buildings had the greatest impact followed by the year of construction, floor area and heating degree days [53].

![Impact of building characteristics on the fossil thermal energy demand](image)

Figure 2.17. *Impact of building characteristics on the fossil thermal energy demand* [53]

### 2.7.5. Quantifying Energy Use in Irish Schools

Hernandez et al. [45] collected the energy performance data of 88 schools in Ireland through questionnaires and building surveys. The median, of measured consumption was $96 \text{kWh/m}^2/\text{yr}$, as shown in Figure 2.18, and it was suggested as a new benchmark for schools. There was a
substantial discrepancy of 54 kWh/m²/yr between the proposed benchmark and the CIBSE TM46 benchmark (150 kWh/m²/yr).

![Figure 2.18. Annual heat energy benchmark for Irish schools][45]

### 2.7.6. CIBSE vs. Design Performance

By mixing data analysis with interviews, Robertson and Mumovic [139] explained the relationship between the legislative framework with energy performance at the design stage. In the analysis, they used CIBSE TM22 and TM46 which are used by building designers and architects as a baseline. CarbonBuzz is an online platform which records and shares actual energy consumption data. In 2012 it comprised of 575 registered users and professional organisations such as architects (141 projects), engineers (82 projects), 74 universities, and 59 engineering consultants [139]. In the assessments, the actual data of CarbonBuzz was used against the benchmarks.

Robertson and Mumovic concluded that 95% of analysed projects have actual electricity consumption higher than design prediction standards and among these 46% were twofold higher than the standard codes. Accordingly, 60% of projects had higher actual heat consumption than the codes and among this 38% were twofold higher. The research showed the design predictions relied on assumptions based on default benchmarks, therefore revising the benchmarks is a necessity.

Regarding the discrepancy between actual measurements and CIBSE TM46 benchmark category of entertainment halls, Heathfield and Bottril [140] conducted research using an energy dataset including more than 100 performing arts building in 2012. According to the assessments, the
authors found that the accurate thermal energy benchmark for this type of buildings is 140 kWh/m²/yr rather than 420 kWh/m²/yr as suggested by CIBSE.

The summary of reviewed literature regarding to energy certification and benchmarks is presented in the Table 2.11.

Table 2.11. Summary of reviewed literature regarding CIBSE TM46

<table>
<thead>
<tr>
<th>Short Title or subject</th>
<th>Method</th>
<th>Findings/results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CIBSE TM46 [99]</td>
<td>Using meter readings to calculate primary energy use in buildings. Buildings are classified to 29 categories and 237 building types. In EU, responsible authorities apply the benchmark to compare energy consumed (fossil and electricity) in a building with that of a typical building to produce a DEC</td>
<td>DEC, BER, CO₂ Emissions Suggestions: 1. Composite benchmark if independent meter available 2. Weather adjustment 3. Hours occupancy adjustment</td>
</tr>
</tbody>
</table>

**Imperfection:**
1. DEC indicates overall primary energy by simply adding fossil and electricity together, however, there is a significant difference between these 2 types of energy sources (Price, CO₂ emissions, weather dependant ratio, aim of consumption, systems, efficiency action plans)
2. DEC shows just the annual energy consumption (kWh/m²) while fossil (mostly use for space and hot water) is weather dependant.
3. DEC does not present efficiency or storage methods for heating, whereas it suggests some general recommendations
4. Despite the suggestion of composite benchmark, in more than 93% of university buildings it was impossible to implement composite benchmark method.
5. The building types suggested by CIBSE for university campus are limited to 4 types. Most of building types that are generally found on campuses were ignored.

| 2 An analysis of DEC (2008-2012) [105] | 36,652 buildings in 29 categories were analysed to validate CIBSE benchmarks. The method assessed DECs issued between 2008 and 2012. Among them, 1,422 university campuses were analysed. | 1. Schools, offices, hospital and universities were responsible for the greatest CO₂ emissions. 2. Revisions of benchmarks in some categories are necessary 3. Only 12% of buildings lodged 4 or more DECs, in addition more than about 50% of all eligible buildings had no DEC 4. 7% of universities applied composite benchmark 5. Natural gas was the main heating fuel of 85% of university buildings |

**Imperfection:** University buildings just limited to the classroom, lecture halls, Sixth form college, and university while there are a variety of other building categories on a campus, such as library, accommodation, gallery, sport centres, and restaurants. The benchmark methodology for UC should comprise various sub-categories under the main title of the UC.

| 3 Assessing building performance: designed using RIBA & CIBSE vs. actual performance [139] | Using actual data of CarbonBuzz dataset and interviews, discrepancy between actual and designed (CIBSE, RIBA) energy codes was analysed. 37 projects were used for comparison to show where variance typically occurs. | 1. Actual heat consumption of 60% of post occupancy projects was greater than the design values, amongst them 38% over 200%. The design stage codes did not predict energy consumption accurately. 2. data collection for determining codes, i.e. design prediction relies upon assumption and default rather than precedent and evidence. The lack of actual energy dataset is the main reason for this. 3. Further research is needed to improve the accuracy of predictions. |
### Literature Review

| 4 | CIBSE review of energy benchmarks using DECs [15] | CIBSE (TM46) reviewed by analysing 45,000 DECs recorded on central landmark dataset in UK | 1. The lack of compliance was found in some CIBSE benchmark categories.  
2. Among 3,621 lodged DECs of university buildings 24% of them got BER with grade of “E”, “F” or “G”.  
3. Analysis showed that 10 building types and 4 benchmark categories have medians outside the threshold of TM46.  
4. Only 3% of buildings used “separable” energy use method.  
5. The heating benchmark of UC was not accurate.  
5. Revising UC benchmark is necessary |
| Imperfection: 1. The research reviewed all 29 building categories to validate CIBSE, therefore the results are general for example, just 5-lines were allocated to the UC. |
| 5 | Assessing energy performance benchmark for performing arts buildings [140] | The robustness of CIBSE TM46 energy benchmark for entertainment halls was assessed against actual consumption of 100 performing arts building | 1. New heating benchmark of 140 kWh/m²/yr for performing arts buildings is more robust than that of CIBSE’s 420 kWh/m²/yr.  
2. Seating capacity is more sensitive and applicable index than floor area suggested by CIBSE |
| Imperfection: 1. suggested UOB benchmark  
2. CIBSE UC heat benchmark is not accurate  
3. Actual electricity consumption was above the benchmark. |
| 8 | Determining of energy use in UK higher education buildings [23] | A pilot study was undertaken to assess end use energy in University Buildings. ANN-based analysis used DEC and building data of other institution such as University College London, Imperial College London, LSE and KCL. The dataset includes 148 DECs covering 97 Individual buildings. 6 types of buildings based on the activity are considered. | 1. suggested UOB benchmark  
2. CIBSE UC heat benchmark is not accurate  
3. Actual electricity consumption was above the benchmark. |
| Imperfection: 1. Suggestion of cultural activities, entertainment halls, office, and laboratory as sub-categories for UC is not appropriate. |

### 2.8. Heat Mapping

A heat map (HM) is a fundamental GIS based method/tool which is used to assess, manage, and track heat demand at an urban district level. HMs are also used for analysing the efficiency and feasibility of District Heating (DH) as well as Combined Heat and Power (CHP) energy systems. DH is an approach to deliver thermal energy in the form of hot water through a local network of highly insulated pipelines [141]. In this way, heat rather than fuel is delivered to buildings. The capability to assess Urban Heat Islands (UHI) is among other advantages of HM. UHI indicates the temperature of surfaces of buildings (roofs) and streets in a city. Two examples in this regard are illustrated in Figures 2.19 and 2.20 where a HM can be used to measure the differences between the surface temperature in a city centre with countryside for instance, to show the impact of cars/motorcycles on street temperature.
HM is used in the current research to assess and manage thermal energy demand at the campus level. A methodology for generating of HMs was developed for smart managing of heat demand-surplus of the university buildings.

The high efficiency of DH systems is a reason for considering it as a key method to reduce fossil energy consumption in several countries such as Denmark, Canada and UK [144-146]. In Scotland initial endeavours to promote HM started in 2007 [147] where a heat map at a resolution of 1 km² was used to indicate the location of both key supply and demand drivers as shown in Figure 2.20.

The ability of combining several data layers in GIS such as geographical, energy & building data, and climate information with urban features is one of the fundamental characters of HM which has led to new urban planning proposals. The technique generates a mapping tool used by urban planners, architects and professionals [19, 148, 149]. Additionally, HM is also a useful tool to assess the end use energy at urban scale. For instance, New York HM illustrated in Figure 2.21
which shows the city’s total annual energy demand density at block level helps policy makers and urban planners to understand the local dynamics of energy consumption of buildings. A web-based annual end use energy consumption database was developed [159] by performing a multiple linear regression to obtain electricity and total fossil fuel density for eight different building types in New York City. Total floor area of each building type was used as a predictor index for electricity and total fuel consumption. To calculate the end use energy density in a building, its total energy consumption per year was divided by total building area.

![Figure 2.21. HM of New York City [150]](image)

Although considering buildings in New York as single use was a weakness of the method, the ability to manage energy consumption at a large scale was a valuable aspect of it. The map shows density of energy demand which is valuable for energy suppliers and other professionals.

In recent studies DH was frequently acknowledged from the environmental, economic, and energy efficiency perspective; hence, it was recommended as a future energy system due to the capability of integration with renewable energy sources [144]. Developing of HM which plots existing and future heat demands vs. existing and future heat supply is a crucial prerequisite for improving DH systems.

HM s involve depicting both heat demand and supply within a group of buildings in a given urban district. In this context, demand refers to the building size, density, functions, orientation, geometry, heat systems efficiency, local energy rules and policy. Heat supply on the other hand, refers to waste heat (machines, human & livestock, industry), surplus heat, urban heat islands, fossil and renewable sources of thermal energy. The structure of HM contains three key factors including sinks, sources, and the heat network and its smart control hub as follows:
Chapter 2

Literature Review

A) Heat sinks [144]:
1. Building physics data such as age, material, orientation, envelop, geometry, size.
2. Estimating heat demand by understating of building types, activities, heating systems, heating policy (in public and large buildings), energy end use
3. All heat losses due to conversion, transmission, and distribution

B) Heat sources [144]:
1. Existing landfill sites (in terms of biomass) and future plans regarding waste heat, for example the heat generated by industry
2. Fossil fuel and renewable sources of energy, potentials and capability
3. Urban morphology regarding UHI as a local source of heat

C) Heat network & network brain (smart hub)
1. Existing and future heat network such as DH/CHP
2. Heat hubs (smart control centres)

2.8.1. Advantages of District Heating

The network based heating system known as District Heating (DH) is a method in which heat energy is generated in a centralised location and then distributed across a network for space heating and domestic hot water (DHW) usage [151]. Historically from the 14th century DH system has been used [152]. In comparison with individual boilers, a DH system is more efficient and produces less CO₂ [153]. Since DH can utilise waste heat from various sources, for example from renewable energy sources, it is more efficient, greener, and more cost-effective in a long term [146, 154, 155]. Table 2.12 shows a momentous growth to approximately 30 million m² in terms of the amount of building area using DH systems in the US and Canada between 2003 and 2006 [156]. DH forms a part of heating systems in the case study universities and based on this fact a new concept of sharing surplus heat was developed in this PhD research. Together with Poland, Germany is the biggest market for DH in EU. The total installed DH capacity in Germany was 49,691 MWth in 2013 [157].

Table 2.12. Growth of floor area serviced by DH from 2003 to 2006 [156]

<table>
<thead>
<tr>
<th>Building type</th>
<th>2003</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US</td>
<td>Canada</td>
</tr>
<tr>
<td>Office and commercial</td>
<td>3600</td>
<td>3200</td>
</tr>
<tr>
<td>Industrial</td>
<td>2600</td>
<td></td>
</tr>
<tr>
<td>Institutional</td>
<td>12,600</td>
<td>7500</td>
</tr>
<tr>
<td>Hotels</td>
<td>1600</td>
<td>1100</td>
</tr>
<tr>
<td>Residential</td>
<td>2200</td>
<td>1100</td>
</tr>
<tr>
<td>Other</td>
<td>6200</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26,600</td>
<td>5400</td>
</tr>
</tbody>
</table>
Recently, a new method of DH was developed which uses low temperature water (30-50 °C) in DH network rather than 70-85 °C as is usually used in the conventional method. The network in the new method is connected with a Thermal Bank (TB) so each member of the network at the boundary of building can apply its own heat source for instance, heat pump or solar thermal to raise the temperature of flow water to a favourite degree [153]. The DH network is similar to the smart electricity grid; however, the smart heat network is in its primary stages and needs to be developed to work as a smart district heating (SDH) system. TB is a large thermal storage place (tank) for storing hot water. Figure 2.22 shows the schematic feature of a DH.

![Schematic feature of a DH system](image)

**Figure 2.22. Schematic feature of a DH system [153]**

The price of supplying an efficient installation can be divided between network members [153]. At a large scale such as a community users of a DH system could make much superior modifications in terms of cost-effective and environmental benefits [158]. DH increases urban air quality by reducing fossil fuel consumption as follows:

1. Building types with a net annual cooling demand such as food stores, refrigerators can act as a heat source
2. Heat could be gathered through passive solar systems, human activity or waste heat from industry or commercial activities
3. Urban heat island can be used as a source of heat

DH has the potential to be used as a smart heating system. Developing and managing the smart systems relies upon IT and mapping tools. Particularly, from the viewpoint of suppliers where the interpretation of heat maps is crucial. Modelling of time-variable heat demand-generation helps
to increase the stability and efficiency of the system and reduce the role of backup (mostly fossil) energy source.

2.9. Solar Thermal Energy

Free solar radiation and zero CO₂ emissions are two advantages of solar thermal energy technology which caused to increase its application around the world. The size selection of evacuated tube solar collector (Figure 2.23) e.g., the number of tube sets with approximate efficiency of 70% [159-161] relies on the peak heat demand and the average annual solar radiation. This means that needing a backup heat source (mainly fossil) in winter and surplus heat during the summer is inevitable. In current research, solar thermal potential using evacuated solar technology was calculated and used as a source of energy in the proposed sharing surplus heat methodology.

![Evacuated solar tubes](image)

**Figure 2.23. Evacuated solar tubes [162]**

2.10. Imperfections of Thermal Energy Storage

Thermal Energy Storage (TES) is a chemical or physical reaction occurs in an accumulator (store) throughout the charge/discharge procedure [163] so that the stored energy can be utilised later for cooling/heating purposes [164]. A wide range of temperature from -40°C to 400°C is applied in various methods of thermal energy storage such as chemical energy (thermo-chemical energy storage method), sensible heat, and latent heat. A variety of technologies and materials such as water, natural beds (mostly rock), hydrates, waxes, sodium, nitrates, and carbonates with various costs of €10-50/kWh are used for thermal storage. High cost is a major barrier to market entry for TES. Each storage method requires a particular TES design to fit specific boundary conditions, so the installation of TES system is simpler and cheaper during the construction process because
many existing buildings do not have enough space for such equipment especially in city centres. In addition, repairing and maintenance of the system are expensive and require professionals [165, 166]. TES faces a series of obstacles such as the large size of stores, expensive technologies and equipment, limited time of storage, stability of material properties, and efficiency of method [166-168].

The reasons for thermal energy storage are as follows:

- Time-variable demands
- Time-variable supply in terms of renewable energy sources (wind and solar)
- The efficiency of energy conversion and utilisation

In most cases the conversion of energy is essential during the storage process which reduces the efficiency of system. In addition, the efficiency of the storage process even without the conversion process in the best systems is less than 80% [163]. In the current research the concept of sharing surplus heat was suggested as an alternative for TES and compared with it.

### 2.11. Summary and Conclusions

The reviewed literature in this chapter showed that educational buildings including schools and universities used approximately 80% of fossil thermal energy for space heating and the rest was used for domestic hot water (DHW) [13]. More than 86% and 88% of thermal energy in UC and schools was provided from gas respectively. Similarly, in other building types such as entertainment halls, cultural activities, and swimming pools, gas accounted for approximately 96%, 83%, and 95% of primary energy respectively [14]. Since most university campuses are equipped with such facilities, increasing of energy efficiency and reducing CO₂ emissions in these types of buildings on a campus is crucial. The fundamental role of UC (University Campus) buildings in the energy action plans because of their large size and high level of heat demand was also highlighted [15, 16].

It was recognised that reduction of fossil energy and relevant CO₂ is the target of many international and national energy action plans [56, 57, 60-62, 70, 97, 169]. To achieve this target, the European 20-20-20 strategy and consequently several detailed studies [59, 61, 62] have led to starting initiative methods such as energy labelling, rating and benchmarking. In the UK and Ireland, the CIBSE TM46:2008 benchmarking method has underpinned the basis of certification method called Display Energy Certificate (DEC).

The reviewed studies have confirmed gaps in the categorising of UC [14, 23] buildings. In addition, the discrepancies between the CIBSE TM46 heat benchmarks and DEC measurements
in schools and university buildings (mostly in UK) were calibrated in several studies and the results revealed a substantial gap in the area [28, 35, 45, 139, 170, 171]. Hence these studies recommended revising the CIBSE TM46 benchmark in order to address the energy efficiency more accurately in the educational buildings in future.

One of the reasons for the discrepancy between CIBSE TM46 benchmarks and actual measurements refers to lack of updating the benchmarks. Therefore, a dynamic dataset as a basis for benchmarking would deliver more accurate data than TM46. Continuous development as well as refining of the dataset in a top-down model is crucial and this moves toward systematic monitoring and collation of a comprehensive database.

The reviewed research mostly focused on the UK, while few studies were found to assess the benchmarking situation in Irish educational buildings. The key role of activity in buildings from the viewpoint of thermal energy demand was underlined by scholars. However, most of studies used the dominant activity (single use) of buildings in the analyses and mixed activities (mixed use) were neglected because of complexity of the method. In this regard the complexity of energy modelling in mixed use buildings as well as the reasons for lack of interest in the topic were reviewed [78, 79, 81, 93, 94, 172].

In some studies, only one index such as median of measurements was used to assess the accuracy of CIBSE TM46 benchmarks. But, using only the median of data in statistical analysis of energy performance is not robust, while the results could be double checked using other statistical tools such as R-squared, the percentage of difference, mean absolute percentage error (MAPE).

TPFER (Total Primary Fossil Energy Required) is a quantity of all the energy types delivered to a building and includes all the energy that is lost beyond the boundary of the building during the transformation, transmission and distribution processes. Usually TPFER is approximately 20% greater than TFC (Total Final Consumption) [99]. This difference refers to the energy losses in the boundary of buildings. TPFER is shown on DECs.

The imperfections of thermal energy storage (TES) [163-166, 172] and the advantages of district heating (DH) systems as a future energy system revealed a pathway toward smart heat network. In this regard, the reviewed literature emphasized the development of heat maps (HM) as a prerequisite of DH [152, 153, 156, 158]. The gaps in the area can be summarised as follows:

- Educational buildings are crucial in terms of heat demand and carbon emission. Further investigations in the area were recommended to predict the heat demand in this type of buildings accurately.
• The category of UC as defined by CIBSE TM46 benchmarks does not reflect the current situation of UC buildings.

• The benchmarking methods and energy modelling need to be developed to fill the current gaps such as approximately 40% discrepancy between benchmark and measurements.

• The low rate of research, lack of feedback, and monitoring systems in Ireland particularly in UC buildings need to be addressed. The lack of an energy database for public buildings in Ireland was highlighted. The available data on energy consumption in Ireland particularly in services sector is limited to the overall sectoral level [24].

• DH is a highly efficient method; however, its foundation, i.e. HM (Heat Map) needs to be developed. Initiative plans in this regard are necessary.

• The difference between TPFER and TFC was approximately 20%.
Chapter 3
A Methodology for Thermal Energy Model Development
Chapter 3. A Methodology for Thermal Energy Model Development

3.1. Introduction

The current thesis developed a new methodology to calibrate the amount of monthly thermal energy demand in college buildings in Dublin. Understanding the accurate amount of thermal energy demand is crucial to develop more effective energy action plans. The methodology also shares more detailed information regarding the buildings located on the studied university campuses. The aim of the developed thermal energy models is to reduce thermal energy in university campus buildings.

This chapter describes the methodology undertaken in this thesis divided into three parts; (i) Development of an Energy Building Database (EBD), which involves the approaches undertaken to create and develop a database by conducting a survey (Survey A) for the purpose of data collection (building function and size) of existing and new buildings. In this part the information of the new buildings at four case study universities are added to the original GIS map and the map is updated. The created database allowed the improvement of the analysis and calibration of energy consumption in typical college buildings.

(ii) Development of monthly thermal energy models for typical college buildings. It includes two methods which are applied to generate the monthly thermal energy models and benchmarks. A further survey (Survey B) to discover the role of mixed activities in typical college buildings is conducted at the floor level. The information obtained from Survey B was used for creating monthly models. CIBSE TM46 University Campus benchmark is assessed against the Display Energy Certificate (DEC) measurements and actual heat consumption. Based on the analysis a new generation of benchmarking, i.e. monthly thermal energy benchmarking was created.

(iii) Development of a District Heat Balance (DHB) tool. This part describes the methodology that was used to create the DHB tool based on EBD database (i), the results of monthly thermal energy demand modelling (ii), and geographical information systems.

Figure 3.1 summarises all three components of the methodology. Parts (i) and (iii) form the start and end processes of the methodology while Part (ii) involves the components for generating monthly thermal models.
Figure 3.1. Detailed schematic of methodology
3.2. Part (i): Creating an Energy Building Database

To develop a robust monthly and consequently seasonal thermal energy demand model, establishing a rich energy database is crucial. As reviewed in the literature [76, 77, 104], access to a database including buildings as well as energy consumption and demand information in Ireland is challenging. Part (i) of the methodology was allocated to create and develop Energy Building Database (EBD). There were three steps involved to create such a database in this research as illustrated in Figure 3.2.

Step (1) was concerned with the upgrading of the original GIS map and building information. Survey A was conducted at the building scale to collect the building information such as site plan of new buildings (location on the campus map), main function and size (number of floors and building area).

The original ArcGIS map, downloaded from Dublinked Website [173], only included building footprint (size) and number of floors. The number of floors in some cases was wrong, but using Survey A this was corrected. In addition, the original ArcGIS map was merged with an AutoCAD file including 29 DXF format files. The DXF files included building location, address and street map. By merging the original GIS map and 29 DXF files, the primary version of the GIS map was generated.

![Creating of EBD diagram](image)

**Figure 3.2. Summary of methods used for creating EBD**

The primary GIS map was compared with the current situation and revealed that it was not up to date e.g., many new buildings were not included. Therefore, updating the primary GIS map was required. Step (1) of the methodology involved the supplementary process of updating the primary
version of GIS map by conducting Survey A to obtain the information of new buildings. Survey A is explained in detail in Section 3.2.2.

The DXF files were merged with the original GIS map to create the primary version of GIS as the process shown in Figure 3.3. This process included TCD (Trinity College Dublin), but did not include UCD (University College Dublin) and DCU (Dublin City University) campuses which are located outside the Dublin city centre.

Using OpenStreetMap, the map of UCD and DCU campuses were added to the primary GIS map. However, double checking of OpenStreetMap of these campuses with Google Map and Google Earth Pro revealed that they did not include new buildings. Since 11 new buildings were constructed in these campuses recently, the updating of GIS map was required. To add the new buildings into the primary GIS map, the Google map of DCU and UCD were inserted into AutoCAD then, new buildings were drawn in AutoCAD and later these AutoCAD files were merged with OpenStreetMap which was developed as a layer in the primary GIS map. Using the Georeferencing tool in ArcGIS, the AutoCAD files were projected with the primary version of the GIS map. Geographic Coordinate System of “GCS_IRENET95” and the Projected Coordinate System of “IRENET95_IRISH_Transverse_Mercator” were used to match the maps accurately. The summary of the process of updating the primary GIS map is illustrated in Figure 3.4.
The attribute table of the original GIS map, downloaded from Dublinked website, contained basic data such as footprint area, footprint perimeter and X & Y coordinates. The attribute table had only 8 columns as illustrated in Table 3.1 and the relevant map to the attribute table, i.e. TCD map is presented in Figure 3.5. In this research this original attribute table was developed by adding further information such as building functions, CIBSE TM46 benchmarks and DEC information. Hence the final attribute table had more than 35 columns. Comparing the final attribute table with the original one, showed the breadth of development of the EBD database.

Table 3.1. The attribute table of original GIS map

<table>
<thead>
<tr>
<th>FID</th>
<th>Shape</th>
<th>BUILDING</th>
<th>AREA_SQR_FT (m²)</th>
<th>BUILDING_PERIM (m)</th>
<th>x</th>
<th>y</th>
<th>X_COORDINATE (m)</th>
<th>Y_COORDINATE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Polygon 2M</td>
<td>30521782</td>
<td>834.577</td>
<td>56.043</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>1</td>
<td>Polygon 2M</td>
<td>0</td>
<td>134.113</td>
<td>2.41</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>2</td>
<td>Polygon 2M</td>
<td>30521781</td>
<td>768.953</td>
<td>7.32</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>3</td>
<td>Polygon 2M</td>
<td>30521785</td>
<td>318.876</td>
<td>103.18</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>4</td>
<td>Polygon 2M</td>
<td>30521783</td>
<td>799.396</td>
<td>10.76</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>5</td>
<td>Polygon 2M</td>
<td>0</td>
<td>6.022</td>
<td>2.44</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>6</td>
<td>Polygon 2M</td>
<td>37.644</td>
<td>2.44</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>7</td>
<td>Polygon 2M</td>
<td>281.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>8</td>
<td>Polygon 2M</td>
<td>280.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>9</td>
<td>Polygon 2M</td>
<td>283.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>10</td>
<td>Polygon 2M</td>
<td>284.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>11</td>
<td>Polygon 2M</td>
<td>285.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>12</td>
<td>Polygon 2M</td>
<td>286.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>13</td>
<td>Polygon 2M</td>
<td>287.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>14</td>
<td>Polygon 2M</td>
<td>288.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
<tr>
<td>15</td>
<td>Polygon 2M</td>
<td>289.441</td>
<td>4.57</td>
<td>71758.184</td>
<td>65.040</td>
<td>59.7388</td>
<td>59.7388</td>
<td>59.7388</td>
</tr>
</tbody>
</table>

Figure 3.5. A sample of the original ArcGIS map
The original attribute table, shown in Table 3.1, includes the following information:

1. **FID** is a unique code assigned to each building in the GIS map. Using FID, the new data joined with existing data.
2. **Shape** shows the shape of footprint of buildings and all of them were a polygon format.
3. **Building-I** is a number allocated to each building in GIS. These numbers were not used in this project.
4. **Area-SQR-M** presents the area of building’s footprint in $m^2$. The information was corrected if necessary. In addition, the footprint area was calculated for all new buildings when upgrading the maps.
5. **Building-H** shows the building height in $m$. The height in most of the cases was wrong, thus at the survey stage they were corrected. The height of the ground floor was measured and multiplied by the number of floors as appropriate. The height was also double checked using Google Earth Pro. In some cases, the height data of Google Earth Pro did not match with the measured value, thus the measured data was applied. Because the number of building floors is a key parameter in the assessment of buildings area, the number of floors of the buildings was carefully surveyed and then the building height as a secondary result was calculated which may be used in future studies. Creating a rich EBD required the inclusion of building height into the dataset.
6. **X & Y** are location coordinates (two separated columns)
7. **Perimeter** is the perimeter of building’s footprint.

To update the GIS map, all new buildings, especially on UCD and DCU campuses, were added into the GIS basemap. To do so, the Google map was inserted into AutoCAD and the roof maps of buildings were drawn and then the ‘dwg’ files (AutoCAD files) were exported into ArcGIS. Roebuck Castle at UCD campus was added into the GIS map and as an example is presented in Figure 3.6. To overlap the AutoCAD drawings with the GIS map in ArcGIS, geoprocessing tools such as Arc Toolbox, Conversion Tools, To Geodatabase, and CAD to Geodatabase were used. The scale of new buildings was matched when they were located in the ArcGIS basemap.
The number of floors and the building functions were obtained by carrying out a survey. For this purpose, a survey Form A (explained further in Section 3.2.2) was designed. The structure of recorded data in EBD is presented in Figure 3.7.

**Figure 3.6.** Adding new buildings into ArcGIS basemap using AutoCAD

**Figure 3.7.** Structural diagram of EBD
3.2.1. Data Sources

Step (2) in creating the EBD involved extracting energy data from three main sources, including Active Energy Management (AEM) software [174], DECs (Display Energy Certificate), and the Estates Office of case study universities, i.e. Trinity College Dublin (TCD), University College Dublin (UCD), Dublin Institute of Technology (DIT) and Dublin City University (DCU).

The actual thermal consumption data was obtained from AEM [174] and these values were used to test the accuracy of developed models. The data of AEM was used to calculate the actual operational hours of heating systems. AEM records the energy consumption of three campuses TCD, DIT, and UCD. For DIT the data was recorded by their Estates Office. The unit of gas consumption at TCD was in kWh, but at UCD, DIT, and DCU it was in $m^3$ thus, the unit of $m^3$ was converted into kWh.

The quarterly hour (15 minutes) gas consumption data of some buildings on these campuses was recorded in AEM. In the AEM, the energy data of all UC buildings was not recorded and this is its limitation. For instance, AEM only recorded the heat consumption of 7 buildings at TCD. The lack of continuous recording of data during a year was another limitation of AEM. For example, the heat consumption of the Hamilton building (TCD) was not continuously recorded in 2010, 2013, 2014, and the first 5 months of 2015. However, the data was used when it was available for one year continuously. For instance, the data of the Hamilton building was continuously recorded in 2011 and 2012. The daily and hourly heat consumption of the Hamilton building at TCD on 13 March 2011 are shown in Figure 3.8 and Figure 3.9 as samples of available data.

![Figure 3.8. An example of daily heat consumption. Hamilton (TCD), March 2011 [174]](image-url)
In this PhD project, the hourly, monthly and annual total final consumption (TFC) heat data recorded on AEM was used for further analysis. The hourly data was used for calculation of daily and consequently monthly operating hours of the heating systems. The operating hours of the heating systems is a key parameter in the modelling of monthly heat demand. The observations of the operating of heating systems showed a difference between energy use strategies in the studied campuses. For example, as shown in Figure 3.10, all typical college buildings at TCD turned the boilers off during the summer, in contrast, in other universities, i.e. UCD, and DCU the boilers were operating in summer.

Furthermore, the reviewed literature showed in non-domestic buildings the operating policy of heating systems was more effective than occupant behaviour [54, 125, 126]. Therefore, in the
conducted PhD methodology the operating procedure was considered as one of the drivers affecting heat consumption.

E3 [130] energy data source was also investigated in this research. The investigation showed that e3 was not an accurate data source and the information on the website was not matched with DEC measurements and surveyed data (in terms of building area and consumed thermal energy). Notable discrepancies were discovered between DECs, AEM data, architectural maps and the data presented on the e3 website. Therefore, this website was removed from the list of data sources.

Display Energy Certificate (DEC) is the other important data source that was used in this PhD project. 84 DECs at four universities in Dublin, i.e. TCD, UCD, DCU, and DIT were collected and the data of DECs extracted and input into the Excel database. Based on the building types some of the DECs were removed for purpose of revising CIBSE TM46 UC (University Campus) benchmark. Further information about DEC selection is presented in Section 3.3.2.

3.2.2. Survey A (Building data collection)

Since function and building size play a fundamental role in the heat consumption and demand, Survey A was conducted to obtain this information. A sample form used for recording the information during the survey is presented in Table 3.2 and an example of a map used in the survey is presented in Figure 3.11. Survey A forms a basic part of Step 2. By visiting of all the buildings belonging to the four university campuses (TCD, UCD, DCU, DIT) the building data were collected. The buildings information obtained by Survey A includes, address & name of buildings, number of floors, building size, and main function. All collected data by Survey A or extracted from the energy data sources such as DECs and AEM were added into EBD.

<table>
<thead>
<tr>
<th>Building index</th>
<th>Building name</th>
<th>Number of floors</th>
<th>Main function</th>
<th>Campus name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Créche</td>
<td>1</td>
<td>Schools</td>
<td>DCU</td>
</tr>
<tr>
<td>2</td>
<td>Albert College</td>
<td>3</td>
<td>College</td>
<td>DCU</td>
</tr>
<tr>
<td>3</td>
<td>The Henry Grattan Building</td>
<td>3</td>
<td>College</td>
<td>DCU</td>
</tr>
<tr>
<td>4</td>
<td>The Helix</td>
<td>3</td>
<td>Entertainment Hall</td>
<td>DCU</td>
</tr>
<tr>
<td>5</td>
<td>DCU language service</td>
<td>4</td>
<td>College</td>
<td>DCU</td>
</tr>
<tr>
<td>6</td>
<td>Hamilton R &amp; D Building</td>
<td>3</td>
<td>College</td>
<td>DCU</td>
</tr>
<tr>
<td>7</td>
<td>Postgraduate residence</td>
<td>4</td>
<td>General accommodation</td>
<td>DCU</td>
</tr>
<tr>
<td>8</td>
<td>Church</td>
<td>1</td>
<td>Public buildings</td>
<td>DCU</td>
</tr>
<tr>
<td>9</td>
<td>Estates Office</td>
<td>2</td>
<td>General office</td>
<td>DCU</td>
</tr>
<tr>
<td>10</td>
<td>Parking</td>
<td>6</td>
<td>Covered parking</td>
<td>DCU</td>
</tr>
<tr>
<td>11</td>
<td>Terence Larkin Theatre</td>
<td>2</td>
<td>Lecture Hall</td>
<td>DCU</td>
</tr>
</tbody>
</table>
Step (3) included the creation of a link in ArcGIS between updated maps (Step 1) and the Excel database (Step 2) which was obtained from the survey.


3.3.1. Survey B (Collection detailed information)

The objective of Survey B was to obtain specific data of 10 typical college buildings at the four case study campuses (TCD, DCU, UCD, and DIT). A typical college building is a type of third level educational building comprising classrooms, labs, offices, restaurant, and shops. Detailed information about all activities (mixed use activities) in these buildings and the relevant area of each activity was used later to create the monthly thermal energy demand models. The list of surveyed buildings is presented in Table 3.3. In Survey B, the architectural plans of buildings were used to determine for example, the area of each activity. In Survey B, the selected buildings were analysed at the floor scale. Availability of complete daily/monthly actual thermal consumption at the quarter-hour level during a year and the availability of architectural plans were two conditions that were used for selection of the buildings.
The purpose of Survey B was to understand the impact of mixed use activities on heat demand in typical college buildings. To understand the activities and the relevant area of each activity, the buildings were inspected room by room. The collected information not only was used to calculate the mixed use heat demand, but also was applied to generate a composite benchmark.

A sample of Survey B for the School of Engineering & Research at DCU is shown in Figure 3.12 in which the activity in each room and the relevant area has been calculated. For instance, the overall area of office, lecture rooms, computer rooms, laboratories, and stores were calculated and the results input into the EBD.
Figure 3.12. A sample of Survey B, School of Engineering & Research, DCU
Since the role of activities and their size in heat analysis is important, the area of mixed use activities of 10 typical college buildings was calculated using the building plans. AutoCAD was used to calculate the area accurately. By adding the area of all activities, the total useful floor area of each building was calculated. In the calculation of useful building area, the definition of ‘Total Useful Floors Area’ (TUFA) as reviewed in the literature was applied. TUFA was defined in Chapter 2, Section 2.4.1. The methodology of TUFA calculation was also used in the DEC methodology in Ireland and clarified in the Irish building legislation [100]. All the detailed information was recorded in the EBD.

As shown in figures (3.13 & 3.14), by clicking on a room in AutoCAD (A seminar room at ground floor of Aras An Phiarsaigh, TCD) and applying the commands of ‘Block’ and ‘List’, the area of room was calculated. This process was undertaken for all rooms and finally the results were categorised based on activity of rooms. The area of seminar rooms, offices, coffee shop, in the building was calculated. The area weighted analysis based on the various activities in the building was used for assessing the role of mixed use on the thermal demand in 10 surveyed buildings. In Chapter 5, the monthly thermal energy models are created using the detailed information obtained from Survey B.

**Figure 3.13.** Ground floor plan

**Figure 3.14.** Calculating the area of a seminar room as an example in AutoCAD
3.3.2. DEC Collection and Selection

As reviewed in the literature in Section 2.7.4, a significant gap between the CIBSE TM46 energy benchmarks (Schools & Universities) and actual measurements of energy usage in educational buildings in the UK was identified. To assess the accuracy of the benchmarking methodology in Ireland, the available DECs of typical college buildings in Dublin were compared with the CIBSE TM46 University Campus (UC) benchmark. Revising the energy benchmark of college buildings was the objective of the comparison.

The CIBSE TM46:2008 [99] divided the building types in an urban context into 29 categories. Detailed information regarding the TM46 benchmark categories was presented in Chapter 2, Section 2.5.1. UC category, because of the building size and high level of heat demand of 240 kWh/m²/yr, is an important category. Ireland uses the CIBSE’s methodology for generating DECs, however, few published studies have been found assessing the energy consumption in Irish third level educational buildings. So, discovering the difference between current heat consumption extracted from DECs and CIBSE TM46 UC benchmark was one of the objectives of this PhD Research.

84 DECs were collected from four universities in Dublin. To compare similar buildings in terms of function only DECs of buildings categorised as UC were taken into account. Therefore, 32 of the collected DECs were removed from the list due to irrelevant building categories such as those categorised as storage facilities and cultural activities. Finally, 52 DECs of college buildings categorised as UC remained in the database for further assessment.

In Chapter 2, Section 2.5.1 a sample of UC DEC was presented in Figure 2.5. Figure 3.15 shows a sample of Non-UC DEC belonging to a storage facility at TCD. The Total Primary Fossil Energy Required (TPFER) data of Non-UC DEC documents was used in energy maps generated in Chapters 6-8. The energy consumption data displayed on UC DECs was used to revise the CIBSE UC benchmark. Further information regarding revising process is presented in Chapter 4.
Figure 3.15. A sample Non-UC DEC
To increase the accuracy of analysis used for revising the CIBSE TM46 UC benchmark, only similar UC categorised buildings were used in the assessment for the following reasons:

1. Using UC category allows the comparison between college buildings to be more specific and increases the accuracy of the method. Comparing buildings categorised as cultural activities within a typical college building does not lead to a precise result in thermal energy modelling. Activity plays a key role in heat consumption, therefore, all other types of buildings except UC were removed from the UC assessment.

2. Among 84 issued DECs, UC was a predominant category. This category covered approximately 62% of all issued DECs, while the other 28 categories such as ‘restaurant’ and ‘cultural activities’ covered 38% of issued DECs. This comparison showed that the UC category comprises a significant percentage of buildings on the studied campuses.

3. UC category in most cases included a series of sub-categories which needs to be investigated in more detail. In contrast, other building categories such as ‘storage facilities’ and ‘general accommodation’ are single function buildings. Due to the effect of mixed use activities on thermal energy consumption [81-83, 87, 175], single use buildings (single function) were not considered in the analysis for generating the seasonal thermal benchmark of typical college buildings. Since activities have a significant impact on energy consumption, understanding the role of actual mixed use activities in the building is essential.

Due to the importance of mixed use activities (in multi-functional buildings) as well as the key role of activities in heat analysis, the activities in each college building were investigated. For example, multi-functionality in TCD buildings is presented in Table 3.4. Chapters 4 and 5 compare the DECs of mixed use buildings categorised as UC with CIBSE TM46 benchmark for this type of building.
Table 3.4. List of activities in UC buildings at TCD

<table>
<thead>
<tr>
<th>TCD campus (DECs)</th>
<th>DEC Category</th>
<th>List of activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moyne Institute</td>
<td>UC</td>
<td>Lab, computer room, office, lecture room, store</td>
</tr>
<tr>
<td>Hamilton Building</td>
<td>UC</td>
<td>Bank, restaurant, lecture room, office, library, shop</td>
</tr>
<tr>
<td>Chemistry Building</td>
<td>UC</td>
<td>Lecture room, lab, office,</td>
</tr>
<tr>
<td>CRANN &amp; Sports Centre</td>
<td>UC</td>
<td>Gallery, lab, coffee shop, swimming pool, fitness, office</td>
</tr>
<tr>
<td>Dixon Hall (SNIAMS)</td>
<td>UC</td>
<td>Computer room, lab, office, lecture theatre, store, plant room, lecture theatre</td>
</tr>
<tr>
<td>Lloyd Building</td>
<td>UC</td>
<td>Computer room, lab, MRI equipment, office, store, plant room, lecture theatre</td>
</tr>
<tr>
<td>Aras An Phiarsaigh</td>
<td>UC</td>
<td>Coffee shop, computer and lab, office, workshop, library</td>
</tr>
<tr>
<td>East End 4&amp;5, The Panoz Institute</td>
<td>UC</td>
<td>Lab, computer room, lecture theatre, plant room, office</td>
</tr>
<tr>
<td>Biotechnology Building (Watts Building)</td>
<td>UC</td>
<td>Office, lab, store</td>
</tr>
<tr>
<td>Book Repository</td>
<td>Storage facility</td>
<td>Bookstore (single use)</td>
</tr>
<tr>
<td>Ussher library</td>
<td>Cultural activities</td>
<td>Library (single use)</td>
</tr>
<tr>
<td>Trinity Hall</td>
<td>General accommodation</td>
<td>Accommodation (single use)</td>
</tr>
<tr>
<td>Gold Smith Hall</td>
<td>General accommodation</td>
<td>Accommodation (single use)</td>
</tr>
</tbody>
</table>

3.3.3. Methodology for Creating the Monthly Thermal Energy Models

The method for generating the monthly and consequently seasonal thermal energy models for a typical college building comprised of several subsections and each subsection involved a comprehensive process. Briefly, the process started from assessing the accuracy of CIBSE UC heat benchmark of 240 kWh/m²/yr [18]. The issues with the benchmark have been found by analysing of 52 UC DECs. By comparing the CIBSE benchmark with DEC measurements the difference between them was calibrated thus, the result of this process is a revised benchmark. This process is discussed in detail in Chapter 4. The revised benchmark was used to estimate the thermal energy demand in typical college buildings.

Based on a significant discrepancy of CIBSE UC benchmark with analysed DECs and the actual measurements extracted from AEM, it was found that activities play a key role in heat consumption. For example, a building used for fitness needs 440 kWh/m²/yr, while an office needs only 120 kWh/m²/yr. Further explanations regarding the impact of activities on heat demand are presented in Chapter 5, Section 5.3. Despite the reviewed literature, assuming the buildings as single use, in this PhD the actual functionality of buildings was considered. In other words, all activities in buildings and their relevant area were surveyed accurately. The statement of mixed use explains the mixed functions of these types of buildings.

The result of the mixed use heat demand method for estimation of heat demand in typical college buildings was much closer to the actual measurements compared with the CIBSE UC benchmark method. However, the difference between the mean of monthly actual measurements and the mixed use method was still significant as illustrated in Figure 3.16. The other gap was that the mixed use method presented a fixed figure similar that of the CIBSE UC benchmark; however, a
monthly profile explains heat demand more accurately. The mixed use method was a horizontal line whereas the study’s aim was to generate a monthly curve. The gap and the aim of monthly modeling is presented in Figure 3.16.

![Figure 3.16. The schematic idea of monthly heat modelling vs. CIBSE TM46 UC](image)

### 3.3.3.1. Monthly Thermal Energy Demand Modelling Using Mixed Use (Method 1)

In this PhD research two methods (1 and 2) were developed to generate the monthly thermal energy models. Considering the fact that the DEC was not provided for a number of buildings for specific reasons, therefore, Method 1 which relies upon the architectural maps to calculate the weight of mixed activities in typical college buildings was applied to generate a monthly thermal energy demand for this kind of buildings. Method 2 relies upon the UC DEC documents and is discussed in Section 3.3.3.2.

One of the reasons that a number of buildings on campus did not apply for DEC is that they are using a District Heating (DH) system. DH system is more efficient than an individual boiler [141, 146, 176]. The heat energy consumed by a district heating system is measured by one central meter therefore, providing separate monthly heat consumption values for each building serviced by DH is impossible. Since DEC needs at least one year of separate metered measurements for each building, providing DEC for buildings serviced by DH system is impractical. CIBSE emphasises the installation of separate meters to measure heat consumption in each individual building. Currently some buildings do not have a private meter, so providing a DEC is not applicable. For example, Museum Building (Department of Engineering and Geology); Parsons Building (Department of Mechanical Engineering); Art Block (Department of Arts and Humanities); The Buttery (restaurant &coffee shops); Graduate Memorial Building, Houses 12,14, 33,35; Book of Kells (old library) and West Chapel (office) at TCD are using district heating systems thus, DECs were not provided for these buildings.
In fact, Method 1 is useful if a DEC is not available. It is applicable for both existing and future buildings. The method relies upon CIBSE benchmarks, i.e. 29 categories, especially those categories found mostly in a typical college building such as general office, restaurant, cultural activities, classrooms, general retail. For calculating a composite benchmark of a typical college building (mixed use building) Method 1 uses architectural maps to calculate the area of each activity. Based on the assessments, a typical college building comprised of several activities which play a crucial role in the heat demand. For example, a general office needs 120 kWh/m²/yr of thermal energy while a restaurant needs 370 kWh/m²/yr [18, 99].

Despite other methods usually considering the buildings as a single use, in Method 1, the actual multiple activities in buildings were taken into account. The method presented in this PhD for calculating the composite benchmark is different from the CIBSE’s method. CIBSE has suggested installing separate meters for each activity more than 1000 m² of area in the building to calculate the composite benchmark. Since approximately all typical college buildings comprise of various activities, installing several meters is impractical, expensive and time consuming. Furthermore, few activities in a UC building have an area of more than 1000 m². So, in practice only 5% of UC buildings have installed separate meters [14, 15].

Using architectural maps to calculate the composite benchmark is inexpensive and does not require any extra equipment, piping, or installation. However, the limitation of the method in existing buildings refers to the availability of architectural maps as well as the requirement to determine the area of activities by survey. Since in future buildings the architectural maps are available, the method can be easily applied.

Using architectural maps the quantity of mixed use heat demand in typical college buildings was calculated based on Equation (3.1).

\[
\text{Mixed use demand (annual)} = \sum_{i=1}^{n} (f_i \times A_i) = \sum_{i=1}^{n} (A_i \times f_i) \quad \text{Equation (3.1)}
\]

Which \((f_i)\) is the CIBSE benchmark of Activity \((i)\), \((A_i)\) is the relevant area (m²) of activity \((i)\)

By dividing the annual heat demand obtained from Equation (3.1) by 12 the mean monthly heat demand can be calculated (Equation 3.2).

\[
\text{Mean monthly heat demand (mixed use method)} = \frac{\sum_{i=1}^{n} (A_i \times f_i)}{12} = \frac{\text{Equation (3.1)}}{12} \quad \text{Equation (3.2)}
\]

The composite benchmark (CB) was calculated by dividing the annual heat demand by the Total Useful Floors Area (TUFA) of the building as shown in Equation (3.3). These equations were developed using the original idea presented in CIBSE TM46:2008.

\[
\text{Composite benchmark (CB)} = \frac{\text{Mixed use demand (annual)}}{\text{TUFA}} \quad \text{Equation (3.3)}
\]
Chapter 3  
A Methodology for Thermal Energy Model Development

Composite Benchmark (CB) = \[ \sum_{i=1}^{n} (A_i \times f_i) \]  
\[ \frac{A(m2)}{A(m2)} \]  
\textit{Equation (3.1)}

Which A is Total Useful Floors Area (TUFA) of building

So far, the study has attempted to develop an approach to estimate heat demand closer to the mean monthly actual measurements. To achieve this goal, the mixed use method was applied and the results were found to be much closer to actual measurements than CIBSE TM46. However, still the objective was to convert the horizontal line (Figure 3.16) into a monthly profile to predict the monthly heat demand accurately. Coefficient \((n)\) which is the ratio of a composite benchmark to the CIBSE UC benchmark as presented in Equation (n) was used to increase the accuracy of the methodology.

Coefficient \((n)\) = \[ \frac{\text{Composite benchmark}}{\text{CIBSE benchmark (240)}} \]  
\textit{Equation (3.3)}

To convert the horizontal line of mixed use demand into a monthly model a series of factors were taken into account. The first factor was Heating Degree Days (HDD) and the base temperature for calculation of heating degree days was 15.5°[18, 99]. The base temperature of 15.5° also was used by CIBSE TM46 for weather adjustment in the operational rating procedure [18, 99]. Heating degree day (HDD) is designed to measure the demand for energy needed to heat a building [177]. The HDD shows how much (°C) and for how long (in days) outside air temperature was lower than a specific (baseline temperature) indoor temperature [178]. The HDD data was obtained from Degree Days.net [178]. Dublin Airport, IE (6.30W, 53.42N), was the location chosen for outdoor temperature and the data of HDD of 2012 and the average of 10 years (2005-2014) is presented in Table 3.5.

\textbf{Table 3.5. Heating Degree Days of 2012 and average of 10 years}

<table>
<thead>
<tr>
<th>Description:</th>
<th>Celsius-based heating degree days for a base temperature of 15.5°C</th>
<th><a href="http://www.degreedays.net">www.degreedays.net</a> (using temperature data from <a href="http://www.worldunderground.com">www.worldunderground.com</a>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source:</td>
<td>No problems detected.</td>
<td>Dublin Airport, IE (6.30W, 53.42N) 2012 HDD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Month</th>
<th>HDD 2012</th>
<th>HDD Monthly</th>
<th>Average 2005-2014 HDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>281</td>
<td>0.12</td>
<td>313</td>
</tr>
<tr>
<td>Feb</td>
<td>253</td>
<td>0.11</td>
<td>286</td>
</tr>
<tr>
<td>Mar</td>
<td>224</td>
<td>0.10</td>
<td>288</td>
</tr>
<tr>
<td>Apr</td>
<td>264</td>
<td>0.12</td>
<td>211</td>
</tr>
<tr>
<td>May</td>
<td>171</td>
<td>0.07</td>
<td>149</td>
</tr>
<tr>
<td>Jun</td>
<td>93</td>
<td>0.04</td>
<td>76</td>
</tr>
<tr>
<td>Jul</td>
<td>65</td>
<td>0.03</td>
<td>43</td>
</tr>
<tr>
<td>Aug</td>
<td>36</td>
<td>0.02</td>
<td>49</td>
</tr>
<tr>
<td>Sep</td>
<td>110</td>
<td>0.05</td>
<td>78</td>
</tr>
<tr>
<td>Oct</td>
<td>214</td>
<td>0.09</td>
<td>144</td>
</tr>
<tr>
<td>Nov</td>
<td>272</td>
<td>0.12</td>
<td>244</td>
</tr>
<tr>
<td>Dec</td>
<td>510</td>
<td>0.14</td>
<td>520</td>
</tr>
<tr>
<td>Total Year</td>
<td>2,294</td>
<td>1.00</td>
<td>2201</td>
</tr>
</tbody>
</table>
Figure 3.17. Heating Degree Days (HDD) of Dublin in 2012, 2014 and Average 2005-2014

The Heating Degree Days (HDD) of 2012, 2014 and average 2005-2014 based on Dublin Airport Weather Station data are presented in Figure 3.17. An average of 10 years of HDD was also used during the modelling/mapping process; however, it did not significantly affect the result. Hence, the annual HDD (of the relevant year) was used to convert the annual (horizontal line) estimation into monthly figures.

Multiplying Equation (3.1) by Coefficient \((n)\) and by \(\frac{\text{HDD}_{\text{month}}}{\text{HDD}_{\text{annual}}}\), Equation (3.4) has been generated. The equation presents the monthly heat demand. The summary of mathematical calculations are as follows.

\[
\left[ \sum_{i=1}^{n} (A_i \times f_i) \right] \times \frac{v_i^{\text{ACTUPA}}}{240} \times \frac{\text{HDD}_{\text{month}}}{\text{Total HDD(annual)}} \quad \text{Equation (3.4)}
\]

\[
\left[ \sum_{i=1}^{n} (A_i \times f_i) \right]^2 \times \frac{1}{240 \times A} \times \frac{\text{HDD}_{\text{month}}}{\text{Total HDD(annual)}} \quad \text{Equation (3.4)}
\]

\[
\left[ \sum_{i=1}^{n} (A_i \times f_i) \right]^2 \times \frac{\text{HDD}_{\text{month}}}{240 \times A \times \text{HDD(annual)}} \quad \text{Equation (3.4)}
\]

Where \((f_i)\) is the CIBSE benchmark of Activity \((i)\), \((A_i)\) is the relevant area \((m^2)\) of activity \((i)\), \(A\) is total useful floors area \((m^2)\), HDD is heating degree day

Equation (3.4) was the basis for the primary version of the monthly heat models. It was calibrated using actual measurements of 10 typical college buildings belonging to 4 universities in Dublin. The analysis showed there was a significant difference between the value of the primary version and actual figures. The difference, especially in summer was notable. Therefore, the primary version, i.e. Equation (3.4) was improved by taking into account further parameters.
The detailed analysis showed in spite of heating degree days which showed the heat demand even during the summer season, the Estates and Facilities Office at TCD turns off the heating systems. This policy drastically reduced heat consumption during the summer. Therefore, another factor, i.e. operational hours of the heating systems was taken into account and multiplied by Equation (3.4). Hence, Equation (3.5) comprised of the primary version (Equation 3.4) and an extra factor, typical operation hours of the heating systems, was generated.

\[
\sum_{i=1}^{n} (A_i \times f_i) \times \frac{\text{HDD month}}{240 \times A \times \text{Total HDD(annual)}} \times \frac{\text{Monthly typical operation (hours)}}{\text{Standard monthly operation (CIBSE, hours)}}
\]

Equation (3.5)

\[
\frac{\text{HDD month}}{240 \times A \times \text{Total HDD(annual)}}
\]

Equation (3.4)

The accuracy of Method (1) was controlled by using absolute percentage error method as well as the R-squared value. The monthly heat model using Equation (3.5) was validated using actual data. The model is detailed in Chapter 5.

3.3.3.2. Monthly Thermal Energy Demand Modelling Based on DECs (Method 2)

The availability of DECs allowed Method 2 to be more straightforward than Method 1 when converting the annual thermal energy demand into monthly profiles. Normally the total primary fossil energy required (TPFER) is presented on DECs in kWh/m²/yr, as illustrated in Figure 2.5 (Chapter 2, Section 2.5.1).

The purpose of Method 2 was to convert TPFER, an annual-fixed number, into a monthly profile. As there is a difference of approximately 20% between TPFER and Total Final Consumption (TFC) [99] as outlined in Chapter 2, Section 2.6, a coefficient of 20% was considered in the analysis to increase the accuracy of the models.

To create a monthly thermal energy demand model using the TPFER values shown on DECs, HDD plays a key role. Equation (3.6) was generated using heating degree days (HDD); however, producing monthly models based on Equation (3.6) was not robust enough, particularly in summer months. Thus, the typical operation hour of heating systems was considered in order to fill the summer gap. The typical operational hours were obtained by calculating the average operational hours of 10 typical college buildings belonging to the 4 universities (TCD, DCU, DIT, UCD) in Dublin. Equation (3.7) was developed using the typical operational hours of heating systems as another key driver.
Using Equations (3.5) and (3.7) the monthly thermal demand of typical college buildings can be calculated. In the next chapters a comprehensive description is presented regarding revising the CIBSE benchmark and seasonal heat demand modelling. Based on monthly thermal energy models, the monthly thermal energy benchmarks were also generated. The capabilities and advantages of the monthly benchmarking methodology were compared with CIBSE TM46 and DEC methodology as presented in Table 3.6. In the table the methodology of DEC and CIBSE were compared with the methodology used in this PhD research.

Table 3.6 compares the abilities of developed monthly thermal energy models with the other methodologies applied by CIBSE TM46 and DEC. For example, DEC considers the dominant (single use) activity in the buildings, while the monthly modelling methodology considers all activities in the buildings. Monthly heating degree days is another factor that was applied in the models, although both DEC and CIBSE neglected its role.
Table 3.6. Comparison of DEC and CIBSE and the monthly benchmarking

<table>
<thead>
<tr>
<th>Content of Method</th>
<th>DEC</th>
<th>CIBSE</th>
<th>monthly benchmarking</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Building size</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>2 Dominant Activity</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Mixed use</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>3 Composite benchmark</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>Taking all activities in the building into account even they not metered separately</td>
</tr>
<tr>
<td>4 Monthly CO₂ emissions</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>5 Monthly HDD</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>HDD: heating degree day</td>
</tr>
<tr>
<td>6 Monthly energy demand</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>7 Monthly heat density</td>
<td>-</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>8 Capability to manage heat demand/generation at campus scale</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>9 Usable for developing/future buildings</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>10 Annual updating</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

3.4. Part (iii): District Heat Balance tool

The District Heat Balance tool (DHB), developed in this PhD research, is a GIS based tool comprised of both energy and building data. DHB is useful to calculate as well as visualise heat demand, heat surplus and to generate the heat maps. Since the heat maps indicate the location of higher and lower thermal energy density buildings, the tool for example, is useful for determining the optimum location of heat generators. DHB helps urban planners, energy professionals, and architects to design and manage energy efficiency/consumption more smartly at the urban regional scale.

Part (iii) of the methodology is dedicated to heat mapping. Considering the future of renewable energy, especially solar thermal, the necessity of a tool to help urban planners, architects and professionals to manage heat balance (heat demand/surplus & sources) at the community scale is vital. Such a tool should comprise of energy usage as well as building physics data.

From energy efficiency and environmental perspective, a district heating (DH) system is a reliable solution and has been utilised in several countries such as Canada, US, and UK [146, 153-156]. DHB tool was used to calculate and manage heat demand-surplus smartly and accurately at the campus scale. In Chapters 6 and 7, the tool is applied to generate heat maps and analyse heat demand and surplus in various buildings in the case study campuses. The DHB tool uses the information recorded in EBD and therefore in ArcGIS it was linked to the attribute table of the EBD. A DHB (District Heat Balance) tool that developed in this PhD research, uses the raw data of EBD to assess and visualise them to generate knowledge and aid decision making.
The EBD includes all information obtained by surveys, generated or calculated during the research process. It contains approximately 120,000 data cells. In four attribute tables of EBD the data of TCD, UCD, DIT and DCU buildings were recorded. The number of rows of the attribute table depends on the number of polygons of GIS map of each campus, while the number of columns in all cases is 30. The tables contain useful data which is necessary for understanding as well as managing monthly, annual thermal energy efficiency, energy demand, energy supply, and the energy consumption patterns at the community scale. An example of the heat maps generated using DHB tool is shown in Figure 3.18. The heat map (HM) of UCD shows the thermal energy density in kWh/m². A sample of attribute table is presented in Table 3.7.

**Figure 3.18. A sample of heat map produced using DHB tool**

**Table 3.7. Attribute table of DHB tool**
The attribute table of DHB tool contains the following information:

- Building physics information: footprint area, number of floors, total useful floor area (TUFA), footprint shape, building name, building height
- Energy information: Building dominant function, CIBSE heat benchmarks, CO₂ benchmark (CIBSE), gross urban heat energy density, footprint urban heat energy density, annual thermal energy demand, monthly heat demand, monthly heat benchmarks, and the overall annual heat demand (at the campus scale)
- To manage the heat balance, e.g., the balance between monthly heat demand and generated heat (renewable potential) the information of renewable heat potential such as solar thermal, biomass and geothermal in Dublin were added into the EBD.
- EBD presents information about the viability of renewable energy systems (solar heating, biomass, geothermal), site assessment and building’s roof and façade information (usable for solar thermal calculations), yard and green space in case of geothermal, location of the yard (if available), green spaces, car access, monthly capability to produce solar thermal, CO₂ emissions, monthly or mean of monthly heat demand, and heat balance, i.e., heat demand or surplus.
- Monthly solar thermal potential models were generated for all buildings on the campuses. To generate the monthly solar radiation maps, the data of NASA Surface Meteorology and Solar Energy [179] was used. In the case of Dublin, the Latitude of 53.34˚ & Longitude of -6.26˚ were used to simulate the solar radiation data. Furthermore, the useful roof area was considered in the calculation of solar thermal potential. The useful roof area based on the orientation was calculated using Google Earth Pro. An example of useful roof area and adjacent green spaces is shown in Figure 3.1.

The above list shows the contribution and development of EBD database. The database also can be used in future studies since in Ireland access to energy dataset is very difficult.
Regarding the geothermal GIS files, the map was downloaded from SEAI website [180] and then the ‘mxd’ format file of geothermal was added into the DHB tool and consequently into the EBD. In Chapter 6 a comprehensive discussion regarding the DHB tool is presented.

### 3.5. Conclusion

The methodology developed in the current research considered several factors such as mixed activities and their significant impact on thermal energy demand. In addition, in the models, the effect of outdoor temperature (monthly heating degree days) was considered to increase the accuracy of the models. During the research a rich database was developed and new methods for generation of heat maps were progressed. Accordingly, a new concept of sharing surplus thermal energy at the campus scale was developed and suggested as an alternative for thermal energy storage. The current research has expanded the boundary of knowledge in the field of thermal energy modelling/management by introducing a new generation of thermal energy benchmarks.

The developed methodology includes three parts; Part (i) of the methodology developed the EBD through creating a detailed database which is the foundation of the research. The existing problems to access such a data to compile a database in Ireland were highlighted in the reviewed literature so, the EBD not only supports this PhD research but also will be made available to be used in future studies. EBD contains approximately 120,000 data cells. Various tools, software, open access database and specific information (for example monthly thermal energy benchmarks), documents (DECs) and maps were used to generate the EBD. The database covers detailed data of 4 universities in Dublin including TCD, UCD, DCU, and DIT.
The characterisation techniques employed to create the EBD database, the criteria used for data selection, data collection process, data sources, the campus and buildings scale surveys, Excel data bank as well as the applied methods during the process have been presented and explained comprehensively.

The methodology of developing and converting the fixed-annual UC benchmark to the informative monthly figures has been presented in Part (ii). In fact, two methods of the conversion process were explained and it was shown which would be applicable in existing and developing buildings. Method (1) is applicable for both future and existing buildings. Method (2) is straightforward and more user friendly; however, it is limited to the existing typical college buildings having DEC. Method (1) relies on the mixed use assessment and building maps to calculate the thermal energy demand. Considering the key factors impacted on the heat demand of typical college buildings, the final version of equations, i.e. Equation (3.5) and Equation (3.7) and the methodology to create the monthly thermal energy models were presented comprehensively.

Approximately 120,000 data cells recorded in the attribute table of the EBD were used as a rich database to generate the Heat Maps (HM). Part (iii) of the methodology described the data recorded in EBD. Such a database can be used in future studies. EBD also shares information about the feasibility of renewable energy systems such as solar thermal, biomass, and geothermal in the studied campuses.
Chapter 4

Revising the CIBSE TM46

University Campus Benchmark
Chapter 4. Revising the CIBSE TM46 University Campus Benchmark

4.1. Introduction

In this chapter based on the data extracted from display energy certificates (DECs) belonging to case study campuses in Dublin, the accuracy of CIBSE (Chartered Institution of Building Services Engineers) TM46 university campus thermal energy benchmark is assessed and then using Descriptive Statistics (DS) methodology, a new benchmark for typical college buildings is presented. The advantages of the updated benchmark in terms of reduction of fossil thermal energy as well as CO₂ emissions are discussed in detail. The process of evaluating the accuracy of CIBSE TM46 university campus benchmark and the revised benchmark is presented in this chapter. Revising the current CIBSE TM46 university thermal energy benchmark is the main goal of this chapter.

CIBSE TM46:2008 methodology is being used to produce Display Energy Certificates (DEC) in both residential and public buildings as required by the EPBD (Energy Performance of Building Directive). Recent studies in the UK [23, 24] explored a significant discrepancy between actual heat energy consumption and CIBSE TM46 benchmarks; however, in Ireland, no studies have been published in which the discrepancy between Irish DECs and CIBSE TM46 UC (University Campus) benchmark were analysed. Relevant research has been reviewed [24, 25, 67, 181-183], but they did not analyse the accuracy of benchmarking of Irish university buildings. This chapter aims to discover the reliability of CIBSE TM46 UC benchmark in Dublin by measuring the standard deviation of the benchmark from DEC measurements.

To assess the difference between DEC figures and the CIBSE TM46 UC standard, the energy performance of four Irish university campuses, including Trinity College Dublin (TCD), University College Dublin (UCD), Dublin City University (DCU) and Dublin Institute of Technology (DIT) were analysed. Based on DECs categorised as UC, the heat consumption is assessed and the results compared with the CIBSE TM46 UC benchmark.

The findings of this analysis confirm a significant difference between CIBSE UC benchmark and DEC measurements. Based on the statistical analyses a revised UC benchmark for typical college buildings in Dublin is suggested. Therefore, by applying the revised UC benchmark a considerable amount of fossil thermal energy can be saved. In addition the environmental impact, i.e. reduced CO₂ emissions, using the revised benchmark is also calculated. The result of energy
assessment of this chapter is used for the creation of monthly thermal benchmarks which is presented in the next chapter.

4.2. Case Studies

CIBSE TM46:2008 is a fundamental benchmarking method and the Irish DEC methodology relies on it to assess the building’s performance. DECs are used as authentic documents in energy action plans. Since the robustness and success of national energy action plans directly depend on the accuracy of the benchmarks, the understanding of the accuracy of CIBSE TM46 UC benchmark in Ireland is crucial.

52 DECs categorised as UC buildings belonging to four university campuses (TCD, UCD, DCU and DIT) in Dublin were analysed from the thermal energy consumption perspective. In Figure 4.1, the locations and view of case study campuses are shown; however, DIT buildings are not centralized on a single campus as they are scattered across the city.

In total, 84 DEC documents belonging to the four case study campuses were collected. Nevertheless, 32 of DECs were removed from CIBSE TM46 UC assessment and 52 DECs categorised as UC buildings were used. The process as well as the logic of data selection was explained in the methodology (Chapter 3, Section 3.3.2). In the following sections, the analysis and the comparison process for each campus are presented in detail.

Figure 4.1. Locations and view of case study campuses, Dublin
4.2.1. Case Study 1: Trinity College Dublin

The first case study was Trinity College Dublin (TCD) which was founded in 1592 and is located in Dublin city centre [184]. Figure 4.2 shows the boundary of TCD campus in Dublin. The campus area is approximately 172,000 m² and its perimeter is about 1,718 m. 68 buildings are located on the campus with a footprint area of 51,615 m². The overall buildings area approximately is 156,665 m². The footprint area shows the area of land used by a building on the campus site while, the overall building area includes the area of all floors such as basement floor. The scattering of case study buildings on the campus is shown in Figure 4.2.

At TCD, 19 DECs were collected and among them 14 buildings were categorised as UC as presented in Table 4.1. To increase the accuracy of the analysis only UC DECs were considered. Other Non-UC categories included storage facilities, general accommodation, hospital, and cultural activities.

Figure 4.2. The boundary of TCD campus [185]
Table 4.1. DEC values, TCD

<table>
<thead>
<tr>
<th>Building Name</th>
<th>TCD campus</th>
<th>Dominant category</th>
<th>TPFER kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moyne Institute</td>
<td>TCD campus</td>
<td>UC</td>
<td>79</td>
</tr>
<tr>
<td>Hamilton Building</td>
<td>UC</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>Biochemistry Building</td>
<td>UC</td>
<td>423</td>
<td></td>
</tr>
<tr>
<td>Chemistry Building</td>
<td>UC</td>
<td>148</td>
<td></td>
</tr>
<tr>
<td>CRANN &amp; Sports Centre</td>
<td>UC</td>
<td>294</td>
<td></td>
</tr>
<tr>
<td>Dixon Hall(SNIMS)</td>
<td>UC</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>Lloyd Building</td>
<td>UC</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Aras and Phiarsaigh</td>
<td>UC</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>School of Nursing</td>
<td>UC</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>East End 4&amp;5, The Panoz Institute</td>
<td>UC</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Biotechnology Building</td>
<td>UC</td>
<td>299</td>
<td></td>
</tr>
<tr>
<td>6-9 South Leinster Street</td>
<td>UC</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>1,3,5 College Green</td>
<td>UC</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Computer Science</td>
<td>UC</td>
<td>167</td>
<td></td>
</tr>
<tr>
<td>Goldsmith Hall</td>
<td>General accommodation</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>Trinity Hall</td>
<td>General accommodation</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>Ussher Library</td>
<td>Cultural activities</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>Book Repository</td>
<td>Storage facility (single campus)</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>St James Hospital</td>
<td>Hospital (single campus)</td>
<td>180</td>
<td></td>
</tr>
</tbody>
</table>

Among 14 typical college buildings (UC), shown in Table 4.1, the greatest heat consumption belonged to the Biochemistry building with 423 kWh/m²/yr, followed by Biotechnology building and CRANN & Sports Centre with 299 and 294 kWh/m²/yr respectively. The most efficient building in terms of heat consumption was Aras and Phiarsaigh with 62 kWh/m²/yr. The highest heat demand of Non-UC categories was 180 kWh/m²/yr belonged to St James Hospital, while the mean demand of two student accommodation buildings was 144 kWh/m²/yr. The high level of heat consumption of Biochemistry and Biotechnology buildings refers the bio incubators and apparatus which need to be heated to a constant temperature throughout the year.

According to the CIBSE TM46:2008 [99] the typical fossil thermal UC benchmark is 240 kWh/m²/yr and accordingly the carbon dioxide benchmark is 45.6 kg/m²/yr. In Figure 4.3 the difference between CIBSE UC heat benchmark with DEC values is presented. The mean of the DECs was calculated as 155 kWh/m²/yr and was presented to allow comparison with CIBSE. Thus, the CIBSE UC heat standard was 1.5 times greater than the mean of 14 buildings. The 35% difference between CIBSE TM46 standard and the mean of DECs showed that the CIBSE TM46 UC benchmark did not match with DEC measurements and the heat consumption of approximately 80% of UC buildings was lower than the benchmark.
Since 2008, when CIBSE TM64 was published, many college buildings have improved from the perspective of heat consumption by replacing double glazing, increasing air tightness and increasing the efficiency of Heating, Ventilation and Air Conditioning (HVAC) systems. In spite of this fast pace of improvement in buildings, CIBSE TM46:2008 has remained as a fixed benchmark without any revision during these 8 years.

Upgrading TM46 benchmarks towards the goals of ‘nearly zero energy buildings’ which is a key milestone in the European energy action plan is crucial. For example, nearly zero energy buildings determined 59 kWh/m² as a benchmark for residential buildings [60, 181], while according to CIBSE TM46 [99] a typical residential building needs 485 kWh/m² of energy [58, 186]. Considering a destination for benchmarking for instance, zero energy building goals for the residential sector, could be extrapolated to other building types. Moving toward nearly zero energy buildings standards could be considered as a final objective of benchmarking. A dynamic benchmark which reduces annually by a smart system toward the benchmarks of nearly zero energy buildings is recommended for future.

Regarding CRANN and the Sports Centre building (Figures 4.4 and 4.5), the detailed analysis showed that two buildings with different activities such as sports (swimming pool & fitness) and cultural activities (science gallery, coffee shop, labs) were merged and assessed on the DEC as one building. Using a shared central heating system between two buildings is a reason for generating one DEC for both buildings. As explained in the literature review, the CIBSE
methodology emphasised on the installation of separate meters for each activity more than 1000 $m^2$ in mixed use buildings such as CRANN and the Sports Centre; however, in practice installing of several independent meters has not been possible which resulted in a shared DEC for CRANN and the Sports Centre buildings.

![Figure 4.4. CRANN & Sports Centre, TCD campus](image)

**Figure 4.4. CRANN & Sports Centre, TCD campus**

![Figure 4.5. Main activities in CRANN & Sports Centre buildings](image)

**Figure 4.5. Main activities in CRANN & Sports Centre buildings**

Instead of categorising both buildings as UC it is recommended to split them into two buildings with two separate DECs based on the relevant categories of cultural activity (Row 10 of CIBSE) and swimming pool (Row 12 of CIBSE). The mistake in categorisation of an irrelevant building as UC was also highlighted in Chapter 2, Section 2.7.2 [14, 23]. The mistake refers to the general meaning of university campus (UC). In the conducted PhD research, among 84 DECs just two cases of irrelevant categorisation were found. The other case was ‘Science Centre Hub & East’ at UCD campus which is an entertainment hall, but categorised as UC.

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The incorrect categorisation of buildings may result in incorrect energy action plans in the building. For example, categorising a gallery as a swimming pool compares the energy consumption of gallery with swimming pools of which the benchmark of a swimming pool is much higher than typical galleries. In connection with CRANN and Sports Centre, separation of DEC in future may involve plans to reduce the heat energy in each building. In spite of the mistake of categorising CRANN and the Sports Centre as UC, the DEC was not removed from TM46 UC assessment.

The assessment UC values at TCD campus confirmed that the energy consumption of 80% of the studied buildings fell below the CIBSE TM46 benchmark, i.e. 240 kWh/m^2/yr as presented in Figure 4.3. In other words, achieving the CIBSE standard is not difficult and thus it does not encourage TCD to further improve building efficiency. While, an effective benchmark should inspire more energy saving.

Figure 4.6.a shows the overall annual predicted heat demand of 14 studied buildings at TCD using CIBSE TM46 benchmark vs. DEC measurements. The overall annual heat consumption based on the DEC values was 10,897,151 kWh/yr while, CIBSE predicted approximately 17,000,000 kWh/yr. Hence, TM46 benchmark predicted nearly 6,000 MWh/yr of fossil thermal energy more than DECs. CO₂ emissions based on DECs were also compared against CIBSE benchmark and the result is shown in Figure 4.6.b. CO₂ analysis showed that the CIBSE benchmark overestimated approximately 1,168,236 kg of CO₂ per year which is a significant gap from an air quality perspective.

**Figure 4.6.a.** Overall annual heat consumption based on DECS vs. CIBSE TM46 UC prediction.  
**Figure 4.6.b.** Overall annual CO₂ emissions based on DECS vs. CIBSE TM46 prediction
The impact of the building area on the heat energy demand in TCD’s UC buildings was analysed and the results are shown in Figure 4.7. Generally, the energy demand will increase if the building area increases. However, the trend depends on the building’s efficiency. For example, the area of the Moyne Institute compared with the area of the Biochemistry building has increased while the energy demand of Moyne Institute has radically decreased as displayed by (1) in Figure 4.7. The footprint area of Moyne Institute was 1,380 m² and its overall area was 3,083 m² while, the footprint area of Biochemistry building was 1,263 m² and its overall area was 2,273 m². The Total Primary Fossil Energy Required (TPFER) of the Biochemistry was 423 kWh/m²/yr, in contrast the TPFER of Moyne Institute which was 79 kWh/m²/yr. The thermal efficiency (heat consumption per 1 m²) of 14 analysed UC buildings is presented in Figure 4.8.

![Figure 4.7](image1.png)

Figure 4.7. The relationship between building area and the annual heat consumption, TCD

![Figure 4.8](image2.png)

Figure 4.8. Thermal efficiency (kWh/m²/yr) of 14 UC buildings, TCD
This similar incompatibility was also observed in Aras An Phiarsaigh and East End 4&5 buildings with efficiency of 62 and 73 kwh/m²/yr respectively as indicated by (2) and (3) in Figure 4.7.

4.2.2. Case Study 2: Dublin Institute of Technology

The second case study was Dublin Institute of Technology (DIT), but the buildings of DIT are not centralised in a single campus [187]. DIT has 15 separate campuses in Dublin such as DIT Aungier St, DIT Kevin St, and DIT Grangegorman. The full list and location of DIT campuses is shown in Figure 4.9. The DIT Bolton Street single campus shown in Figure 4.10 as an example.

Figure 4.9. The location of DIT campuses in Dublin

Figure 4.10. The boundary of DIT Bolton St single campus [185]
The energy consumption of UC buildings at Dublin Institute of Technology (DIT) were analysed and the results compared with the CIBSE TM 46 benchmark. 14 buildings at DIT campus have provided DEC. Among them, 10 typical college buildings were categorised as UC as presented in Table 4.2. UC buildings have formed approximately 71% of DIT buildings with a DEC.

<table>
<thead>
<tr>
<th>Building Name</th>
<th>Dominant category</th>
<th>TPFER kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beresford Street</td>
<td>UC</td>
<td>117</td>
</tr>
<tr>
<td>DIT Aungier Street</td>
<td>UC</td>
<td>130</td>
</tr>
<tr>
<td>DIT Bolton Street, Zhivago</td>
<td>UC</td>
<td>101</td>
</tr>
<tr>
<td>DIT Chatham Row</td>
<td>UC</td>
<td>181</td>
</tr>
<tr>
<td>DIT Church Lane</td>
<td>UC</td>
<td>95</td>
</tr>
<tr>
<td>DIT Kevin Street</td>
<td>UC</td>
<td>142</td>
</tr>
<tr>
<td>DIT Mountjoy Square</td>
<td>UC</td>
<td>66</td>
</tr>
<tr>
<td>DIT Rathmines School of Music</td>
<td>UC</td>
<td>128</td>
</tr>
<tr>
<td>DIT Sackville Place</td>
<td>UC</td>
<td>121</td>
</tr>
<tr>
<td>DIT E block, Bolton Street</td>
<td>UC</td>
<td>113</td>
</tr>
<tr>
<td>DIT Cathal Brugha St</td>
<td>Long term residential</td>
<td>133</td>
</tr>
<tr>
<td>DIT focus Building</td>
<td>Laboratory/operating theatre</td>
<td>109</td>
</tr>
<tr>
<td>DIT Linen St</td>
<td>Workshop</td>
<td>93</td>
</tr>
<tr>
<td>Rathmines House</td>
<td>General office</td>
<td>94</td>
</tr>
</tbody>
</table>

The annual heat consumption of 10 typical college buildings was analysed and the mean consumption has been calculated and compared with the CIBSE TM46 benchmark. The results are presented in Figure 4.11. The mean heat consumption of UC buildings was 119 kWh/m²/yr which showed a difference of 121 kWh/m²/yr with CIBSE TM46 UC benchmark. This means the error of CIBSE standard was 50%. All the analysed buildings consumed less energy than the CIBSE prediction. The results of heat consumption assessments at DIT revealed that the CIBSE standard was not accurate for energy benchmarking and needs to be revised because its error is crucial. The twofold error of CIBSE prediction can cause the energy planners at DIT to be complacent with the current performance of buildings while an accurate benchmark will inspire more energy efficiency as well as CO₂ reduction than the CIBSE TM46 benchmark of 240 kWh/m²/yr.
According to the analysis presented in Figure 4.11, the DIT Chatham Row building consumed the greatest amount of thermal energy per unit area (181 kWh/m$^2$/yr) among 10 UC analysed buildings. In contrast, DIT Mountjoy Square, just consumed 66 kWh/m$^2$/yr, making it the most efficient building at DIT. The high level of thermal energy demand at Chatham Row (Conservatory of Music and Drama) building refers to the mixed activities in the building such as entertainment halls, music classes, and offices. The other reasons were single glazing windows and the architectural form of the building as shown in Figure 4.12 and Figure 4.13. The U shape of the building creates more envelope area (more exposed external walls) which loses more thermal energy comparing with a square building plan. In addition, the airtightness of the building is weak.

![Figure 4.11. DEC measurements vs. CIBSE TM46 UC benchmark, DIT](image)

**Figure 4.11. DEC measurements vs. CIBSE TM46 UC benchmark, DIT**

![Figure 4.12. Single glazing and low airtightness, DIT Chatham Row](image)

**Figure 4.12. Single glazing and low airtightness, DIT Chatham Row**
Furthermore, the heat assessment of UC buildings at DIT showed the overall annual heat consumption was 13,043,978 kWh/m²/yr, while CIBSE benchmark predicted 26,444,400 kWh/m²/yr. Accordingly, CO₂ emissions based on DEC values were approximately 2,478,356 kg/yr, whereas CIBSE TM46 has predicted 5,024,436 kg/yr. In other words, the predicted CO₂ emissions were approximately 2.5 million kg/yr greater than the DEC measurements which is a considerable gap.

The relationship between the building area and heat demand is presented in Figure 4.14. As discussed previously, there is a direct relationship between the buildings area and heat demand; however, there were two exceptions which showed despite an increase of building area the heat consumption fell as illustrated by (1) and (2) in the figure. The data analysis revealed the building efficiency as presented in Figure 4.15, was a factor causing a reduction of thermal energy consumption.
4.2.3. Case Study 3: Dublin City University

The third case study was Dublin City University (DCU) campus comprising of 28 buildings as shown in Figure 4.16. The central campus of DCU is located in Glasnevin, Dublin 9 [188]. The campus area is 192,920 m² and its perimeter is 2,103 m. DCU opened in 1980 and the campus developed quickly [188].

Table 4.3 shows the heat consumption data extracted from 10 UC DECs at DCU campus. According to the analysed data, the mean heat consumption of UC buildings was 143 kWh/m²/yr while CIBSE predicted 240 kWh/m²/yr. The Hamilton R&D building (Figure 4.16, No 15) had the greatest heat consumption of 285 kWh/m²/yr, which was in contrast with the lowest consumption of 64 kWh/m²/yr belonging to the Computer Applications building.

Figure 4.15. The heat consumption per unit area of 10 UC buildings, DIT

Figure 4.16. The Boundary of DCU campus [185]

Table 4.3 shows the heat consumption data extracted from 10 UC DECs at DCU campus. According to the analysed data, the mean heat consumption of UC buildings was 143 kWh/m²/yr while CIBSE predicted 240 kWh/m²/yr. The Hamilton R&D building (Figure 4.16, No 15) had the greatest heat consumption of 285 kWh/m²/yr, which was in contrast with the lowest consumption of 64 kWh/m²/yr belonging to the Computer Applications building.
Chapter 4  Revising the CIBSE TM46 University Campus Benchmark

**Table 4.3. DEC Values, DCU**

<table>
<thead>
<tr>
<th>Building Name</th>
<th>Dominant category</th>
<th>Fossil consumption (DEC) kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCU campus</td>
<td>UC</td>
<td>177</td>
</tr>
<tr>
<td>Albert College &amp; Restaurant</td>
<td>UC</td>
<td>166</td>
</tr>
<tr>
<td>Bea Orpen Building</td>
<td>UC</td>
<td>87</td>
</tr>
<tr>
<td>Business Administration</td>
<td>UC</td>
<td>64</td>
</tr>
<tr>
<td>Computer Applications</td>
<td>UC</td>
<td>142</td>
</tr>
<tr>
<td>Engineering &amp; Research Building</td>
<td>UC</td>
<td>154</td>
</tr>
<tr>
<td>Henry Grattan &amp; Extension</td>
<td>UC</td>
<td>134</td>
</tr>
<tr>
<td>The Hub &amp; Student Centre</td>
<td>UC</td>
<td>285</td>
</tr>
<tr>
<td>R&amp;D Building</td>
<td>UC</td>
<td>145</td>
</tr>
<tr>
<td>School of Nursing</td>
<td>UC</td>
<td>79</td>
</tr>
<tr>
<td>BDI</td>
<td>Laboratory</td>
<td>246</td>
</tr>
<tr>
<td>DCU car park</td>
<td>Covered car park</td>
<td>6</td>
</tr>
<tr>
<td>Hamstead Residence</td>
<td>Long term accommodation</td>
<td>216</td>
</tr>
<tr>
<td>Houses 11,12 &amp;13</td>
<td>Long term accommodation</td>
<td>173</td>
</tr>
<tr>
<td>Houses 14,15 &amp;16</td>
<td>Long term accommodation</td>
<td>200</td>
</tr>
<tr>
<td>Invent</td>
<td>General office</td>
<td>153</td>
</tr>
<tr>
<td>Larkfield residences</td>
<td>Long term accommodation</td>
<td>194</td>
</tr>
<tr>
<td>LIRC</td>
<td>Cultural activities</td>
<td>61</td>
</tr>
<tr>
<td>NICB</td>
<td>Laboratory</td>
<td>340</td>
</tr>
<tr>
<td>Post Graduate Residences A &amp; B</td>
<td>Long term accommodation</td>
<td>361</td>
</tr>
<tr>
<td>Sciences &amp; Sports Science</td>
<td>Laboratory</td>
<td>248</td>
</tr>
<tr>
<td>Sports Complex</td>
<td>Dry sports &amp; leisure facilities</td>
<td>129</td>
</tr>
<tr>
<td>Swimming Pool &amp; Houses 17,18&amp;19</td>
<td>Long term accommodation</td>
<td>228</td>
</tr>
<tr>
<td>The Helix</td>
<td>Entertainment halls</td>
<td>79</td>
</tr>
</tbody>
</table>

According to the data assessment presented in Table 4.3, DCU campus of all four case studies had the greatest number of Non-UC categories. The long term accommodation (six buildings) followed by the laboratory (three buildings) were the most frequent categories among the Non-UC buildings respectively.

Furthermore, the evaluation of UC data which is illustrated in Figure 4.17, shows that CIBSE heat benchmark was around 40% greater than the mean of DEC values at DCU campus. Despite 240 kWh/m²/yr being suggested by CIBSE TM46 as a benchmark, the mean of measurements was 143 kWh/m²/yr. Since, the college buildings are large buildings with a large area this difference is crucial.
Moreover, the heat analysis of UC buildings at DCU campus showed the overall annual heat consumption was 8,598,531 kWh/yr, while CIBSE benchmark predicted 15,082,560 kWh/yr. Accordingly, CO₂ emissions were approximately 1,633,721 kg/yr, whereas the CIBSE predicted 2,865,686 kg/yr. In other words, the predicted CO₂ emissions by CIBSE was nearly 1.2 million kg/yr more than DECs measurements.

The relationship between building area and heat consumption of UC buildings at DCU campus was analysed. As illustrated by (1) in Figure 4.18, despite increasing the building area of Computer Application building the heat consumption fell. The similar exception was also observed in Business Administration Building (2). Likewise, the same trend can be observed in the Henry Grattan & Extension and Engineering & Research buildings (3), whereas the area of both buildings is nearly constant the heat consumption of Engineering & Research building reduced. The renovation of buildings and implementation of double glazing, insulation of building’s envelope, and the airtightness reduced the heat demand. The other incompatibility was seen between R&D building and the Hub & Student Centre (4).

**Figure 4.17.** **DEC measurement vs. CIBSE TM46 UC benchmark, DCU**
The reason for incompatibility between building area and heat consumption is due to the efficiency of buildings as shown in Figure 4.19. For instance, the area of both Computer Application (5,236 m$^2$) and Physics and Electronic (5,242 m$^2$) buildings is very similar; however, the efficiency of the first building was 64 kWh/m$^2$/yr and the efficiency of second one was 79 kWh/m$^2$/yr as shown in Figure 4.19. The annual thermal consumption of the first building was 335,104 kWh, whereas the annual consumption of the second building was 414,118 kWh which showed a difference of approximately 80,000 kWh per year.
4.2.4. Case Study 4: University College Dublin

The fourth case study was University College Dublin (UCD) which is the largest campus with more than 106 buildings illustrated in Figure 4.20. The campus area is 1,290,702 m$^2$ and its perimeter is 6,609 m. With nearly 30,000 students, it is the largest university in Ireland [189].

![UCD campus](image)

Figure 4.20. UCD campus

In this section, DEC data of UCD buildings categorised as UC were assessed and compared with the CIBSE TM46:2008 UC benchmark. The heat consumption of 18 UC buildings was analysed and the data is presented in Table 4.4. According to the analysis, the highest heat consumption belonged to the Science Centre Hub & East with 623 kWh/m$^2$/yr followed by Student Centre and Veterinary Science Centre with 269 and 254 kWh/m$^2$/yr respectively. In contrast, the lowest heat consumption belonged to the Newstead building with 67 kWh/m$^2$/yr.

The reason for the high thermal energy demand in the Veterinary Science Centre is due to the mixed use activities in the building. For example, the incubators, laboratories, and bathrooms use a lot of thermal energy (for space heating and hot water) over a year. While, Newstead building...
is a typical college building which did not need much thermal energy for space heating during the summer and holiday periods.

### Table 4.4. DEC values, UCD

<table>
<thead>
<tr>
<th>Building Name</th>
<th>Dominant category</th>
<th>Fossil consumption (DEC) kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG. &amp; Food SCI. Building, UCD</td>
<td>UC</td>
<td>134</td>
</tr>
<tr>
<td>Belfield House, UCD</td>
<td>UC</td>
<td>102</td>
</tr>
<tr>
<td>Engineering &amp; MAT. SCI. Centre</td>
<td>UC</td>
<td>88</td>
</tr>
<tr>
<td>James Joyce Library</td>
<td>UC</td>
<td>152</td>
</tr>
<tr>
<td>Medical Bureau of Road Safety</td>
<td>UC</td>
<td>83</td>
</tr>
<tr>
<td>Newman Building: DING</td>
<td>UC</td>
<td>181</td>
</tr>
<tr>
<td>Newman House, 85 Saint Stephens Green</td>
<td>UC</td>
<td>125</td>
</tr>
<tr>
<td>Newstead Building</td>
<td>UC</td>
<td>67</td>
</tr>
<tr>
<td>Nova UCD</td>
<td>UC</td>
<td>122</td>
</tr>
<tr>
<td>Quinn School of Business</td>
<td>UC</td>
<td>122</td>
</tr>
<tr>
<td>Richview Campus</td>
<td>UC</td>
<td>148</td>
</tr>
<tr>
<td>Roebuck</td>
<td>UC</td>
<td>123</td>
</tr>
<tr>
<td>Science Centre Hub &amp; East</td>
<td>UC</td>
<td>623</td>
</tr>
<tr>
<td>Science Centre North</td>
<td>UC</td>
<td>247</td>
</tr>
<tr>
<td>Science Centre West</td>
<td>UC</td>
<td>134</td>
</tr>
<tr>
<td>Student Centre</td>
<td>UC</td>
<td>269</td>
</tr>
<tr>
<td>UCD Belfield Campus</td>
<td>UC</td>
<td>116</td>
</tr>
<tr>
<td>Veterinary Science Centre</td>
<td>UC</td>
<td>254</td>
</tr>
<tr>
<td>Tierney Building</td>
<td>General office</td>
<td>75</td>
</tr>
<tr>
<td>Sports Centre</td>
<td>Dry sports &amp; leisure facility</td>
<td>142</td>
</tr>
<tr>
<td>SLLS</td>
<td>Swimming pool</td>
<td>997</td>
</tr>
<tr>
<td>Science Centre South Quarter</td>
<td>Laboratory/operating theatre</td>
<td>313</td>
</tr>
<tr>
<td>Restaurant</td>
<td>Restaurant</td>
<td>243</td>
</tr>
<tr>
<td>O'Reilly Hall</td>
<td>Entertainment halls</td>
<td>145</td>
</tr>
<tr>
<td>Health science phase 1 &amp; 2</td>
<td>Laboratory/operating theatre</td>
<td>140</td>
</tr>
<tr>
<td>Conway Institute &amp; biotech</td>
<td>Laboratory/operating theatre</td>
<td>86</td>
</tr>
<tr>
<td>Charles institute &amp; SB1</td>
<td>Laboratory/operating theatre</td>
<td>145</td>
</tr>
</tbody>
</table>

Among 9 Non-UC categories, laboratory/operating theatre was the most frequent category (4 buildings). Student Learning Leisure and Sports (SLLS) facility, including a swimming pool, had the greatest heat demand of 997 kWh/m²/yr followed by Science Centre South Quarter and a restaurant with 313 and 243 kWh/m²/yr respectively.

In the context of UC category, as shown in Figure 4.21, the mean energy consumption of 18 buildings was 172 kWh/m²/yr, while the CIBSE standard was nearly 28% greater than the mean of the measurements. Approximately 78% of UC buildings consumed less heat energy than the benchmark.
Figure 4.21. DEC measurements vs. CIBSE TM46 UC benchmark, UCD

The analyses showed the overall annual heat consumption based on DECs was 45,687,376 kWh/yr, whereas the CIBSE TM46 benchmark prediction was 62,786,880 kWh/m²/yr which showed around 17 million kWh/yr more than DEC measurements. Furthermore, from carbon dioxide viewpoint, the annual gap between DEC measurements and the benchmark was approximately 3,200 tonne per year.

Regarding the exceptions between heat demand and building area, when the building area increased, there were two disagreements (1) and (2) as illustrated in Figure 4.22. The building efficiency has impacted and generated these incompatibilities. The efficiency (consumption per unit area) of building is shown in Figure 4.23.

Figure 4.22. The relationship between building area and heat consumption, UCD
4.3. Detailed Assessment of Heat Consumption in Four Case Study universities

The findings of DEC assessments of four university campuses in Dublin showed a significant discrepancy between DEC values and CIBSE TM46:2008 UC benchmark. Likewise, a crucial discrepancy between calculated CO₂ emissions using DEC measurements and CIBSE benchmark was found. Considering the huge size of UC buildings, the CIBSE benchmark gap is substantial. The percentage of UC category and Non-UC categories at each campus are presented in Table 4.5. The frequency percentage of UC category was approximately 62% in all case studies.

Table 4.5. DEC of four universities in Dublin

<table>
<thead>
<tr>
<th>Campus name</th>
<th>Number of issued DECs</th>
<th>Number of DECs categorised as UC</th>
<th>Other categories (Non-UC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCD</td>
<td>19</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>DIT</td>
<td>14</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>DCU</td>
<td>24</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>UCD</td>
<td>27</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>52</td>
<td>32</td>
</tr>
<tr>
<td>%</td>
<td>100%</td>
<td>62%</td>
<td>38%</td>
</tr>
</tbody>
</table>
4.3.1. Discrepancy Between Analysed DECs and CIBSE TM46 UC Benchmark

To calculate a new UC revised benchmark (UCrb), 52 UC DECs with a building area of 505,845 m² belonging to four case study campuses were analysed in further detail.

A further objective was to discover which UC building of all the analysed samples is more efficient and what is the difference between the heat consumption of the most efficient building and the worst. The comparison aimed to reveal the span of heat consumption in the UC category which led to a detailed analysis of the university campus category (UC) suggested by CIBSE TM46:2008.

The mean of heat consumption and the overall area of UC buildings in four universities are summarised in Table 4.6. According to the mean of the annual heat consumption, DIT was the most efficient campus in contrast, UCD was the lowest.

<table>
<thead>
<tr>
<th>Campus</th>
<th>Number of UC DECs</th>
<th>Mean of heat consumption kWh/m²/yr</th>
<th>UC area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCD</td>
<td>14</td>
<td>155</td>
<td>71,204</td>
</tr>
<tr>
<td>DIT</td>
<td>10</td>
<td>119</td>
<td>110,185</td>
</tr>
<tr>
<td>DCU</td>
<td>10</td>
<td>143</td>
<td>62,844</td>
</tr>
<tr>
<td>UCD</td>
<td>18</td>
<td>172</td>
<td>261,612</td>
</tr>
<tr>
<td>Overall</td>
<td>52</td>
<td>-</td>
<td>505,845</td>
</tr>
</tbody>
</table>

Using the database developed in this PhD, the heat demand based on DECs and CIBSE benchmark was calculated and the results are presented in Table 4.7. According to the assessment, the mean annual heat consumption of these 52 buildings based on DECs was 152 kWh/m²/yr. By comparing the mean heat consumption of these buildings with the CIBSE UC benchmark (240 kWh/m²/yr), the CIBSE benchmark was around 37% greater than the mean of DECs.
Through multiplying the building area by TPFER, the annual heat consumption was calculated. The analysis showed the overall heat consumption of 52 analysed UC buildings was 76,968,172 kWh/yr and accordingly produced 14,863,137 kg of CO₂ per year. In contrast, TM46 benchmark estimated 121,402,800 kWh/yr which showed approximately 44,000,000 kWh/yr more than DEC
values. The percentage difference between DEC documents and CIBSE TM46 predictions in each building fluctuated between 3% and 160% as shown in Table 4.7.

According to the results of annual heat consumption analysis presented in Figure 4.24, only approximately 10% of buildings consumed more heat energy than the TM46 standard. This means almost 90% of the buildings performances were under the benchmark. In addition, the annual heat consumption of 75% of the analysed buildings was between 65 and 160 kWh/m²/yr.

![Figure 4.24. Analysis of heat consumption of 52 college buildings against CIBSE UC](image)

### 4.3.2. UC Category Assessment

Discovering the range of variation of heat consumption in UC buildings was one of the objectives of this chapter. Understanding the differences of heat demand of peer buildings (similar function) in a category such as UC delivers a set of information which can be used in energy efficiency analysing and planning. Thus, the variation range of UC consumption values was studied. According to Figure 4.25, the greatest heat consumption belonged to Science Centre Hub at UCD with annual consumption of 623 kWh per unit area followed by Biochemistry building and CRANN & Sports Centre at TCD with 423 and 404 kWh per unit area respectively. The mixed use activity such as fitness, swimming pool and labs was the reason for high demand. In contrast, the lowest annual heat consumption belonged to Aras an Phiarsaigh at TCD (A typical college building) with 62 kWh per unit area. The range of values was 561 kWh/m²/yr. In arithmetic, the range of a set of values is the difference between the largest and smallest. The highest (623 kWh/m²/yr) heat consumption was over ten times the lowest (62 kWh/m²/yr) heat consumption.
which illustrated that the CIBSE TM46 UC category is too general and therefore not representative of actual UC buildings. The general meaning of UC caused the DEC assessors to classify some buildings on the campus as UC which are not typical college buildings. Therefore, the definition of UC needs to be clarified.

Figure 4.25. Variation range of heat demand per building area in 52 UC buildings

The activities such as those in CRANN & Sports Centre (TCD) and Science Centre Hub (UCD) are not normal in college building types. These two miscategorised buildings were removed in the following analysis to calculate an accurate relationship between building area and heat demand at typical college buildings. The R-squared method which indicates how close the data are to the fitted regression line was applied to assess the relationship between building area (thermal energy predictor factor) and the consumed thermal energy.

Figure 4.26. The relationship between building area and consumed thermal energy

The R-squared value of 0.9686 (Figure 4.26) showed a strong relationship between the building area and heat demand in typical college buildings. The result confirmed the impact of the building
area on heat demand. Thus, the building area \( A, \ m^2 \) in the modelling of heat demand was considered as one of the predictor factors.

### 4.3.3. University Campus Revised Benchmark

Benchmarking includes the process of calculating the amount of delivered energy to the buildings and then comparing the delivered energy with the median consumption of peers (similar function). The aim of benchmarking is to assess building performance and provide future actions based on the result [190]. In this section, the benchmarking methodology, i.e. descriptive statistics (DS) method used by other scholars [27, 28, 49, 52, 94, 96, 109, 191-194] was applied to define a new benchmark for typical college buildings. This means that the most appropriate index to present the typical performance of building stock is the median rather than the mean of values [45]. However, the mean of values was used to calculate the standard deviation of samples.

To calculate a new UC benchmark, the percentage cumulative frequency distribution of thermal consumption values of 52 UC buildings were compared with CIBSE TM46 as shown in Figure 4.27. The percentage cumulative distribution indicated that the heat consumption of approximately 90% of the analysed buildings was lower than the TM46 benchmark of 240 kWh/m²/yr. The mean (see also Table 4.7) of heat consumption values was 152 kWh/m²/yr; however, the performance of nearly 75% of buildings was lower than the mean.

Statistically, the median of values in a percentage cumulative frequency distribution model indicates the performance of 50% of buildings. The performance of half of the samples in the model was considered as a benchmark. Likewise, the median heat consumption of UC buildings was calculated. According to the analysis, the median of values was 130 kWh/m²/yr. The mean and the median of values for further comparison is shown in Figure 4.27.
Based on the benchmarking methodology, 130 kWh/m²/yr, the median of samples, was considered as a revised heat benchmark for typical college buildings. So, the University Campus revised benchmark (UCrb) of 130 kWh/m²/yr is used in future energy assessments and monthly thermal energy models in this study instead of 240 kWh/m²/yr suggested by CIBSE TM46:2008. UCrb reduced the gap by 46% between TM46 benchmark and actual conditions. A band of 10-75 percentiles is presented in Table 4.8. The typical performance (50th percentile) in the literature was known as a benchmark and 25th percentile was considered to exemplify ‘good practice’ performance [105]. According to the assessments, the 25th percentile was 95 kWh/m²/yr. Therefore, the good practice index for typical college buildings in Dublin is 95 kWh/m²/yr. It is suggested that this good practice index is shown on future Irish DECs as a motivator.

Table 4.8. Thermal energy assessments of UC buildings

<table>
<thead>
<tr>
<th>Fossil thermal density (kWh/m²/yr)</th>
<th>10th %</th>
<th>20th %</th>
<th>25th %</th>
<th>30th %</th>
<th>40th %</th>
<th>50th %</th>
<th>75th %</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Good Practice) or (UCrb)</td>
<td>73</td>
<td>87</td>
<td>95</td>
<td>101</td>
<td>121</td>
<td>130</td>
<td>154</td>
</tr>
</tbody>
</table>

Figure 4.27. UCrb benchmark
4.3.3.1. Assessment of Robustness of UCrb for Typical College Buildings

The robustness and validity of the new benchmark (UCrb) was assessed using statistical analysis. To demonstrate the accuracy of the recommended benchmark, a hypothesis testing was employed. Statistically, constructing confidence intervals are an accepted method to make inference about a population. The associated confidence interval was constructed using the confidence level of 95%.

The results of DS analysis are presented in Table 4.9. According to the results the mean and median were 152 $kWh/m^2/yr$ and 130 $kWh/m^2/yr$ respectively. The lower bound of samples was 125 $kWh/m^2/yr$ while the upper bound was 179 $kWh/m^2/yr$. It can be seen that the UCrb benchmark was located between the lower and upper bound with a confidence level of 95%. So, the UCrb of 130 $kWh/m^2/yr$ is an accurate index validated by DS analysis.

<table>
<thead>
<tr>
<th>Table 4.9. Results of Descriptive Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
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<td><strong>Standard Error</strong></td>
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<td><strong>Median</strong></td>
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<tr>
<td><strong>Mode</strong></td>
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<tr>
<td><strong>Standard Deviation</strong></td>
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<td><strong>Sample Variance</strong></td>
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<td><strong>Kurtosis</strong></td>
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<td><strong>Skewness</strong></td>
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<td><strong>Range</strong></td>
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<td><strong>Sum</strong></td>
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<td><strong>Count</strong></td>
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<tr>
<td><strong>Confidence Level (95.0%)</strong></td>
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<tr>
<td><strong>Upper Bound</strong></td>
</tr>
<tr>
<td><strong>Lower bound</strong></td>
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</table>

Since the interval (125, 179) was large, to assess the accuracy of UCrb more sensitively further DS analyses were applied. Using the bootstrapping methodology, the number of samples was increased to 800. Raising the number of samples grows directly the truthfulness of hypothesis test [105]. By resampling technique, bootstrapping generates large number of values using statistical methods [195]. This method for testing the accuracy of energy determinants was also used by other scholars [105]. Four sample sizes were explored including 80, 160, 320, and 800. The resample values generated using bootstrapping is presented in Table 4.10. The results of Descriptive Statistics of resampled values are shown in Table 4.11.
Table 4.10. An example of the resamples generated using bootstrapping technique

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</table>

According to the DS analysis (Table 4.11), when number of values in hypothesis was increased the interval between lower bound and upper bound (confidence interval) decreased. For example, the lower and upper bound of a hypothesis test conducted using 80 samples were 126 and 156. While the lower and upper bounds of a test using 320 samples were 128 and 137 respectively.

The analysis with 800 resampled values indicated that the median of data (130 kWh/m²/yr) was between the lower bound of 129.48 and the upper bound of 131.42 and therefore, the UCrb with 95% confidence level is a precise description of an up-to-date typical performance of college buildings in Dublin.
The methodology used to develop the UCrb relies upon the heat consumed in similar UC buildings based on DECs. Therefore, thermal energy sources such as cogeneration, Combined Heat and Power (CHP) do not impact on the methodology. The heat source in benchmarking methodology is not matter. However, from the perspective of CO$_2$ emission the fuel type was investigated and in most of the cases gas is the main fuel. No renewable energy source was recorded on the assessed DECs.

### 4.3.3.2. The Effects of Applying UCrb on CO$_2$ Emissions

Considering the huge area of UC buildings ($505,845 \text{ m}^2$) reducing the threshold of benchmark from 240 kWh/m$^2$/yr (CIBSE TM46 UC) into 130 kWh/m$^2$/yr (UCrb) has a large impact on the fossil energy consumption in UC buildings. According to the UCrb, 50% of analysed UC buildings are not energy efficient and they need to implement effective measurements to adjust with the new benchmark.

UCrb dramatically impacts on the fossil thermal energy reduction and accordingly CO$_2$ emissions if applied as an Irish UC benchmark. Based on comparison of TM46 UC benchmark with UCrb, if the revised benchmark applied, almost more than 55,000,000 kWh of fossil thermal energy consumption would be reduced annually. Likewise, more than 10,500 tonnes of CO$_2$ emissions could be prevented. Additionally, the financial aspect of the issue is important. The CIBSE TM46:2008 UC benchmark was approximately 1.85 times greater than the UCrb. Figure 4.28, presents the amount of improved energy consumption as well as CO$_2$ emissions using UCrb.

<table>
<thead>
<tr>
<th>Table 4.11. The results of DS analysis of resampled values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resample size 80</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Median</td>
</tr>
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</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Mode</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Sum</td>
</tr>
<tr>
<td>Count</td>
</tr>
<tr>
<td>Upper bound</td>
</tr>
<tr>
<td>Lower bound</td>
</tr>
</tbody>
</table>
In Table 4.12 the results of current studies that reviewed the accuracy of CIBSE TM46 in educational buildings is compared. According to the results, the minimum error of CIBSE TM46 thermal benchmarks was 10% belonging to primary schools in the UK. In this context, the error in Irish primary schools was 36%, which is a significant discrepancy compared with UK schools. In addition, the errors of CIBSE TM46 benchmark in university buildings were greater than schools. For example, in the UK the errors of 25% and 39% were observed. The error that was found in the current study was 46%.

Table 4.12. Comparing the results of UCrb with the results of similar studies

<table>
<thead>
<tr>
<th>Scholars</th>
<th>Country</th>
<th>Building type</th>
<th>TM46:2008 Thermal benchmark kWh/m²/yr</th>
<th>% of Discrepancy Between TM46 and measurements</th>
<th>Discovered performance kWh/m²/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patxi Hernandez [45]</td>
<td>Ireland</td>
<td>Primary schools</td>
<td>150</td>
<td>36</td>
<td>96</td>
</tr>
<tr>
<td>Sung-Min Hong [105]</td>
<td>UK</td>
<td>Primary schools</td>
<td>150</td>
<td>20</td>
<td>121</td>
</tr>
<tr>
<td>Daniel Godoy-Shimizu [16]</td>
<td>UK</td>
<td>Primary schools</td>
<td>150</td>
<td>10</td>
<td>136</td>
</tr>
<tr>
<td>Sung-Min Hong [105]</td>
<td>UK</td>
<td>Secondary schools</td>
<td>150</td>
<td>26</td>
<td>111</td>
</tr>
<tr>
<td>Daniel Godoy-Shimizu [16]</td>
<td>UK</td>
<td>Secondary schools</td>
<td>150</td>
<td>12</td>
<td>132</td>
</tr>
<tr>
<td>Xuefeng Gao [93]</td>
<td>USA</td>
<td>Non-residential (a Group of buildings)</td>
<td>-</td>
<td>-</td>
<td>167.3</td>
</tr>
<tr>
<td>Hawkins [23]</td>
<td>UK</td>
<td>UOB</td>
<td>240</td>
<td>25</td>
<td>180</td>
</tr>
<tr>
<td>Current PhD research</td>
<td>Ireland</td>
<td>University Campus</td>
<td>240</td>
<td>46</td>
<td>130</td>
</tr>
</tbody>
</table>

From 2008 that CIBSE TM46 published, the thermal demand reduced annually as indicated in 52 case study buildings. The reasons for this reduction were discussed comprehensively in this
chapter previously. Considering the difference (110 kWh/m$^2$) between TM46 UC benchmark and UCr, the gradual reduction of benchmark could be recommended as a goal toward zero fossil thermal energy by 2040 in existing buildings, and zero fossil thermal energy for all new buildings by 2030. Such goals can be defined based on the zero energy buildings standards.

4.4. Conclusion

The heat consumption of 52 UC buildings belonging to 4 major Irish universities in Dublin e.g., TCD, DIT, DCU, and UCD were analysed. Based on DEC measurements the heat consumption was compared with the CIBSE UC benchmark. The UC category consists of nearly 62% of buildings having DEC. According to the assessments, a significant discrepancy of 46% between DEC measurements and CIBSE TM46 was found. In addition, the relationship between the building area and heat demand was assessed and the linear regression value of 0.91 revealed a strong relationship.

Further analysis revealed that the mean annual heat consumption was 152 kWh/m$^2$/yr. By comparing the mean heat consumption with the CIBSE benchmark of 240 kWh/m$^2$/yr, it can be concluded that the difference between DEC consumption measurements with the CIBSE standard was 88 kWh/m$^2$/yr. The result of evaluation confirmed a significant gap between measured data and CIBSE prediction.

In this regard, the results of DS analyses showed that the performance of approximately 90% of UC buildings was lower than the benchmark. Accordingly, the annual heat consumption of 75% of the analysed buildings was between 65 and 160 kWh/m$^2$/yr.

Moreover, among four analysed campuses DIT with a mean consumption of 119 kWh/m$^2$/yr was the most energy efficient campus, in contrast, the lowest energy efficiency was found at UCD with a mean consumption of 172 kWh/m$^2$/yr. In this context, the most energy efficient building was Aras an Phiarsaigh at TCD with annual heat consumption of 62 kWh per unit area, while the greatest heat consumption belonged to Science Centre Hub at UCD with an annual heat consumption of 623 kWh per unit area followed by Biochemistry building, Biotechnology Building, and CRANN & Sports Centre at TCD with 423, 299 and 294 kWh/m$^2$/yr respectively. The mixed use activities was a factor which increased the heat demand in these buildings.

The broad consumption range and significant difference between the greatest (623 kWh/m$^2$/yr) heat consumption and lowest (62 kWh/m$^2$/yr) shows the category of UC covers various building types.
The percentage cumulative frequency distribution analyses showed that the median heat consumption of 52 college buildings was nearly 130 kWh/m$^2$/yr which reflected the consumption of 50% of the analysed samples. Based on the definition of the energy benchmark, the median consumption was suggested as a UC revised benchmark (UCrb). UCrb decreases fossil fuel consumption and CO$_2$ emissions in UC buildings. Using UCrb approximately 55 million kWh of fossil thermal energy as well as more than 10,500 tonnes of CO$_2$ can be saved annually. Furthermore, the 25$^{th}$ percentile of samples was 95 kWh/m$^2$/yr which indicates the good practice index. It is suggested that this index is displayed on future Irish DECs as a motivator.

Since energy benchmarking in buildings underpins the DEC methodology and on the other hand DECs form the foundation of energy action plans at local as well as national scale, revising the current benchmark is crucial to provide accurate energy efficiency plans. The revised benchmark increases the energy efficiency of buildings comparing CIBSE TM46 benchmark and consequently, reduces the fossil thermal consumption and CO$_2$ emission. Considering the large size and number of college buildings the impact of revised benchmark (UCrb) on mitigation of global warming is significant. Other advantages such as reduction of fuel expenses are also important.

The revised UCrb benchmark will be used in the heat modelling methods (in chapter 5) in order to improve the accuracy of the thermal demand estimations. Finally, the energy assessment presented in this chapter highlighted three key parameters which affect heat demand in the typical college buildings including, building area, energy efficiency, and UCrb. These factors will be used to create the monthly heat models for typical college buildings.
Chapter 5

Monthly Thermal Energy Modelling and Benchmarking
Chapter 5. Monthly Thermal Energy Modelling and Benchmarking

5.1. Introduction

In this chapter, two new methodologies are presented to create a new generation of thermal energy benchmarks. Unlike the CIBSE (Chartered Institution of Building Services Engineers) TM46 benchmark which predicts thermal energy demand at the annual scale, the developed methodologies can predict the demand at the monthly level which is more informative and effective in energy efficiency planning. The aim of the chapter is to progress the knowledge in the field of thermal energy modelling and benchmarking and consequently preparing more successful and detailed energy action plans to reduce fossil energy consumption in typical college buildings.

CIBSE TM46 has presented a fixed-annual benchmark of 240 $kWh/m^2/yr$ for college buildings under the category of university campus in 2008. As the heat consumption strongly depends on the ambient temperature, this fixed-annual benchmark is not suitable for predicting and evaluating of monthly variable heat demands. In fact, the benchmark does not differentiate between summer and winter figures. In contrast the Monthly Thermal Energy Benchmarks (MTEBs) concept proposed in this chapter is more informative for management of heat consumption/supply at a university campus level.

The ability to estimate the monthly heat demand underpins efficient energy action plans. Two methods for generating the monthly heat demand models/benchmarks for typical college buildings using mixed activities and Display Energy Certificates (DECs) are proposed in this chapter. The models rely upon mixed activity patterns in the buildings for heat estimation instead of assuming a single use within each building as is found in the literature [14, 16, 22, 23, 35, 53, 72, 105, 196]. Five key factors are used to generate the models. Using actual conditions and data, the primary versions of the models are generated and analysed in detail. Following this, the models are further developed to increase the accuracy of the results. The final versions of the models are advanced based on typical data rather than actual data.
5.2. Mixed Use Method for Calculation of Heat Demand

Many college buildings have various functions such as classrooms, library, computer rooms, labs, offices. The mixed use (mixed activities, or mixed functions) plays a key role in the heat consumption of college buildings. The idea of the ‘composite benchmark’, presented by CIBSE TM46:2008, suggested installation of separate meters for measuring the heat consumption of each activity. In practice the idea was implemented in only 5% of UC (University Campus) buildings [14, 15]. Two reasons for the failure of the CIBSE composite benchmarking concept being put into practice were; (i) the minimum area of 1000 \( m^2 \) for each activity; and (ii) installation of separate meters to measure the consumption of each activity in the building. The minimum 1000 \( m^2 \) threshold is high and it covers few activities in typical college buildings. Moreover, installation of separate meters is time consuming and in some cases for example in district heating (DH) systems is impossible or involves adding the parts to the heating system such as new piping and equipment.

In this chapter the idea of the composite benchmark proposed by CIBSE TM46:2008/2009 [18, 99] was applied in a new applicable method. Instead of installing separate meters for each activity, the composite benchmark was calculated using the building plans. Using building plans (architectural maps) to calculate the composite benchmark is very cheap and does not require extra equipment, piping, or installation.

In the current research the methodology for calculating heat demand in a typical college building was outlined in Section 3.3.3.1 and is called the mixed use method. Using the mixed use methodology, monthly thermal energy demand was estimated based on Equations (3.1), (3.2), and (3.3).

The advantages of mixed use functions in terms of energy efficiency in an urban context was frequently addressed [81, 83, 87, 197]. However, it was applied in few energy modelling methods at building scale due to its complexity. The barriers to mixed use method at the building scale was explained in literature review (Section 2.3.2).

By conducting Survey B as described in Chapter 3, Section 3.3.1, the mixed activities and their relevant areas at the floor scale in 10 typical college buildings, listed in Table 3.3, which belong to four case study universities were assessed. All ten selected buildings were surveyed by taking each room individually. To conduct the survey, the architectural maps of buildings were obtained from Estates and Facilities Office of the case study universities. The obtained maps did not have any dimensions on them. So, during the survey, each activity and its related space dimensions were measured and recorded. Following the measurements of the floor area, the architectural
maps were input into AutoCAD and the area of each space was calculated precisely by the software.

Nine buildings were selected from TCD, UCD, and DCU campuses (three buildings from each campus) and one building was selected from DIT campus as the actual consumption data of DIT was not recorded by Active Energy Management (AEM software used to record energy usage, detailed in Chapter 3, Section 3.2). Four criteria were considered when selecting the buildings for the calculation of mixed use heat demand.

1. Availability of building plans (architectural maps), particularly all plans at floor level
2. Availability of DECs for detailed heat analysis
3. Complete annual actual heat data [174]
4. Buildings are mainly used for educational purposes, i.e. college function

Using the Equations (3.1-3.3) and detailed information obtained from Survey B, the annual heat demand based on the mixed use method was calculated for selected buildings. In the following section, the calculations are explained in further detail.

5.2.1. Calculation of Annual Heat Demand for Hamilton Building (TCD)

The location of the selected buildings for Survey B on TCD campus is shown in Figure 5.1. In the calculations of annual heat demand using mixed use method, instead of CIBSE UC benchmark of 240 kWh/m²/yr, the revised benchmark of UCrb of 130 kWh/m²/yr (calculated in Chapter 4) was used.

![Figure 5.1. The location of selected buildings for Survey B on TCD campus](image)
Hamilton Building is located at the most eastern boundary of TCD campus (built in 1993) and has four floors including ground level and three upper levels. [198]. The ground floor houses Synge and Salmon lecture theatres. It also contains a restaurant and a bank. Toilets and other unconditioned spaces were not included in Survey B or the energy analysis. The first floor contains Constantia Maxwell, Jolly, McNeil lecture theatres in addition to a restaurant. The second and third floors comprise of a library, research rooms and offices. The larger scale building plans and the DEC document are presented in Appendices 2 and 3 respectively. The following information was extracted from the Hamilton DEC:

\[
\begin{align*}
\text{Useful floor area} &= 3,839 \text{ m}^2 \\
\text{Main heating fuel: Gas} \\
\text{BER: C3} \\
\text{Electricity demand} &= 249kWh/m^2/yr \\
\text{TPFER} &= 131kWh/m^2/yr
\end{align*}
\]

In order to calculate the composite benchmark, first the heat demand was calculated using the mixed use method. Then, this value was used for the calculation of composite benchmark. The architectural maps were applied to calculate the composite benchmark. The architectural maps and pictures of Hamilton Building are presented in Figure 5.2.a and Figure 5.2.b (See also Appendix 2).
Results of Survey B

- Building Footprint Area: 1,315 $m^2$; Number of floors: 4
- Building area: 5,260 $m^2$
- Ground floor TUFA: 481.6 $m^2$
- First floor TUFA: 755 $m^2$
- Second and third floors TUFA: $1,037.5 \times 2 = 2,075 m^2$
- Building TUFA: 3,311 $m^2$ (Total Useful Floor Area)
Ground Floor

- Synge lecture theatre area: \(6.40 \times 9.50 = 60.8 \, \text{m}^2\)
- Salmon lecture theatre area: \(6.40 \times 9.50 = 60.8 \, \text{m}^2\)
- Bank: 146 \(\text{m}^2\)
- Restaurant: 177 \(\text{m}^2\)
- Shop: 37 \(\text{m}^2\)

First Floor

- Constantia lecture theatre area: \(8.60 \times 15 = 129 \, \text{m}^2\)
- Joly lecture theatre area: \(15 \times 12.74 = 191 \, \text{m}^2\)
- MacNeill lecture theatre area: \(17.0 \times 17.05 = 290 \, \text{m}^2\)
- Restaurant: 108 \(\text{m}^2\)
- Office: 37 \(\text{m}^2\)

Second and third floors

- Library: 2,075 \(\text{m}^2\)

Area of unconditioned spaces = 5,260 – 3,311 = 1,949 \(\text{m}^2\)

Figure 5.2.b. Hamilton Building, (i) Third floor plan, (ii) View of library
Overall building:
1. Seminar and research room: 731 m²
2. Office: 37 m²
3. Restaurant: 285 m²
4. Bank: 146 m²
5. Shop: 37 m²
6. Library: 2,075 m²

3,311 m² Conditioned Spaces (TUFA)

Based on Survey B the area-weighted activities in Hamilton Building is presented in Table 5.1.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area (m²)</th>
<th>% of TUFA</th>
<th>Category name</th>
<th>Category No</th>
<th>CIBSE benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research room</td>
<td>731</td>
<td>22</td>
<td>UC</td>
<td>18</td>
<td>240 UCrb:130</td>
</tr>
<tr>
<td>Office</td>
<td>37</td>
<td>1</td>
<td>General office</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Restaurant</td>
<td>285</td>
<td>9</td>
<td>Restaurant</td>
<td>7</td>
<td>370</td>
</tr>
<tr>
<td>Bank</td>
<td>146</td>
<td>4</td>
<td>High St Agency</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Shop</td>
<td>37</td>
<td>1</td>
<td>General retail</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Library</td>
<td>2,075</td>
<td>63</td>
<td>Cultural activities</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>3,311</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The annual heat demand estimation using the mixed use method as defined in Equation (3.1) with figures taken from CIBSE (Table 5.2) =

\[
[130 \times 731 + 200 \times 2075 + 120 \times 37 + 370 \times 285 + 0 \times 146 + 0 \times 37] = [95,030 + 415,000 + 4,440 + 105,450 + 0 + 0] = 619,920 \text{ kWh/yr}
\]

Mean monthly heat demand using mixed use method = 51,660 kWh/month

And composite benchmark = 187 kWh/m²

5.2.2. Calculation of Annual Heat Demand for Aras An Phiarsaigh (TCD)

Aras An Phiarsaigh, constructed in 1993, is a modern five-storey building that contains the School of Business Studies, Department of Psychology and Department of Electronic and Electrical Engineering [199]. The architectural plans of five floors as well as pictures of the building are presented in Figure 5.3.a and 5.3.b. The larger scale building plans and DEC document are presented in Appendices 2 and 3 respectively. The following information was extracted from Aras An Phiarsaigh DEC.
Useful floor area: 4,820 m²
Main heating fuel: Gas
BER: B3
Electricity demand= 201 kWh/m²/yr
TPFER= 62 kWh/m²/yr

Figure 5.3.a. Aras An Phiarasigh, (i) View of building, (ii) Ground floor plan, (iii) First floor plan, (iv) Second floor plan, (v) Third floor plan, (vi) Fourth floor plan
Number of floors: 6
Ground floor area: $1,175 \text{ m}^2$ (Include corridors, toilets, and all unconditioned spaces)
First floor area: $1,003 \text{ m}^2$ (Include corridors, toilets, and all unconditioned spaces)
Second floor area: $1,003 \text{ m}^2$ (Include corridors, toilets, and all unconditioned spaces)
Third floor area: $768 \text{ m}^2$ (Include corridors, toilets, and all unconditioned spaces)
Fourth floor area: $629 \text{ m}^2$ (Include corridors, toilets, and all unconditioned spaces)
Fifth floor area: $242 \text{ m}^2$ (Include corridors, toilets, and all unconditioned spaces)
Overall floors area: $(1,175 + 1,003 + 1,003 + 768 + 629 + 242) = 4,820 \text{ m}^2$

Main activities list and area:
1. Computer rooms & Laboratory: $1,014 \text{ m}^2$
2. Office: $1,651 \text{ m}^2$
3. Seminar, class & Research room: $817 \text{ m}^2$
4. Workshops: $48 \text{ m}^2$
5. Coffee shop: $47 \text{ m}^2$
6. Library: $70 \text{ m}^2$

Area of unconditioned spaces = $4,820 - 3,647 = 1,173 \text{ m}^2$

Based on Survey B the area-weighted activities in Aras An Phiarsaigh is presented in Table 5.2.
The annual heat demand estimation using the mixed use method as defined in Equation (3.1) = 

\[160 \times 1014 + 130 \times 817 + 120 \times 1651 + 370 \times 47 + 180 \times 48 + 200 \times 70\] =

\[162,240 + 106,210 + 198,120 + 17,390 + 8,640 + 14,000\] = 506,600 kWh/yr

Mean monthly heat demand using mixed use method = 42,217 kWh/month

And composite benchmark = 139 kWh/m²/yr

5.2.3. Calculation of Annual Heat Demand for Museum Building (TCD)

The Museum Building is located on the south of New Square just beside the Berkeley Library. The building was designed by Thomas Deane and Benjamin Woodward and its architectural style inspired by Byzantine of Venice while, the finishing details were inspired by Lombardo-Romanesque. The building opened in 1857 and hosts departments of Geology and Geography in the east part and School of Engineering and Department of Civil, Structural, and Environmental Engineering in the west part [200, 201]. The north view of the building is presented in Figure 5.4.
The Museum building did not have a DEC, however, using an architectural map the annual heat demand and composite benchmark were calculated for the building. The plans of all floors are presented in Appendix 2.

The result of Survey B are as follows:

Results of Survey B

- Basement floor area: 1,248 m²
- Ground floor area: 1,248 m²
- First floor area: 1,151 m²
- Second floor area: 947 m²
- All floors area = (1,248+1,248+1,151+947) = 4,594 m²

Main activities list and the relevant area:

1. Computer rooms & Laboratory: 683 m²
2. Office: 1,553 m²
3. Seminar, class & Research room: 1,142 m²
4. Library: 324 m²
5. Stores: 120 m²

All floors area = (1,248+1,248+1,151+947) = 4,594 m²

Based on Survey B the area-weighted activities in Museum Building is presented in Table 5.3.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area (m²)</th>
<th>% of TUFA</th>
<th>Category name</th>
<th>Category No</th>
<th>CIBSE benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research</td>
<td>1,142</td>
<td>30</td>
<td>UC</td>
<td>18</td>
<td>240 UCrb:130</td>
</tr>
<tr>
<td>room</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office</td>
<td>1,553</td>
<td>41</td>
<td>General office</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Computer rooms &amp;</td>
<td>683</td>
<td>18</td>
<td>Laboratory</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stores</td>
<td>120</td>
<td>3</td>
<td>Storage facility</td>
<td>28</td>
<td>160</td>
</tr>
<tr>
<td>Library</td>
<td>324</td>
<td>8</td>
<td>Cultural activities</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>3,822</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area (m²)</th>
<th>% of TUFA</th>
<th>Category name</th>
<th>Category No</th>
<th>CIBSE benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research</td>
<td>1,142</td>
<td>30</td>
<td>UC</td>
<td>18</td>
<td>240 UCrb:130</td>
</tr>
<tr>
<td>room</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office</td>
<td>1,553</td>
<td>41</td>
<td>General office</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Computer rooms &amp;</td>
<td>683</td>
<td>18</td>
<td>Laboratory</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stores</td>
<td>120</td>
<td>3</td>
<td>Storage facility</td>
<td>28</td>
<td>160</td>
</tr>
<tr>
<td>Library</td>
<td>324</td>
<td>8</td>
<td>Cultural activities</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>3,822</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The annual heat energy demand estimation using the mixed use method as defined in Equation (3.1) = [160 × 683 + 130 × 1142 + 120 × 1553 + 200 × 324 + 160 × 120] = [109,280 + 148,460 + 186,360 + 64,800 + 19,200] = 528,100 kWh/yr

Mean monthly heat demand using mixed use method = 44,008 kWh/month

And composite benchmark = 138 kWh/m²/yr
5.2.4. Calculation of Annual Heat Demand for Engineering & Research (DCU)

The School of Engineering and Research is located at the axis of the main entrance of Dublin City University (DCU) at east of the campus. The location of the building is presented in Figure 5.5.

**Figure 5.5. School of Engineering & Research, (i) View from Collins Avenue, (ii) The location of the building**

The building DEC information is as follows:

\[
\text{DEC:}\begin{cases} 
\text{Total Useful Floor Area: } 1,0587 \text{ m}^2 \\
\text{Main heating fuel: Gas} \\
\text{BER: D2} \\
\text{Electricity demand= 436 kWh/m}^2/yr} \\
\text{TPFER= 142 kWh/m}^2/yr}
\end{cases}
\]

The building has five floors, of which two plans as samples are presented in Figure 5.6 and Figure 5.7. The area of activities was calculated in AutoCAD. The complete plans and DEC are presented in Appendices 2 and 3 respectively.
Figure 5.6. (i) Ground floor plan, (ii) Interior view of lobby, School of Engineering & Research

Figure 5.7. First floor plan, School of Engineering & Research
Chapter 5

Monthly thermal energy modelling and benchmarking

Results of Survey B

- Basement floor area: 3,449 m²
- Ground floor area: 2,542 m²
- First floor area: 2,726 m²
- Second floor area: 2,573 m²
- Third floor area: 2,094 m²

All floors area = (3,449+2,542+2,726+2,573+2,094) = 13,384 m²

Main activities list and their relevant area:

1. Computer rooms & Laboratory: 5,866 m²
2. Office: 2,303 m²
3. Class room: 94 m²
4. Entertainment hall: 521 m²
5. Stores: 231 m²

Area of unconditioned spaces such as corridors, toilets, and plant room: 4,369 m²

Based on Survey B, the area-weighted activities in School of Engineering and Research are presented in Table 5.4.

Table 5.4. Mixed activities in the School of Engineering and Research

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area (m²)</th>
<th>% of TUFA</th>
<th>Category name</th>
<th>Category No</th>
<th>CIBSE benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research room</td>
<td>94</td>
<td>1</td>
<td>UC</td>
<td>18</td>
<td>240 UCrb:130</td>
</tr>
<tr>
<td>Office</td>
<td>2,303</td>
<td>25</td>
<td>General office</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Computer rooms &amp; Laboratory</td>
<td>5,866</td>
<td>65</td>
<td>Laboratory</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>Stores</td>
<td>231</td>
<td>3</td>
<td>Storage facility</td>
<td>28</td>
<td>160</td>
</tr>
<tr>
<td>Entertainment Hall</td>
<td>521</td>
<td>6</td>
<td>Entertainment</td>
<td>11</td>
<td>420</td>
</tr>
<tr>
<td>Total</td>
<td>9,015</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The annual energy demand estimation using the mixed use method as defined in Equation (3.1) =

\[
160\times5866 + 130\times94 + 120 \times 2303 + 420\times521 + 160\times231 = [938,560 + 12,220 + 276,360 + 218,820 + 36,960] = 1,482,920 \text{ kWh/yr}
\]

Mean monthly heat demand using mixed use method = 123,577 kWh/month

And composite benchmark = 164 kWh/m²/yr
5.2.5. Calculation of Annual Heat Demand for Bolton Street (DIT)

Dublin Institute of Technology Bolton Street, located near Dublin City Centre, is presented in Figure 5.8. The school is divided into four sub-sites including the Main Building, E-block, Linen Hall and Beresford St. The college was funded in 1911 as a technical institute, designed and built for technical and technological education [202]. Currently the College of Engineering & Built Environment, Construction, Civil and Mechanical Engineering, Architecture, and Printing are housed in the building.

![Location on Dublin map](image1) ![View from Bolton Street](image2)  
(i) Location on Dublin map (ii) View from Bolton Street

![Close up location](image3) ![View from west](image4)  
(iii) Close up location (iv) View from west

**Figure 5.8. College of Technology (DIT), (i) Location on Dublin map, (ii) View from Bolton Street, (iii) Close up location, (iv) View from west**

The building DEC information is as follows:

**DEC**
- Useful Floor Area: 25,437 m²
- Main heating fuel: Gas
- Electricity demand = 169 kWh/m²/yr
- TPFER = 101 kWh/m²/yr
- Total energy: 270 kWh/m²/yr

**Results of Survey B**
- Ground floor area: 7,044 m²
- First floor area: 6,588 m²
- Second floor area: 6,049 m²
- Third floor area: 3,893 m²
- All floors area = (7,044+6,588+6,049+3,893) = 23,574 m²
Main activities list and their relevant area:

1. Computer rooms & Laboratory: 6,053 m²
2. Office: 3,375 m²
3. Seminar, class & Research room: 2,298 m²
4. Workshop: 1,251 m²
5. Store: 1,110 m²
6. Bank: 61 m²
7. Shop: 48 m²
8. Restaurant: 970 m²
9. Library: 1,414 m²

Based on Survey B the area-weighted activities in College of Technology is presented in Table 5.5.

**Table 5.5. Mixed activities in the Institute of Technology**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area (m²)</th>
<th>% of TUFA</th>
<th>Category name</th>
<th>Category No</th>
<th>CIBSE benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research room</td>
<td>2,298</td>
<td>14</td>
<td>UC</td>
<td>18</td>
<td>240 UCrb:130</td>
</tr>
<tr>
<td>Office</td>
<td>3,375</td>
<td>20</td>
<td>General office</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Computer rooms &amp; Laboratory</td>
<td>6,053</td>
<td>36</td>
<td>Laboratory</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>Stores</td>
<td>1,110</td>
<td>6</td>
<td>Storage facility</td>
<td>28</td>
<td>160</td>
</tr>
<tr>
<td>Workshop</td>
<td>1,251</td>
<td>8</td>
<td>Workshop</td>
<td>27</td>
<td>180</td>
</tr>
<tr>
<td>Bank</td>
<td>61</td>
<td>0.5</td>
<td>High Street Agency</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Shop</td>
<td>48</td>
<td>0.5</td>
<td>General retail</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Restaurant</td>
<td>970</td>
<td>6</td>
<td>Restaurant</td>
<td>7</td>
<td>370</td>
</tr>
<tr>
<td>Library</td>
<td>1,414</td>
<td>9</td>
<td>Cultural activities</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16,580</strong></td>
<td><strong>100</strong></td>
<td></td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

The annual energy demand estimation using mixed use method as defined in Equation (3.1) =

\[
[160 \times 6053 + 130 \times 2298 + 120 \times 3375 + 180 \times 1251 + 160 \times 1110 + 0 \times 61 + 0 \times 48 + 370 \times 970 + 200 \times 1414] = \\
[968,480 + 298,740 + 405,000 + 225,180 + 177,600 + 0 + 0 + 358,900 + 282,800] = 2,716,700 \text{ kWh/yr}
\]

Mean monthly heat demand using mixed use method = 226,392 kWh/month

And composite benchmark= 164 kWh/m²/yr
5.2.6. Calculation of Annual Heat Demand for Nova Building (UCD)

Nova Building at UCD (Figure 5.9) is located in the south east of the campus. It is a centre for new ventures and entrepreneurs. [203].

![Nova Building](image)

(i) Location on Dublin map   (ii) Entrance view

(iii) Google Earth view   (iv) View of coffee shop

**Figure 5.9. Nova Building.** (i) Location on Dublin map, (ii) Entrance view, (iii) Google Earth view, (iv) View of coffee shop

The DEC information is as follows:

**DEC**

- Useful Floor Area: 4,691 m²
- Main heating fuel: Gas
- Electricity demand= 144 kWh/m²/yr
- TPFER= 122 kWh/m²/yr
- Total energy: 266 kWh/m²/yr

**Results of Survey B**

- Ground floor area: 2,632 m²
- First floor area: 2,481 m²
- Second floor area: 637 m²
- All floors area = (2,632+2,481+637) = 5,750 m²
Main activities list and area in the building:

1. Computer rooms & Laboratory: 362 m²
2. Office: 2,170 m²
3. Seminar, class & Research room: 601 m²
4. Workshop: 350 m²
5. Store: 398 m²
6. Coffee shop: 185 m²

\[
\text{TUFA} = 4,066 \text{ m}^2
\]

Area of unconditioned spaces: 5,750 - 4,066 = 1,684 m²

Based on Survey B the area-weighted activities in Nova Building is presented in Table 5.6.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area (m²)</th>
<th>% of TUFA</th>
<th>Category name</th>
<th>Category No</th>
<th>CIBSE benchmarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research room</td>
<td>601</td>
<td>15</td>
<td>UC</td>
<td>18</td>
<td>240 UCrb:130</td>
</tr>
<tr>
<td>Office</td>
<td>2,170</td>
<td>53</td>
<td>General office</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Computer rooms &amp; Laboratory</td>
<td>362</td>
<td>9</td>
<td>Laboratory</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>Stores</td>
<td>398</td>
<td>10</td>
<td>Storage facility</td>
<td>28</td>
<td>160</td>
</tr>
<tr>
<td>Workshop</td>
<td>350</td>
<td>8</td>
<td>Workshop</td>
<td>27</td>
<td>180</td>
</tr>
<tr>
<td>Coffee shop</td>
<td>185</td>
<td>5</td>
<td>Restaurant</td>
<td>7</td>
<td>370</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4,066</strong></td>
<td><strong>100</strong></td>
<td><strong>---</strong></td>
<td><strong>---</strong></td>
<td><strong>---</strong></td>
</tr>
</tbody>
</table>

The annual energy demand estimation using mixed use method as defined in Equation (3.1) =

\[
[160\times362 + 130\times601 + 120\times2170 + 180\times350 + 160\times398 + 370\times185] =
\]

\[
[57,920 + 78,130 + 260,400 + 63,000 + 63,680 + 68,450] = 591,580 \text{ kWh/yr}
\]

Mean monthly heat demand using mixed use method = 49,298 kWh/month

And composite benchmark = 145 kWh/m²/yr

### 5.3. Advantages of the Mixed Use Method and the Impacts

The results of recent studies revealed that there is a significant difference between DEC data and CIBSE benchmarks in educational buildings [16, 23, 53, 140]. Similar results were found in this study as presented in Chapter 4 and based on the results a revised benchmark (UCrb) was presented. For example, DEC data of Hamilton building on TCD campus shows that the building consumed 452,618 kWh/yr of heat energy while, CIBSE predicts 794,640 kWh/yr. This means the CIBSE UC thermal benchmark was approximately 43% greater than DEC measurement. In
Ireland and UK most college energy managers are using CIBSE UC benchmark for energy management, while the accuracy of CIBSE UC is under question. Therefore, in this PhD project, first the CIBSE UC heating benchmark was revised. Then, the UC revised benchmark (UCrb) was used to increase the accuracy of heat estimation. The mixed use method is based on the consideration of all activities in the buildings as well as using UCrb (130 kWh/m²/yr) instead of CIBSE UC (240 kWh/m²/yr).

In contrast to the CIBSE method for the calculation of composite benchmark, in this methodology architectural maps were used to evaluate the impact of various activities on heat demand by assessing the percentage of area of all activities. To assess the overall heat demand, the area of all activities in 10 typical college buildings were surveyed, then the area of each activity was calculated in AutoCAD. In Table 5.7 based on the analysis of mixed use activities in the surveyed buildings the results of assessments are presented.

10 main activities were found in the analysed typical college building. The average percentage of each activity in the surveyed buildings was calculated and presented in Table 5.7. The percentages area less than 2% of the total building area as well as the activity that was found only in a building were removed in the calculation of typical activities. For instance, the entertainment hall with an area of 3% was not considered in the assessment because it was found only in a building. Therefore, 7 activities were selected as typical activities in a college building.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Hamilton (UC)</th>
<th>Area An (UC)</th>
<th>Phoenix (UC)</th>
<th>Museum (UC)</th>
<th>Engineering &amp; Research (UC)</th>
<th>College Technology (UC)</th>
<th>Nova (UC)</th>
<th>School of Engineering (UC)</th>
<th>Belfield House (UC)</th>
<th>Medical Bureau of Road (UC)</th>
<th>Engineering &amp; MAT. Sci (UC)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seminar &amp; research room</td>
<td>22</td>
<td>22</td>
<td>3</td>
<td>1</td>
<td>14</td>
<td>15</td>
<td>13</td>
<td>18</td>
<td>14</td>
<td>14</td>
<td>26</td>
<td>18</td>
</tr>
<tr>
<td>Office</td>
<td>1</td>
<td>45</td>
<td>4</td>
<td>25</td>
<td>20</td>
<td>53</td>
<td>25</td>
<td>24</td>
<td>27</td>
<td>25</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Restaurant (coffee shop)</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bank</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shop</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Library</td>
<td>63</td>
<td>2</td>
<td>8</td>
<td>9</td>
<td>15</td>
<td>20</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Computer &amp; Laboratory</td>
<td>0</td>
<td>29</td>
<td>1</td>
<td>65</td>
<td>36</td>
<td>9</td>
<td>42</td>
<td>38</td>
<td>39</td>
<td>35</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Workshop</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>12</td>
<td>4</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Stores</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>10</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Entertainment hall</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Based on data analysis presented in Table 5.7, a typical college building can be defined as follows: A typical college building is a type of educational building, usually comprising of seven mixed activities such as computer rooms & laboratories (31%), offices (29%), seminar & research rooms (18%), library (14%), workshop (4%), stores (3%), and restaurant or coffee shop (1%).

To calibrate the advantages of the mixed use method, the results of annual thermal energy estimations calculated in Section 5.2 are compared with CIBSE UC benchmark estimations and actual heat consumption. The process aims to assess the effect of consideration of all activities in energy estimation against CIBSE UC (single use method). The actual heat data used in the analysis was available on AEM [174].

Figure 5.10 shows the result of heat estimation using mixed use and CIBSE methods against the actual monthly consumption in Hamilton Building (TCD) in 2012. The mean monthly estimation based on the CIBSE method was calculated as follows:

\[
\text{CIBSE mean monthly estimation} = \frac{(240 \text{ kWh/m}^2/\text{yr} \times TUFA \text{ m}^2)}{12} = \frac{240 \times 3,311}{12} = 66,220 \text{ kWh/yr}
\]

In Figure 5.10, (a) and (M) show the mean monthly estimations of CIBSE UC and the mixed use methods respectively, while (b) presents the actual (mean monthly) consumption. The differences between CIBSE (mean monthly) and mixed use method (mean monthly) estimations against the mean monthly of actual consumptions were 41% and 24% respectively. The graph shows the mixed use method improved the heat estimation by approximately 22%. Despite this significant improvement compared with CIBSE, the difference of mixed use method estimation with the mean monthly of actual thermal energy consumption was 24% as shown in the graph. To fill this gap, a coefficient \((n)\) was applied as outlined in Section 3.3.3.1.
Coefficient \((n)\) is the ratio of composite benchmark to CIBSE UC benchmark. Coefficient \((n)\) for the Hamilton building equals:

\[
\frac{\text{Composite benchmark}}{\text{CIBSE UC benchmark}} = \frac{187}{240} = 0.78.
\]

Coefficient \((n)\) multiplied by the mixed use estimation. In the graph, line (N) shows the impact of coefficient \((n)\).

The process reduced the difference between mixed use estimation method and mean monthly actual thermal energy consumption so that the difference was only 3%. To validate the methodology further samples are presented.

The estimated value of TM46 was shown by line (a) and the mean of actual measurement value was shown by line (b) therefore, the value of dotted line of \((a+b)/2\), equals to the mean values of line (a) and (b) as shown in the figure. Since in the estimations the mean value of monthly heat demand was used, the results are fixed during a year and therefore, shown as lines.

Statistically, the mean of (a) and (b) was used to determine the situation of mixed use method compared with the mean of CIBSE TM46 UC benchmark estimation and actual measurements. It can be observed that the result of the mixed use method is close to the mean of (a) and (b).

The thermal energy demand analysis for Aras An Phiarsaigh is presented in Figure 5.11 which shows the mixed use method, compared with TM46 method, improved the accuracy of estimation by approximately 42%. The mean monthly prediction of CIBSE was 72,940 kWh and the mixed
use method prediction was 42,217 kWh, while the mean actual consumption was 23,015 kWh. The ratio of the composite benchmark (calculated in Section 5.2.2) to CIBSE TM46 UC benchmark, called coefficient \( n \), was used to fill the gap between the mixed use method and actual measurement. Coefficient \( n \) was \((139/240)\) 0.58. The discrepancy between mixed use method and mean actual consumption (monthly) after applying the coefficient \( n \) decreased to 6%. The impact of coefficient \( n \) was shown in Figure 5.11 by line N.

![Figure 5.11. CIBSE UC & mixed use method heat estimation against actual data, Aras An Phiarsaigh, TCD](image)

A similar analysis was carried out for the other buildings in Survey B (Chapter 3, Section 3.3.1) and in all the cases a significant impact of the mixed use method to increase the accuracy of estimations was observed which some examples are shown in Figures 5.10 – 5.15. In the figures, Line (M) shows the impact of mixed use method for calculating the thermal energy demand in typical college buildings. In Engineering & Research building (DCU) the mean monthly of CIBSE TM46 UC thermal estimation (Figure 5.12) was 180,300 kWh; however, the mixed use method predicted 123,577 kWh which was closer to the actual (mean monthly) consumption of 97,012 kWh. The mixed use method overestimated approximately 26,000 kWh, while TM46 overestimated nearly 83,000 kWh.
Figure 5.12. CIBSE UC & mixed use method heat estimation against actual data, Engineering & Research building, DCU

Figure 5.13. CIBSE UC & mixed use method heat estimation against actual data, Museum Building, TCD
Figures 5.14-15 present the significant role of the mixed used method for calculation of thermal demand in college buildings. They also show a positive impact of coefficient \( n \) (Line N, in the figures). For example, the improvement of mixed use method to predict thermal energy compared with TM46 method, in Hamilton Building (TCD), Aras An Phiarsaigh (TCD), Engineering &
Research building (DCU), Museum Building (TCD), College of Technology (DIT), and Nova Building (UCD) were 22%, 42%, 31%, 42%, 32%, and 39% respectively.

The mean of improvements was nearly 35% which was a significant development. However, a discrepancy between mixed use method and the actual measurements (AEM) [174] were also found. For instance, the gaps are presented in Figures 5.10, 5.11, 5.12, and 5.15 and were 24%, 45%, 21%, and 25% respectively. To fill the gap between the mixed use method and actual data, the coefficient (n) was defined and applied in all assessments. Line N shows the key role of coefficient (n) in increasing the accuracy of the method where it reduced the gap to 3-19%.

Using the revised thermal energy benchmark (UCrb=130 kWh/m²/yr) in the mixed use method as well as the coefficient (n) the accuracy of mean monthly heat estimation increased significantly compared with CIBSE TM46 method.

5.4. Creating Monthly Thermal Energy Models Based on Architectural Maps, Method (1)

The following sections present a comprehensive method to create the monthly thermal energy models (MTEMs) to calculate the monthly thermal energy benchmarks (MTEBs) which consider the variations of heat demand over the course of a year. In Section 5.3, using the mixed use method the mean monthly thermal energy estimation was developed so that the difference of estimation with actual measurements was maximum 19%, while the mean of differences of CIBSE method with actual data was approximately 52%. The maximum error of TM46 method was 68% observed in Aras An Phiarasgaigh.

The aim of monthly thermal energy modelling and benchmarking is to convert the horizontal fixed-index (line N in Figures 5.10 to 5.15) into monthly figures. Two methods were developed to create the monthly heat models.

Methodology (1) is useful if a DEC is unavailable. As a result, this method is applicable for both existing buildings and developing or future buildings. The method relies upon CIBSE benchmarks, including 29 building categories, particularly those categories realised in a typical college building. Method (1) uses architectural maps to calculate the composite benchmark (CB) in college buildings. Based on the analysis, most of the college buildings comprise several activities, i.e. mixed use functions. In fact, activity plays a key role in heat demand, for example a general office needs 120 kWh/m²/yr of thermal energy, while a restaurant needs 370 kWh/m²/yr [99].
Chapter 5

Monthly thermal energy modelling and benchmarking

Heating degree days (HDD) was applied as a factor that considers the impact of temperature in the heat demand assessment. The HDD data was obtained from Degree Days.net [178]. Dublin Airport, IE (6.30W, 53.42N) was chosen as a weather station and a base temperature of 15.5° was selected for calculation of heating degree days. HDD data of 2012 is presented in Table 5.8 as an example.

Table 5.8. Heating Degree Days 2012 [178]

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDD</td>
<td>281</td>
<td>253</td>
<td>224</td>
<td>264</td>
<td>171</td>
<td>93</td>
<td>66</td>
<td>36</td>
<td>110</td>
<td>214</td>
<td>272</td>
<td>310</td>
</tr>
<tr>
<td>Annual</td>
<td>2,294</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HDD values, the mean monthly heat estimated using mixed use method are presented in Figures 5.16-5.18. The graphs show the differences in heat demand in 2012 and 2014.

Figure 5.16. Comparing HDD values, mixed use method and actual measurements, Hamilton Building
Figure 5.17. Comparing HDD values, mixed use method and actual measurements, Aras An Phiarasgaigh

The compatibility of HDD with monthly changes of actual heat consumption in three typical college buildings shows that HDD is an appropriate parameter to convert the mean monthly estimation (N) into the monthly heat demand model. Thus, using HDD tool, i.e. \( \frac{HDD \text{ month}}{HDD \text{ annual}} \) along with Equations (3.1), (3.2), and (3.3) (as detailed in Chapter 3) the monthly heat models were generated. Using Equation (3.4) the primary version of monthly heat models was created. Further explanation was presented in Chapter 3. Equation (3.4) for modelling monthly heat demand was calibrated using actual measurements of ten typical college buildings listed in Survey B.
Equation (3.4) is created to estimate the first series of monthly heat demand models. The accuracy of monthly heat demand models was calibrated against the actual monthly data available on AEM [174]. The rules and statistical boundaries used to accept, test, and validate the accuracy of models were as follows:

1. The Mean Absolute Percentage Error (MAPE) and Absolute Percentage Error (APE) methodologies were used to assess the accuracy of the monthly models. The MAPE method for validating energy models has been used frequently in energy studies in buildings [204, 205]. The best MAPE result obtained using ANN (Artificial Neural Network) to identify the annual energy determinants in educational buildings was 19% [105]. The similar error (22%) was obtained in a modelling methodology conducted by Hawkins et al. in 2013 [23]. The referenced studies assessed the energy determinants at the annual level not the monthly level. Obviously, predicting energy demand at the monthly level is more complicated than the annual level and consequently obtaining a high level of accuracy is more difficult.

2. The maximum accepted mean absolute percentage error (MAPE) at the annual level was 18%.

3. The maximum accepted APE error at the monthly scale was 21%. This threshold for monthly errors is nearly half of the annual error of current CIBSE TM46 UC benchmark in Dublin. The 46% annual error of CIBSE TM46 UC was discovered in Chapter 4. The Maximum monthly error of CIBSE TM46 was nearly 100%.

4. The result of linear regression assessments must be more then 0.85.

The curved red line in Figure 5.19.a is the first version of the monthly heat demand model created using Equation (3.4). The result of linear regression assessment was 0.743 which showed a weak relationship between actual data and estimated values (Figure 5.19.b). To understand the size of errors in each month the APEs (absolute percentage errors) were calculated and presented in Table 5.9.
According to data presented in Table 5.9, the APEs of monthly heat estimation in June, July, August, and September were 100%. However, the error of overall annual estimation was only overestimated by 3%.

Similar results were found in other analysed buildings. For example, the analysis of heat demand estimation in Aras An Phiarsaigh using Eq (3.4) showed 100% difference in summer months as presented in Figure 5.20. The monthly errors are presented in Table 5.10.
The monthly heat demand of College of Engineering and Research Building at DCU was estimated using Equation (3.4) and the accuracy of the approach was assessed and the results are shown in Figure 5.21. The monthly errors of the model are presented in Table 5.11.
100% difference between estimated heat demand and actual consumption was observed in July, while the differences in January, October, February, and May were 31%, 22%, 20%, and 19% respectively (Table 5.11). The energy assessment at TCD college buildings such as Hamilton and Aras An Phiarasaigh indicated that the consumed heat during summer season (2012 & 2014) was 0 kWh and the reason refers to the energy management policy at the campus. Such strategy was not observed at other campuses. According to the analysis, modelling heat demand using Equation (3.4) did not match with actual thermal energy consumption.

To improve the accuracy of Equation (3.4) the average of HDD of five recent years (2009-2014) as well as the average of ten recent years (2005-2014) were also tested instead of using the HDD of one year, however the results did not progress as shown in Figure 5.22. The average HDD from 2005 to 2014 obtained from Degree Days.net [178]. As shown in Figure 5.22 the results obtained using various HDD series were very similar. Thus, the annual HDD was used in the models.
Due to the significant errors of the predicted monthly heat consumption based on Equation (3.4), especially in summer months, this section develops a methodology to further reduce the error. In the previous analysis, it was found that in summer months the actual heat consumption in typical college buildings at TCD campus was 0 kWh/yr, however the HDD shows there is a heat demand in summer (as presented in Table 5.8). For example, in June, July, and August the heating degree days were 93, 66, and 36 respectively, whereas the actual consumption in TCD did not follow this trend.

Based on the analysis of heat consumption in ten of the surveyed buildings, it was found that the energy management policy of universities impacted on the energy consumption. Most of the heating systems in universities are controlled by Estates and Facilities Offices. The energy policy plan determines the operation schedule of heating systems. So, the operating pattern was considered as another factor in the monthly modelling method.

Based on the hourly data recorded by AEM [174], the monthly operational hours of heating systems in ten typical buildings were calculated. The ratio of monthly actual operational hours of heating systems to the mean monthly operational hours suggested by CIBSE TM46 was calculated and multiplied by Equation (3.4). According to CIBSE TM46 UC category [99], the annual thermal operational reference hours is 2,450. In other words, the mean operational hours of heating systems in a typical college building is 204 hours per month. Regarding the actual operational hours, for example, the actual operational hours of the heating system of Aras An Phiersaigh on Thursday 2nd January 2014 was recorded as 14 hours and 30 minutes. The operational hours were not delivered on AEM directly. As shown in Figure 5.23, the heating system switched on from 04.00am to 18.30 continuously. Considering the operational pattern Equation (5.1) was created.
Equation (5.1) was produced by adding a new factor of monthly operational hours as follows:

\[
\left[ \sum_{n=1}^{24} (A_i \times f_i) \right] \times \frac{\text{HDD month}}{240 \times \text{HDD (annual)}} \times \frac{\text{Monthly Actual operation (hours)}}{\text{Standard monthly operation (CIBSE, hours)}} \tag{5.1}
\]

Equation (3.4)

Ten monthly heat demand models were created based on Equation (5.1) and models were validated against actual data, which some examples of calibrated models were presented in detail. Based on Equation (5.1) the heat demand for Aras An Phiarsaigh was calculated. Table 5.12 shows the improvement of this new calculation. The improvement especially in summer months which was a gap in the primary models (Equation 3.4) was considerable. The actual monthly heating schedule is also presented in the table.

<table>
<thead>
<tr>
<th>Aras An Phiarsaigh (month)</th>
<th>HDD 2014</th>
<th>Aras heating system schedule (hours) 2014</th>
<th>Eq (3.4) kWh</th>
<th>Eq (5.1) kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>303</td>
<td>328</td>
<td>42,940</td>
<td>68,985</td>
</tr>
<tr>
<td>February</td>
<td>274</td>
<td>290</td>
<td>38,831</td>
<td>55,155</td>
</tr>
<tr>
<td>March</td>
<td>267</td>
<td>311</td>
<td>37,839</td>
<td>57,638</td>
</tr>
<tr>
<td>April</td>
<td>182</td>
<td>282</td>
<td>25,793</td>
<td>35,625</td>
</tr>
<tr>
<td>May</td>
<td>133</td>
<td>41</td>
<td>18,848</td>
<td>3,785</td>
</tr>
<tr>
<td>June</td>
<td>63</td>
<td>0</td>
<td>8,928</td>
<td>0</td>
</tr>
<tr>
<td>July</td>
<td>32</td>
<td>0</td>
<td>4,535</td>
<td>0</td>
</tr>
<tr>
<td>August</td>
<td>70</td>
<td>0</td>
<td>9,920</td>
<td>0</td>
</tr>
<tr>
<td>September</td>
<td>72</td>
<td>0</td>
<td>10,204</td>
<td>0</td>
</tr>
<tr>
<td>October</td>
<td>132</td>
<td>152</td>
<td>18,707</td>
<td>13,927</td>
</tr>
<tr>
<td>November</td>
<td>225</td>
<td>201</td>
<td>31,886</td>
<td>31,392</td>
</tr>
<tr>
<td>December</td>
<td>316</td>
<td>178</td>
<td>44,783</td>
<td>39,043</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2,069</td>
<td>1,783</td>
<td>293,213</td>
<td>305,551</td>
</tr>
</tbody>
</table>
The monthly heat demand models produced based on the Equations (3.4) and (5.1) were compared and illustrated in Figure 5.24.a. This new monthly modelling method considers the operational hours of the heating system and predicts the heat demand more accurately during summer. The accuracy of the new version of the MTEMs has been calibrated by using linear regression. The R-squared of 0.9778 showed a high level correlation between actual measurements and the estimated data as presented in Figure 5.24.b.

**Figure 5.24.a.** Aras An Phiarasgaigh (TCD), the actual thermal energy consumption along with the predicted thermal energy consumption using equations (3.4) and (5.1). (b) Calibration of accuracy of model (5.1) by $R^2$

Furthermore, the monthly heat estimation using Equation (5.1) in Hamilton Building was calculated and the results are shown in Figure 5.25.a. The R-squared was 0.8355 as shown in Figure 5.25b.

**Figure 5.25.a.** Hamilton Building (TCD), the actual thermal energy consumption along with the predicted thermal energy consumption using equations (3.4) and (5.1). (b) Calibration of accuracy of model (5.1) by $R^2$
In this regard, the MTEMs using Equation (5.1) for Engineering & Research (DCU), Nova Building (UCD), College of Technology (DIT), and Parsons Building (TCD) were generated and the accuracy of modelling was calibrated using actual monthly consumption data and the results are presented in Figure 5.26-5.29.

**Figure 5.26.a.** Engineering & Research (DCU), the actual thermal energy consumption along with the predicted thermal energy consumption using equations (3.4) and (5.1), (b) Calibration of accuracy of model (5.1) by $R^2$

**Figure 5.27.a.** Nova UCD, the actual thermal energy consumption along with the predicted thermal energy consumption using equations (3.4) and (5.1), (b) Calibration of accuracy of model (5.1) by $R^2$
Figure 5.28.a. College of Technology (DIT), the actual thermal energy consumption along with the predicted thermal energy consumption using equations (3.4) and (5.1). (b) Calibration of accuracy of model (5.1) by $R^2$

In TCD campus the heating systems were switched off during the summer months, as shown in Figure 5.24, Figure 5.25 and Figure 5.2, while other campuses did not follow that policy. The high level of $R^2$ e.g., 0.9978 (TCD), 0.9957 (DCU), 0.9924 (UCD), and 0.9942 (DIT) showed the accuracy of models generated using Eq (5.1).

Figure 5.29.a. Parsons (TCD), the actual thermal energy consumption along with the predicted thermal energy consumption using equations (3.4) and (5.1). (b) Calibration of accuracy of model (5.1) by $R^2$

MTEMs explained in this section were generated using five key factors including

1. Mixed use method
2. Revised CIBSE UC benchmark (UCrb)
3. Multi functionality, (mixed activities)
4. Heating degree days

5. Actual operational hours of heating systems

Nevertheless, the model was constructed based on some specific data which needed to be independent from them. The generalisation process of the model, its final version and validation will be addressed in the next section.

5.4.1. Final Monthly Thermal Energy Models

In this section the Monthly Thermal Energy Models (MTEMs) based on the mixed use method and typical operational hours of the heating systems have been developed. The accuracy of the model has been assessed and compared with the CIBSE UC benchmark as well as actual consumption. In Equation (5.1) actual data was used to generate the heat models, however the final version of MTEMs was generated using typical data instead of actual data. Using typical data instead of specific data in the models is fundamental because it increases the usefulness of the models and allows a broader range of users. Acquiring specific data is difficult as it needs access to the buildings to conduct surveys in contrast, acquiring general information is easier.

To understand the specific variables in a version developed using Eq (5.1), the parameters are presented in Table 5.1. To improve the model specific (actual) data should be replaced by general/typical data.

<table>
<thead>
<tr>
<th>Methodology (1)</th>
<th>Data used in the model</th>
<th>Data type/access</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation (5.1)</td>
<td>CIBSE benchmarks</td>
<td>General data</td>
<td>CIBSE TM46:2008</td>
</tr>
<tr>
<td>Equation (5.1)</td>
<td>Revised UC benchmark</td>
<td>General data</td>
<td>This revision done in this PhD research can share</td>
</tr>
<tr>
<td>Equation (5.1)</td>
<td>Mixed use method</td>
<td>General (methodology)</td>
<td></td>
</tr>
<tr>
<td>2. Specific (obtaining activities area)</td>
<td>Obtains by survey of building</td>
<td>Specific data</td>
<td>Such as building maps, DEC, or online information</td>
</tr>
<tr>
<td>Equation (5.1)</td>
<td>Building area</td>
<td>Specific data</td>
<td>Available online</td>
</tr>
<tr>
<td>Equation (5.1)</td>
<td>HDD</td>
<td>General</td>
<td></td>
</tr>
<tr>
<td>Equation (5.1)</td>
<td>Actual operation hours</td>
<td>Specific data</td>
<td></td>
</tr>
</tbody>
</table>

*The actual monthly consumption data did not used in the models, but they used for validating it.*

As summarised in Table 5.13 the models were created based on two series of specific data including building area and actual operational hours of the heating systems as displayed by red rectangles. Therefore, to generalise the models these specific data should be replaced with general/typical values.
Based on the definition of a typical college building and the results of data assessment presented in Section 5.3, the typical activity values (percentage of area of activities) in a typical college building are classified in Table 5.14.

**Table 5.14. The average weight of activities in a typical college building**

<table>
<thead>
<tr>
<th>Activities</th>
<th>CIBSE benchmark NO</th>
<th>CIBSE thermal fossil benchmark (kWh/m²/yr)</th>
<th>Typical % of area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Computer &amp; laboratories</td>
<td>24</td>
<td>160</td>
<td>31</td>
</tr>
<tr>
<td>2 Office</td>
<td>1</td>
<td>120</td>
<td>29</td>
</tr>
<tr>
<td>3 Seminar &amp; research rooms</td>
<td>18</td>
<td>240 UC</td>
<td>130 UCrb</td>
</tr>
<tr>
<td>4 Library</td>
<td>10</td>
<td>200</td>
<td>14</td>
</tr>
<tr>
<td>5 Workshops</td>
<td>27</td>
<td>180</td>
<td>4</td>
</tr>
<tr>
<td>6 Stores</td>
<td>28</td>
<td>160</td>
<td>3</td>
</tr>
<tr>
<td>7 Restaurant or Coffee Shop</td>
<td>7</td>
<td>370</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Assuming that the area of a typical college building as presented in Table 5.14, is 100 m², using the mixed use method the annual heat estimation and composite benchmark are as follows:

The annual heat energy demand estimation using mixed use method as defined in Equation (3.1) and Table 5.14 = 15,150 kWh/yr

**Annual consumption per 1 m² based on mixed use method = 151.50 ≈ 152 kWh/m²/yr**

Thus, a typical college building with 1 m² of area needs approximately 152 kWh/m² of thermal energy per year. For any other typical mixed use college buildings, if building useful area is A (m²), the heat demand equals 152A. It is also equal to the mean of 52 analysed DEC values explained in Chapter 4.

Regarding the generalisation of operational hours of heating systems, the mean operational hours of heating systems of the ten surveyed buildings were calculated and used as typical operation. The monthly typical operational hours are presented in Table 5.15.

**Table 5.15. Typical operational hours**

<table>
<thead>
<tr>
<th>Months</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours</td>
<td>300</td>
<td>280</td>
<td>260</td>
<td>250</td>
<td>240</td>
<td>85</td>
<td>45</td>
<td>80</td>
<td>223</td>
<td>249</td>
<td>229</td>
<td>2,276</td>
<td></td>
</tr>
</tbody>
</table>
The typical mixed use activity values and typical operational hours were replaced in Equation (5.1) and consequently the Equation (3.5), explained in detail in Chapter 3, was generated as follows:

\[
\left( \frac{152 A}{2400} \times \frac{HDD_{\text{monthly}}}{HDD_{\text{annual}}} \right) \times \frac{\text{Monthly typical operation (hours)}}{\text{Standard monthly operation (CIBSE, hours)}}
\]

Equation (3.5)

\[
\left( 96.27 \times \frac{A}{HDD\_{\text{monthly}}} \right) \times \frac{HDD\_{\text{monthly}}}{HDD\_{\text{annual}}} \times \frac{\text{Monthly typical operation (hours)}}{204 \times \text{CIBSE (hours)}}
\]

Equation (3.5)

Equation (3.5) was created based on typical data or free access data. Typical operational hours was presented in Table 5.15 and HDD can be found online [178]. Finally, by knowing the building useful area and using Equation (3.5), MTEMs for typical college buildings in Dublin can be created. The accuracy of the model is validated in the next section.

### 5.4.2. Validation of MTEMs in Typical College Buildings

The final version of Monthly Thermal Energy Models (MTEMs) was generated using Equation (3.5) in which the typical values were used. Based on heating degree days and typical operational hours provided in Table 5.15, the monthly heat demand for several buildings were created and the accuracy of models validated against actual data. Besides 10 surveyed buildings where the model was created and calibrated based on their actual data, it was also validated in several other buildings.

The estimated monthly thermal energy demand of Newman House at UCD campus against the actual consumption is shown in Figure 5.30.a. The total useful area of building (TUFA) was 2,726 m\(^2\). The relationship between the modelled values and actual measurements assessed by linear regression which was 0.99 (Figure 5.30.b). In addition, the absolute percentage error (APE) was calculated and presented in Table 5.16. The minimum error was 3% and was found during the month of January, while the maximum monthly error was 21% in November. On the other hand, the CIBSE UC estimation (mean monthly) shows a significant difference of more than 90% in June, July, August, and September. The annual error of CIBSE was 49% (overestimated) while the annual error of MTEMs was 9%.
Belfield House at UCD was the second building used to validate the MTEBs. According to the data analysis presented in Figure 5.31.a, the model was well matched with the actual consumption properly and the accuracy of model assessed by the $R^2$ value which was 0.99 as shown in Figure 5.31.b. The accuracy of monthly estimation was validated against the actual consumption. The absolute percentage error (APE) was calculated and used to validate the model. In addition, the model was also compared with CIBSE estimations and the results are shown in Table 5.17.
Chapter 5  
Monthly thermal energy modelling and benchmarking

The percentage differences between predicted monthly heat demand using the monthly model and actual figures have fluctuated between 0% and 16%, while the CIBSE errors altered from 7% to 99%. The annual error of the model was 11%, in contrast the annual error of CIBSE UC was 59%.

Table 5.17. Percentage difference between monthly heat model and actual, Belfield House, (UCD)

<table>
<thead>
<tr>
<th>Month</th>
<th>HDD 2014</th>
<th>Typical operation (hours)</th>
<th>Eq 3.5 kWh</th>
<th>% Difference Eq3.5 with actual</th>
<th>CIBSE estimation average monthly kWh</th>
<th>% difference between CIBSE and actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>303</td>
<td>300</td>
<td>28,070</td>
<td>11</td>
<td>27,100</td>
<td>7</td>
</tr>
<tr>
<td>February</td>
<td>274</td>
<td>280</td>
<td>23,692</td>
<td>7</td>
<td>27,100</td>
<td>19</td>
</tr>
<tr>
<td>March</td>
<td>267</td>
<td>260</td>
<td>21,410</td>
<td>13</td>
<td>27,100</td>
<td>31</td>
</tr>
<tr>
<td>April</td>
<td>182</td>
<td>250</td>
<td>14,051</td>
<td>5</td>
<td>27,100</td>
<td>51</td>
</tr>
<tr>
<td>May</td>
<td>133</td>
<td>240</td>
<td>9,857</td>
<td>12</td>
<td>27,100</td>
<td>68</td>
</tr>
<tr>
<td>June</td>
<td>63</td>
<td>85</td>
<td>1,654</td>
<td>10</td>
<td>27,100</td>
<td>94</td>
</tr>
<tr>
<td>July</td>
<td>32</td>
<td>45</td>
<td>445</td>
<td>16</td>
<td>27,100</td>
<td>99</td>
</tr>
<tr>
<td>August</td>
<td>70</td>
<td>35</td>
<td>757</td>
<td>5</td>
<td>27,100</td>
<td>97</td>
</tr>
<tr>
<td>September</td>
<td>72</td>
<td>80</td>
<td>1,779</td>
<td>0</td>
<td>27,100</td>
<td>93</td>
</tr>
<tr>
<td>October</td>
<td>132</td>
<td>223</td>
<td>9,097</td>
<td>13</td>
<td>27,100</td>
<td>71</td>
</tr>
<tr>
<td>November</td>
<td>225</td>
<td>249</td>
<td>17,312</td>
<td>15</td>
<td>27,100</td>
<td>46</td>
</tr>
<tr>
<td>December</td>
<td>316</td>
<td>229</td>
<td>22,379</td>
<td>13</td>
<td>27,100</td>
<td>28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2,069</td>
<td>2,276</td>
<td>150,503</td>
<td>11</td>
<td>325,200</td>
<td>59</td>
</tr>
</tbody>
</table>

School of Nursing at DCU was the third building in which the monthly heat model was tested. The results, shown in Figure 5.32.a & 5.32.b, were similar to the previous tests. The detailed information and monthly errors of the model and CIBSE UC benchmark are presented in Table 5.18.
The percentage difference between estimated monthly heat demand using the monthly model and the actual figures in School of Nursing have fluctuated between 10% and 20%, while the CIBSE errors were varied from 1% to 98%. The annual error of the model was 15%, in contrast the annual error of CIBSE UC was 47%. The high level of CIBSE TM46 estimation refers to the fixed annual benchmark.

Table 5.18. Percentage difference between monthly heat model and actual, School of Nursing (DCU)

<table>
<thead>
<tr>
<th>month</th>
<th>HDD 2014</th>
<th>Typical operation (hours)</th>
<th>Eq 3.5 kWh</th>
<th>% Difference Eq3.5 with actual</th>
<th>CIBSE estimation average monthly kWh</th>
<th>% difference between CIBSE and actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>303</td>
<td>300</td>
<td>150,482</td>
<td>10</td>
<td>145,280</td>
<td>14</td>
</tr>
<tr>
<td>February</td>
<td>274</td>
<td>280</td>
<td>127,008</td>
<td>13</td>
<td>145,280</td>
<td>1</td>
</tr>
<tr>
<td>March</td>
<td>267</td>
<td>260</td>
<td>114,775</td>
<td>15</td>
<td>145,280</td>
<td>9</td>
</tr>
<tr>
<td>April</td>
<td>182</td>
<td>250</td>
<td>75,324</td>
<td>11</td>
<td>145,280</td>
<td>42</td>
</tr>
<tr>
<td>May</td>
<td>133</td>
<td>240</td>
<td>52,843</td>
<td>13</td>
<td>145,280</td>
<td>59</td>
</tr>
<tr>
<td>June</td>
<td>63</td>
<td>85</td>
<td>8,865</td>
<td>14</td>
<td>145,280</td>
<td>93</td>
</tr>
<tr>
<td>July</td>
<td>32</td>
<td>45</td>
<td>2,384</td>
<td>10</td>
<td>145,280</td>
<td>98</td>
</tr>
<tr>
<td>August</td>
<td>70</td>
<td>35</td>
<td>4,056</td>
<td>20</td>
<td>145,280</td>
<td>97</td>
</tr>
<tr>
<td>September</td>
<td>72</td>
<td>80</td>
<td>9,536</td>
<td>20</td>
<td>145,280</td>
<td>92</td>
</tr>
<tr>
<td>October</td>
<td>132</td>
<td>223</td>
<td>48,767</td>
<td>18</td>
<td>145,280</td>
<td>60</td>
</tr>
<tr>
<td>November</td>
<td>225</td>
<td>249</td>
<td>92,810</td>
<td>20</td>
<td>145,280</td>
<td>24</td>
</tr>
<tr>
<td>December</td>
<td>316</td>
<td>229</td>
<td>119,971</td>
<td>20</td>
<td>145,280</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>2,069</td>
<td>2,276</td>
<td>806,821</td>
<td>15</td>
<td>1,743,360</td>
<td>47</td>
</tr>
</tbody>
</table>

TUFA 7,264 m²
5.5. Creating the Monthly Models Based on DECs, Method (2)

Display Energy Certificate (DEC) presents the building energy efficiency which is calculated using the Total Primary Energy Required (TPER). The other index displayed on DECs is Total Primary Fossil Energy Required (TPFER) which shows the annual fossil energy delivered to the boundary of building. In method (2) the TPFER, an annual index, was used to generate the MTEMs in buildings having a DEC.

Total Final Consumption (TFC) or actual consumption or recorded consumption is the amount of energy consumed in the building. TFC is measured by a meter and it is typically the quantity shown on bills in kWh [13]. Generally, there is approximately 20% difference between TPFER and TFC [111]. Due to energy losses beyond the boundary of the building, TFC is nearly 20% lower than TPFER [111].

Method (2) explains the methodology applied to convert the TPFER into monthly heat models which are more informative. If DEC documents are available, method (2) will be easier to use than method (1).

To create a monthly heat demand model using DECs, similar to the Method (1), HDD plays a key role. To make the monthly models as close as possible to the actual consumption, the maximum coefficient of 20% was considered. The maximum unit interval of 20% \( \frac{80}{100} = [0.80, 1] \) refers to the difference between TPFER and TFC [111]. DECs consider all primary energy types delivered to the boundary of building including the lost energy during transformation, transmission and distribution processes, while TFC or actual heat consumption is the value of consumed energy. To increase the accuracy of monthly simulation this difference was taken into account and called coefficient \( m \). So, using TPFER, coefficient \( m \), and heating degree days the primary version of the monthly heat models using DECs was created. Equation (3.6) was generated to create the models. The detailed information about the equation was presented in Chapter 3.

5.5.1. Monthly Thermal Energy Models Using DEC

Based on the TPFER shown on DECs, building area (TUFA), and heating degree days the primary version of monthly thermal energy model (MTEM) was generated. The accuracy of the model was calibrated using actual data. Equation (3.6) was used to generate the primary monthly heat demand models. Since method (2) relies on DECs, it was not applicable for future buildings. In addition, method (2) is not applicable in existing buildings which do not have a DEC; however, the simplicity is main advantage of the method.
The first example of generating monthly heat demand by converting TPFER into informative models was Hamilton Building at TCD. According to the DEC document of Hamilton, it needed 131 kWh/m²/yr (TPFER) of non-electrical energy (see Section 5.2.1) in 2012. The Total Useful Floor Area (TUFA) of building is 3,839 m². Figure 5.33 shows the MTEMs estimation compared with the actual data. The R-squared of 0.742 revealed that the model is not accurate enough. The detailed analyses of monthly errors of the model are presented in Table 5.19.

![Image](a)

**Figure 5.33.a. MTEMs, method (2) vs. actual data using Eq (3.6), (b) $R^2$ value**

**Table 5.19. Monthly errors of model using Eq (3.6), Hamilton Building (TCD)**

<table>
<thead>
<tr>
<th>month</th>
<th>Actual Gas Consumption, Hamilton building 2012 kWh</th>
<th>Eq3.6 kWh</th>
<th>% Difference of Eq (3.6) with actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>99,373</td>
<td>55,443</td>
<td>79</td>
</tr>
<tr>
<td>February</td>
<td>79,082</td>
<td>49,918</td>
<td>58</td>
</tr>
<tr>
<td>March</td>
<td>77,144</td>
<td>44,196</td>
<td>74</td>
</tr>
<tr>
<td>April</td>
<td>41,963</td>
<td>52,089</td>
<td>19</td>
</tr>
<tr>
<td>May</td>
<td>27,588</td>
<td>33,739</td>
<td>18</td>
</tr>
<tr>
<td>June</td>
<td>0</td>
<td>18,349</td>
<td>100.00</td>
</tr>
<tr>
<td>July</td>
<td>0</td>
<td>13,022</td>
<td>100.00</td>
</tr>
<tr>
<td>August</td>
<td>0</td>
<td>7,103</td>
<td>100.00</td>
</tr>
<tr>
<td>September</td>
<td>0</td>
<td>21,704</td>
<td>100.00</td>
</tr>
<tr>
<td>October</td>
<td>29,435</td>
<td>42,223</td>
<td>30.29</td>
</tr>
<tr>
<td>November</td>
<td>51,927</td>
<td>53,667</td>
<td>3.24</td>
</tr>
<tr>
<td>December</td>
<td>64,467</td>
<td>61,165</td>
<td>5.40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>470,979</strong></td>
<td><strong>452,618</strong></td>
<td><strong>4.06</strong></td>
</tr>
</tbody>
</table>

According to the data analysis, the absolute percentage monthly errors of heat estimation in 4 months including, June, July, August, and September were 100% (overestimation). In January and March, the errors were more than 74% and in February it was 58%. However, the annual error was 4%.

DIT at Bolton St was used as a second building to create monthly models based on its DEC. According to the DEC, the building’s TPFER was 101 kWh/m²/yr and building area was 25,437 m². Figure 5.34 shows the monthly heat model generated for DIT, Bolton Street. The data
assessment is presented in Table 5.20. The errors in July, August and September were approximately 78%, 57%, and 55% respectively. The reason for errors in summer months was due to the energy management or strategy of the building. The model (Eq3.6) did not consider the operational hours of heating systems.

Figure 5.34. Monthly heat model using Eq (3.6), College of Technology, DIT

| Table 5.20. Comparing monthly estimations using Eq (3.6) with actual measurements |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Month           | Actual Gas Consumption, Bolton St 2014 (kWh) | Eq (3.6)        | % absolute error Eq3.6 |
| January         | 349,782         | 300,995         | 16.21           |
| February        | 311,560         | 272,187         | 14.47           |
| March           | 278,060         | 265,233         | 4.84            |
| April           | 182,512         | 180,796         | 0.95            |
| May             | 107,768         | 132,120         | 18.43           |
| June            | 57,096          | 62,583          | 8.77            |
| July            | 7,100           | 31,788          | 77.66           |
| August          | 29,954          | 69,537          | 56.92           |
| September       | 32,348          | 71,524          | 54.77           |
| October         | 135,348         | 131,127         | 3.22            |
| November        | 264,408         | 223,511         | 18.30           |
| December        | 300,480         | 313,909         | 4.28            |
| **Total**       | **2,056,416**   | **2,055,310**   | **0.05**        |

Figure 5.35.a illustrates the Nova Building at UCD, where the TPFER was converted into monthly heat estimation. Similar to the other analysed buildings, a significant discrepancy in summer months was observed. Table 5.21 shows the absolute percentage monthly errors.
Equation (3.6) was used to estimate MTEMs in the above mentioned buildings and the results showed a significant discrepancy between actual and the model data especially in summer months. To improve the accuracy of the model, the operational hours of the heating systems were taken into consideration. The operation pattern is a key factor which affected the heat energy consumption in college buildings. Thus, in Equation (5.2) the operation pattern of heating systems is applied.

\[
\text{Equation (5.2)} \\
[TPFER \times (m) \times A \times \frac{HDD_{\text{month}}}{HDD_{\text{annual}}} \times \frac{\text{Monthly Actual operation (hours)}}{\text{Standard monthly operation (CIBSE hours)}}]
\]

Where A is total useful floors area (m²), HDD is heating degree day, and TPFER is a value shown on DEC, coefficient (m) ∈ [0.80, 1] & (m) ∈ N (Natural numbers)

Using Equation (5.2) the monthly heat demand models were generated and the accuracy of the updated models was calibrated using actual data. Equation (5.2) was applied in three buildings. For example; the MTEMs were created for Hamilton Building and presented in Figure 5.36. The updated version of the model was compared with previous version (Eq3.6) to calibrate the improvement of updated version.
The data analysis shown in Table 5.22, revealed a great improvement in the results especially during the summer months. The maximum monthly error of the updated version was 20% while the maximum monthly error of previous version was 100%. The annual error of updated version was 2% and indicated that the annual estimation was very close to the actual data. The reduction of errors of the model based on Eq (5.2) revealed the important role of operational hours. The R-squared value of 0.966 (Figure 5.37) showed the high level of accuracy of monthly model generated based on Equation (5.2).

**Table 5.22. Comparing monthly errors using Eq (3.6) & Eq (5.2), Hamilton Building (TCD)**

<table>
<thead>
<tr>
<th>month</th>
<th>Eq (3.6) kWh</th>
<th>Eq (5.2) kWh</th>
<th>% Difference of Eq (3.6) with actual</th>
<th>% Difference of Eq (5.2) with actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>55,443</td>
<td>86,898</td>
<td>79.24</td>
<td>14</td>
</tr>
<tr>
<td>February</td>
<td>49,918</td>
<td>75,794</td>
<td>58.42</td>
<td>4</td>
</tr>
<tr>
<td>March</td>
<td>44,196</td>
<td>64,076</td>
<td>74.55</td>
<td>20</td>
</tr>
<tr>
<td>April</td>
<td>52,089</td>
<td>44,137</td>
<td>19.44</td>
<td>5</td>
</tr>
<tr>
<td>May</td>
<td>33,739</td>
<td>24,292</td>
<td>18.23</td>
<td>14</td>
</tr>
<tr>
<td>June</td>
<td>18,349</td>
<td>0</td>
<td>100.00</td>
<td>0</td>
</tr>
<tr>
<td>July</td>
<td>13,022</td>
<td>0</td>
<td>100.00</td>
<td>0</td>
</tr>
<tr>
<td>August</td>
<td>7,103</td>
<td>0</td>
<td>100.00</td>
<td>0</td>
</tr>
<tr>
<td>September</td>
<td>21,704</td>
<td>0</td>
<td>100.00</td>
<td>0</td>
</tr>
<tr>
<td>October</td>
<td>42,223</td>
<td>36,398</td>
<td>30.29</td>
<td>19</td>
</tr>
<tr>
<td>November</td>
<td>53,667</td>
<td>57,829</td>
<td>3.24</td>
<td>10</td>
</tr>
<tr>
<td>December</td>
<td>61,165</td>
<td>72,798</td>
<td>5.40</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>452,618</strong></td>
<td><strong>462,222</strong></td>
<td><strong>4.06</strong></td>
<td><strong>2</strong></td>
</tr>
</tbody>
</table>
Furthermore, the model (Figure 5.38.a) for Aras An Phiarsaigh building (TCD) was calibrated and the R-squared value is presented in Figure 5.38.b. The high value of R-squared (0.98) showed the model is reliable.

Despite the acceptable results obtained using Eq (5.2), the model depends on the actual operational hours which is a specific factor. To generalise the model, the actual operation hours should be replaced by the typical operational hours. The typical operational hours were presented in Table 5.15.
Therefore, the final version of monthly model based on Method (2), was developed using the typical/general information. To create such models only the buildings useful area and TPFER were required both of which could be found on DECs. HDD can be obtained online [178] and the typical operation hours can be extracted from Table 5.15. Thus, Equation (3.7) which was generated to create the monthly heat demand based on typical data. Equation (3.7) was explained in detail in Chapter 3, Section 3.3.3.2.

Based on Equation (3.7), three monthly models for Engineering & Research at DCU campus (Figure 5.39, & Table 5.23), Medical Bureau of Road Safety at UCD campus (Figure 5.40, & Table 5.24) and R&D Building at DCU campus (Figure 5.41, & Table 5.25) were generated. As shown in the Figures 5.39-5.41 and Tables 5.23-5.25, the monthly models were well matched with actual consumption data and $R^2$ of more than 0.960 confirmed the reliability of the models. Furthermore, the percentage of monthly errors (percentage of differences with actual consumption) in all the cases were less than 20%, while the annual errors were 11%, 1%, and 3% respectively.

![Figure 5.39.a](image1.png)  
![Figure 5.39.b](image2.png)

**Figure 5.39.a.** The actual thermal energy consumption along with the predicted MTEBs using equation (3.7), (b) Calibration the accuracy of model, Engineering & Research (DCU)
Table 5.23. Monthly heat model and its accuracy, using Eq (3.7), Engineering & Research (DCU)

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual Gas Consumption, Engineering &amp; Research DCU 2014 (kWh)</th>
<th>HDD 2014</th>
<th>Typical operation (hours)</th>
<th>Eq (3.7)</th>
<th>% absolute error Eq (3.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>224,908</td>
<td>303</td>
<td>300</td>
<td>258,803</td>
<td>15</td>
</tr>
<tr>
<td>February</td>
<td>192,157</td>
<td>274</td>
<td>280</td>
<td>218,431</td>
<td>14</td>
</tr>
<tr>
<td>March</td>
<td>188,937</td>
<td>267</td>
<td>260</td>
<td>197,394</td>
<td>4</td>
</tr>
<tr>
<td>April</td>
<td>121,583</td>
<td>182</td>
<td>250</td>
<td>129,544</td>
<td>7</td>
</tr>
<tr>
<td>May</td>
<td>78,010</td>
<td>133</td>
<td>240</td>
<td>90,880</td>
<td>16</td>
</tr>
<tr>
<td>June</td>
<td>16,897</td>
<td>63</td>
<td>85</td>
<td>15,246</td>
<td>10</td>
</tr>
<tr>
<td>July</td>
<td>4,506</td>
<td>32</td>
<td>45</td>
<td>4,100</td>
<td>9</td>
</tr>
<tr>
<td>August</td>
<td>8,189</td>
<td>70</td>
<td>35</td>
<td>6,975</td>
<td>15</td>
</tr>
<tr>
<td>September</td>
<td>16,356</td>
<td>72</td>
<td>80</td>
<td>16,399</td>
<td>0</td>
</tr>
<tr>
<td>October</td>
<td>79,221</td>
<td>132</td>
<td>223</td>
<td>83,870</td>
<td>6</td>
</tr>
<tr>
<td>November</td>
<td>149,363</td>
<td>225</td>
<td>249</td>
<td>159,617</td>
<td>7</td>
</tr>
<tr>
<td>December</td>
<td>174,405</td>
<td>316</td>
<td>229</td>
<td>206,329</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>1,254,532</td>
<td>2,069</td>
<td>2,276</td>
<td>1,387,580</td>
<td>11</td>
</tr>
</tbody>
</table>

Figure 5.40.a. The actual thermal energy consumption along with the predicted MTEBs using equation (3.7), (b) Calibration the accuracy of model, Medical Bureau of Road Safety

Table 5.24. Monthly heat model and its accuracy, using Eq (3.7), Medical Bureau of Road Safety (UCD)

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual Gas Consumption, Medical Bureau of Road Safety (UCD)</th>
<th>HDD 2014</th>
<th>Typical operation (hours)</th>
<th>Eq (3.7)</th>
<th>Absolute percentage error Eq (3.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>36,117</td>
<td>303</td>
<td>300</td>
<td>34,037</td>
<td>6</td>
</tr>
<tr>
<td>February</td>
<td>30,375</td>
<td>274</td>
<td>280</td>
<td>28,727</td>
<td>5</td>
</tr>
<tr>
<td>March</td>
<td>22,338</td>
<td>267</td>
<td>260</td>
<td>25,961</td>
<td>16</td>
</tr>
<tr>
<td>April</td>
<td>18,560</td>
<td>182</td>
<td>250</td>
<td>17,037</td>
<td>8</td>
</tr>
<tr>
<td>May</td>
<td>12,543</td>
<td>133</td>
<td>240</td>
<td>11,952</td>
<td>5</td>
</tr>
<tr>
<td>June</td>
<td>2,472</td>
<td>63</td>
<td>85</td>
<td>2,005</td>
<td>19</td>
</tr>
<tr>
<td>July</td>
<td>640</td>
<td>32</td>
<td>45</td>
<td>539</td>
<td>16</td>
</tr>
<tr>
<td>August</td>
<td>1,100</td>
<td>70</td>
<td>35</td>
<td>917</td>
<td>17</td>
</tr>
<tr>
<td>September</td>
<td>2,306</td>
<td>72</td>
<td>80</td>
<td>2,157</td>
<td>6</td>
</tr>
<tr>
<td>October</td>
<td>9,376</td>
<td>132</td>
<td>223</td>
<td>11,030</td>
<td>18</td>
</tr>
<tr>
<td>November</td>
<td>24,982</td>
<td>225</td>
<td>249</td>
<td>20,992</td>
<td>16</td>
</tr>
<tr>
<td>December</td>
<td>22,828</td>
<td>316</td>
<td>229</td>
<td>27,136</td>
<td>19</td>
</tr>
<tr>
<td>Total</td>
<td>183,637</td>
<td>2,069</td>
<td>2,276</td>
<td>182,490</td>
<td>1</td>
</tr>
</tbody>
</table>
5.5.2. Validation of MTEMs Generated Based on DECs

The final version of monthly thermal energy models (MTEMs) which were generated based on DECs (Method 2) was validated using several buildings. Method (2) was tested for Belfield House at UCD, and the results are shown in Figure 5.42 and Table 5.26. The R-squared and the monthly percentage of differences against actual consumption were calculated and the accuracy of the model was assessed. According to the analysis, the minimum and maximum monthly differences were 0% and 18% in July and September respectively however, the annual difference was 5%. The R-squared of model was 0.93.
Chapter 5  
Monthly thermal energy modelling and benchmarking

Figure 5.42. (a) The actual thermal energy consumption along with the predicted MTEBs using equation (3.7), (b) Calibration the accuracy of model, Belfield Building (UCD)

Table 5.26. Test of method 2, Belfield House (UCD)

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual Gas Consumption, Belfield Building 2014 (kWh)</th>
<th>HDD 2014</th>
<th>Typical operation (hours)</th>
<th>Eq (3.7)</th>
<th>Percentage of difference of Actual with Eq (3.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>25,116</td>
<td>303</td>
<td>300</td>
<td>23,793</td>
<td>6</td>
</tr>
<tr>
<td>February</td>
<td>21,938</td>
<td>274</td>
<td>280</td>
<td>20,081</td>
<td>9</td>
</tr>
<tr>
<td>March</td>
<td>18,618</td>
<td>267</td>
<td>260</td>
<td>18,147</td>
<td>3</td>
</tr>
<tr>
<td>April</td>
<td>13,344</td>
<td>182</td>
<td>250</td>
<td>11,910</td>
<td>12</td>
</tr>
<tr>
<td>May</td>
<td>8,630</td>
<td>133</td>
<td>240</td>
<td>8,355</td>
<td>3</td>
</tr>
<tr>
<td>June</td>
<td>1,493</td>
<td>85</td>
<td>1,402</td>
<td>1,402</td>
<td>7</td>
</tr>
<tr>
<td>July</td>
<td>373</td>
<td>45</td>
<td>377</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>720</td>
<td>35</td>
<td>641</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>1,780</td>
<td>80</td>
<td>1,508</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>7,943</td>
<td>223</td>
<td>7,711</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>14,683</td>
<td>249</td>
<td>14,674</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>19,545</td>
<td>229</td>
<td>18,969</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td><strong>134,183</strong></td>
<td><strong>2,069</strong></td>
<td><strong>2,276</strong></td>
<td><strong>127,567</strong></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

5.6. Further Validation of Monthly Thermal Energy Models Generated Based on the Mixed Use Method (Method 1) & DECs (Method 2)

Both final versions of MTEMs which were generated based on the mixed use (method 1, Equation 3.5) and DECs (method 2, Equation 3.7) were validated in six typical college buildings belonging to the four case study universities. For the validation, various buildings were used rather than those of Survey B. School of Nursing DCU, Belfield House UCD, Quinn School of Business UCD, Newman House at UCD, Newman Building UCD, and Albert College DCU were used to validate both methods. Both methods (1&2) were validated against the actual thermal consumption and the results are presented in Figure 5.43.
Figure 5.43. Validating of methods 1 & 2 in more 6 typical college buildings, (a) School of Nursing DCU, (b) Belfield House UCD, (c) Quinn School of Business, (d) Newman House UCD, (e) Newman Building UCD, (f) Albert College DCU

In the six validation checks the results of MTEMs estimation using DEC's (method 2) were compared with the actual thermal consumption data [174]. The R-squared which shows the relationships between the model and the actual data was calculated and the results showed the robustness of the model. The R-squared of figures 5.43(a – f) are as follows:

(a) = 0.99  
(b) = 0.93  
(c) = 0.97  
(d) = 0.99  
(e) = 0.90  
(f) = 0.95

In addition the maximum and minimum percentage of monthly differences with actual figures in all models fluctuated between 4% and 21% while, the annual errors were less than 18%.
Furthermore, the results of MTEMs estimation using mixed use method (method 1) were compared with the actual thermal consumption data [174]. The R-squared of figures 5.43(a – f) are as follows:

(a) = 0.99  (c) = 0.9775  (e) = 0.97
(b) = 0.99  (d) = 0.99  (f) = 0.89

Thus, both methods are highly accurate.

5.7. Creating Monthly Thermal Energy Benchmarks

Based on Method 1 and Method 2, validated in the previous sections, as well as the typical data such as typical operational hours and the HDD of 2014, the Monthly Thermal Energy Benchmarks (MTEBs) were generated. In current research, the MTEB is defined as a typical monthly thermal energy demand of a college building per unit area (1m\(^2\)) over a month.

As calculated in Section 5.4.1, using the mixed use method the annual consumption of a mixed use typical college building per 1 m\(^2\) was found to be 152 kWh/m\(^2\)/yr. Assuming the area of a typical college building is 1 m\(^2\) (unit area of benchmark), using both Methods 1 and 2, the monthly thermal energy benchmarks were calculated. For TPFER in Equation (3.7), the mean consumption of 52 analysed DECs, i.e. 152 kWh/m\(^2\)/yr was used. The other necessary data, e.g. HDD and typical operational hours, were used to calculate the MTEBs and are presented in Table 5.27.

<table>
<thead>
<tr>
<th>Month</th>
<th>HDD 2014</th>
<th>Typical operation (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>303</td>
<td>300</td>
</tr>
<tr>
<td>February</td>
<td>274</td>
<td>280</td>
</tr>
<tr>
<td>March</td>
<td>267</td>
<td>260</td>
</tr>
<tr>
<td>April</td>
<td>182</td>
<td>250</td>
</tr>
<tr>
<td>May</td>
<td>133</td>
<td>240</td>
</tr>
<tr>
<td>June</td>
<td>63</td>
<td>85</td>
</tr>
<tr>
<td>July</td>
<td>32</td>
<td>45</td>
</tr>
<tr>
<td>August</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>September</td>
<td>72</td>
<td>80</td>
</tr>
<tr>
<td>October</td>
<td>132</td>
<td>223</td>
</tr>
<tr>
<td>November</td>
<td>225</td>
<td>249</td>
</tr>
<tr>
<td>December</td>
<td>316</td>
<td>229</td>
</tr>
<tr>
<td>Total</td>
<td>2,069</td>
<td>2,276</td>
</tr>
</tbody>
</table>

The MTEBs were calculated for a typical college building based on Equations (3.5) and (3.7) and the results were presented in Table 5.28.
Table 5.28. Creating MTEBs based on method 1 & 2

<table>
<thead>
<tr>
<th>Month</th>
<th>MTEBs Method (1) kWh/m²</th>
<th>MTEBs Method (2) kWh/m²</th>
<th>MTEBs mean of Methods (1) &amp; (2) kWh/m²</th>
<th>Mean actual consumption of 10 buildings kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>21</td>
<td>28</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>February</td>
<td>17</td>
<td>23</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>March</td>
<td>16</td>
<td>21</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>April</td>
<td>10</td>
<td>14</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>May</td>
<td>7</td>
<td>10</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>July</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>August</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>September</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>October</td>
<td>7</td>
<td>9</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>November</td>
<td>13</td>
<td>17</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>December</td>
<td>17</td>
<td>22</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>111</td>
<td>149</td>
<td>130</td>
<td>128</td>
</tr>
</tbody>
</table>

The mean values of both Methods (1) and (2) was selected as MTEBs because it was very close to the actual values. According to the Table 5.28, it can be concluded that the overall MTEBs (annual benchmark), i.e. 130 kWh/m²/yr equals with the UCrb recommended in Chapter 4 as a revised annual benchmark.

The accuracy of MTEBs was assessed against the mean actual consumption of 10 case study buildings (Survey B) and the results are presented in Figure 5.44. In addition, the new idea, i.e. MTEB was compared with the original fixed-annual CIBSE UC heat benchmark. The development, accuracy and contribution of MTEBs were significant.
MTEBs were also validated using linear regression and the evaluated results of 144 values are shown in Figure 5.45. Using MTEBs the monthly heat demand calculated for 12 typical college buildings and the results compared with actual consumption. The R-squared of 0.9619 showed the high level of reliability of monthly thermal energy benchmarks.

In addition the actual data of the EBD (Energy Building Dataset) belonging to buildings in Survey B was used for analysing the accuracy of MTEBs as presented in Table 5.29. According to the MTEBs, a typical college building, needed 24 kWh/m² thermal energy in January followed by 20, 19, 15, 12, and 9 kWh/m² in February, March/December, November, April, and May respectively. Accordingly, it needed nearly 0-2 kWh/m² in June, July, August, and September. It can be seen the trend was reduced radically in summer months. The trend after October increased from 8 kWh/m² to 15 and 19 kWh/m² in November and December respectively.

Figure 5.44. Monthly Thermal Energy Benchmarks (MTEBs) vs TM46 UC

Improvement of MTEBs
Compared with the fixed-annual benchmark of 240 kWh/m²/yr suggested by CIBSE TM46 in 2008, MTEBs are more informative and accurate for thermal energy estimation in typical college buildings. For instance, by multiplying the MTEB of April (12 kWh/m²/yr) by the useful area of a given college building the heat demand in April can be estimated easily. Such an estimation for each month is applicable and the results can be used for preparing detailed energy action plans. Such information is also valuable for energy suppliers. The method is more worthwhile if applied at a neighbourhood scale such as a campus. The comparison of MTEBs with the CIBSE UC annual benchmark shows a significant contribution of the monthly modelling and benchmarking to give more information regarding the heat demand pattern during a year.

Table 5.29. MTEBs vs. the actual consumption per 1m²

<table>
<thead>
<tr>
<th>Months</th>
<th>Eng.1, method [1]</th>
<th>Eng.2, method [2]</th>
<th>MTEBs</th>
<th>NonRes HkWh/m²</th>
<th>NonRes HkWh/m²</th>
<th>NonRes HkWh/m²</th>
<th>NonRes HkWh/m²</th>
<th>NonRes HkWh/m²</th>
<th>NonRes HkWh/m²</th>
<th>Mean actual 10 Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>21</td>
<td>28</td>
<td>24</td>
<td>15</td>
<td>14</td>
<td>16</td>
<td>11</td>
<td>22</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>February</td>
<td>17</td>
<td>23</td>
<td>20</td>
<td>14</td>
<td>14</td>
<td>16</td>
<td>12</td>
<td>18</td>
<td>18</td>
<td>44</td>
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<tr>
<td>March</td>
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<tr>
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<td>9</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>August</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
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<td>5</td>
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<td>13</td>
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</tr>
<tr>
<td>December</td>
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<td>14</td>
<td>11</td>
<td>20</td>
<td>17</td>
<td>19</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>Total</td>
<td>111</td>
<td>140</td>
<td>130</td>
<td>95</td>
<td>78</td>
<td>147</td>
<td>115</td>
<td>137</td>
<td>127</td>
<td>270</td>
</tr>
</tbody>
</table>

Figure 5.45. Assessing the accuracy of Monthly Thermal Energy Benchmarks (MTEBs)
5.8. Conclusion

The fixed-annual fossil thermal benchmark of 240 kWh/m²/yr was presented by CIBSE TM46 in 2008 which was a fundamental step toward energy certification, efficiency and energy management in buildings; however, it does not match accurately with actual conditions. As heat consumption largely depends on the ambient temperature, the benchmark is not suitable because it does not deliver any difference between summer and winter figures. In addition, a huge discrepancy between the benchmark and actual consumption was found and calibrated using the actual data of college buildings in Dublin. Particularly, the gaps in summer months were nearly 100%.

To fill these gaps, the idea of monthly thermal energy models (MTEMs) was presented, developed, and validated. Two methods (1&2) for monthly modelling of heat demand in typical college buildings were examined in detail. The MTEMs were created using five key factors including the mixed use method, revised CIBSE UC benchmark (UCrb), mixed activities, heating degree days, and typical operational hours of heating systems. To generate the models, 10 typical college buildings were surveyed and their information used to generate the models. Method (1) was developed based on the mixed use method. The method relies on architectural maps and considers all activities in the building. It is applicable for existing and future buildings. Method (2) is more user-friendly, however it is limited to the existing buildings having DECs. Equations (3.5) and (3.7) were generated and validated to produce the MTEMs.

The accuracy of both models was calibrated and validated against the actual heat consumption data. The absolute percentage of monthly errors as well as the linear regression analysis confirmed the high level of accuracy of the models. Several examples were validated and the results explained comprehensively. Furthermore, to understand the advantages and the quantity of effectiveness and accuracy of the idea, the models were also compared with CIBSE TM46 UC benchmark. Compared with approximately a 100% error of monthly prediction of CIBSE UC, the maximum 21% errors of monthly models were a great improvement. The annual error of MTEMs was less than 18%.

Finally, based on methods 1&2, the Monthly Thermal Energy Benchmarks (MTEBs) were created and validated against actual consumption. Despite the fixed annual benchmark of CIBSE UC, the MTEBs altered from 24 kWh/m² in January to 1 and nearly zero kWh/m² in June and July respectively. The R-squared value of more than 0.96 confirmed the reliability of MTEBs method. MTEBs also share more effective information than the current CIBSE UC benchmark so they can be used by urban planners, energy suppliers, energy planners and other professionals to assess and analyse monthly heat demand of college buildings. The models can be extrapolated to other
building types. Due to the significant development of the original CIBSE UC as well as reducing the annual benchmark by presenting the MTEBs idea, the environmental aspect of the idea, e.g. reduction of CO₂ emissions is also crucial. The MTEBs provide detailed information that could be used in energy action plans.
Chapter 6

Heat Mapping
Chapter 6. Heat Mapping

6.1. Introduction

This chapter explains the methodology for generating the monthly heat maps at the case study universities, i.e. Trinity College Dublin (TCD), University College Dublin (UCD), Dublin Institute of Technology (DIT), and Dublin City University (DCU). It focuses on the analysis of the efficiency of thermal consumption as well as the assessment of the amount of fossil thermal energy consumption at the campus scale. Understanding the amount and pattern of heat consumption of the studied campuses is the main objective of this chapter in order to develop the efficiency of heat consumption and reduce CO\textsubscript{2} emissions in a group of buildings.

In addition, based on the Energy Building Database (EBD), a GIS based tool called District Heat Balance (DHB) tool, was developed and used to generate the heat maps. Then, the heat maps were applied to discover thermal demand density, baseload and peak load of case study buildings.

The main purpose of heat maps is to understand heat consumption (size) and Geo-Scattering of thermal anchor loads. Heat maps can be used to extract meaningful policies to reduce thermal energy at the campus scale.

6.2. Development of a Campus Heat Map

A heat map (HM) methodology has been developed which is a suitable GIS based method for analysis and management of heat demand or surplus at the community scale in this case, campus scale. HM has also been applied for assessing the efficiency and feasibility of District Heating (DH) systems. In recent studies [144-146], the advantages of the DH system were highlighted from economic, environmental, and energy efficiency viewpoint. Therefore, it was recommended as a future campus thermal energy system because of the potential of integrating with renewable energy sources [144].

In order to generate a robust base for a DH system, energy models and maps are essential [206]. Since a DH relies upon local thermal energy demand densities and resources, energy maps which involve a detailed analysis of energy in the buildings are a prerequisite to develop a DH system. Recently, Ireland started moving toward application of DH, when its first Spatial Energy Demand Analyses have been produced for the South Dublin in 2015 [207]. According to the result of the study more than 75% of Dublin City had a thermal energy demand density of 150 TJ/km\textsuperscript{2} which is appropriate for the installation of DH system [207]. The thermal energy density increased to
500 TJ/km² around TCD. However, no further study regarding the thermal energy mapping and monthly/seasonal modelling at the campus level in Ireland has been undertaken.

The heating system at TCD is a mixed system including a DH system and individual boilers. The systems are not connected, with each system being run, managed and serviced independently. The DH heating system in TCD was compared with individual boiler systems. All systems are illustrated on the campus map in Figure 6.1.

Figure 6.1. The current heating systems of TCD

In addition, based on the detailed data shared by Estates Office of TCD, the overall annual heat loss of the boiler systems was calculated. Accordingly, the heat loss of each boiler was assessed.

Since the amount of heat demand is modified based on the activities in buildings, modelling the accurate amount of thermal energy demand in energy mapping is fundamental. This challenge was addressed comprehensively in Chapter 5 and monthly thermal energy models (MTEMs) were generated for typical college buildings and validated against actual data. However, a campus also includes other types of buildings which are important from the heat demand perspective. Sports centres, libraries, amphitheatres, and restaurants are usually found on a campus and they need a large amount of heat energy per unit area. For example, a restaurant needs 370 kWh/m² per year [99]. Unfortunately, enough data was not available to investigate the relationship between mixed activities and thermal energy demand in these types of buildings. However, the role of these types of buildings was not ignored in heat mapping.

The other types of buildings in a campus except typical college buildings were called Non-UC buildings. The monthly heat demand estimations in Non-UC buildings are also essential to discover the quantity of energy demand at the campus scale. The HM methodology developed in this chapter considers all types of buildings on a campus to calculate the heat demand at the
campus scale. The mapping method and the capability of DHB tool will be explained in further detail in the following sections.

6.3. Assessment of Heat Losses at TCD Campus

The heating systems at TCD can be divided into two groups; (1) District Heating (DH) system, and (2) individual boiler systems. The first system is in the west part of the campus (yellow in Figure 6.1) and serves the Buttery Restaurant, Atrium, Houses 4, 10, 12, 14, 24, 26, &35, Graduate Memorial Building, Provost’s House, Public theatre, Reading room, and Dining Hall. Individual boilers on the other hand, serve the rest of the buildings on the campus. The size of green circles on the map in Figure 6.1 shows the number of boilers installed in each building. For example, in Berkeley Library six boilers were installed. As seen in Figure 6.1, it is possible in the future to connect individual boilers to create the second or third DH zones on the campus.

Based on the analysis using ArcGIS, the overall useful area of buildings serviced by DH system was 43,793 $m^2$. According to the CIBSE TM46:2008 benchmarks and monthly thermal energy models (MTEMs), they needed (in 2012) 11,312,468 kWh thermal energy per year. These buildings occupy approximately 14,916 $m^2$ of campus land (the overall area of footprint of buildings). The detailed information including area and thermal energy demand of all buildings heated by DH system is presented in Table 6.1.

Table 6.1. Information of buildings heating by DH system

<table>
<thead>
<tr>
<th>Building name</th>
<th>Footprint area ($m^2$)</th>
<th>Thermal energy demand CIBSE (kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dining Hall</td>
<td>2290</td>
<td>1,488,961</td>
</tr>
<tr>
<td>Art Block College</td>
<td>1410</td>
<td>737,633</td>
</tr>
<tr>
<td>Graduate’s Memorial</td>
<td>1004</td>
<td>757,904</td>
</tr>
<tr>
<td>Provost’s House</td>
<td>998</td>
<td>244,911</td>
</tr>
<tr>
<td>Disin House</td>
<td>923</td>
<td>182,179</td>
</tr>
<tr>
<td>Trinity College Dublin, New Square</td>
<td>863</td>
<td>24,735.84</td>
</tr>
<tr>
<td>Entertainment Hall</td>
<td>774</td>
<td>473,999</td>
</tr>
<tr>
<td>West Chapel accommodation Office</td>
<td>773</td>
<td>683,524</td>
</tr>
<tr>
<td>Student Residential</td>
<td>727</td>
<td>530,247</td>
</tr>
<tr>
<td>Student accommodation 1</td>
<td>718</td>
<td>920,199</td>
</tr>
<tr>
<td>Graduates Reading Room</td>
<td>690</td>
<td>417,820</td>
</tr>
<tr>
<td>Electrical Engineering</td>
<td>659</td>
<td>779,786</td>
</tr>
<tr>
<td>Trinity Accommodations</td>
<td>622</td>
<td>2,236,607</td>
</tr>
<tr>
<td>General Office 3</td>
<td>573</td>
<td>4,816,8384</td>
</tr>
<tr>
<td>Trinity College Dublin</td>
<td>561</td>
<td>30,307.2</td>
</tr>
<tr>
<td>Student accommodation 2</td>
<td>310</td>
<td>76,7509</td>
</tr>
<tr>
<td>General Office 2</td>
<td>179</td>
<td>176,309</td>
</tr>
<tr>
<td>Chief Stewards House</td>
<td>144</td>
<td>241,915</td>
</tr>
<tr>
<td>Laundry</td>
<td>53</td>
<td>327,108.672</td>
</tr>
<tr>
<td>Chief Stewards House 1</td>
<td>23</td>
<td>285,996</td>
</tr>
</tbody>
</table>
The Estates Office of TCD in 2015 reported that the boilers (listed in Table 6.2) were switched off at night time, between 7 pm and 6 am, throughout the year [208]. The temperature of water in the boiler’s tank before switching off was 70 °C but, in the morning it was 20 °C. The 50 °C difference between evening and morning temperature of water showed a significant heat loss. The Estates Office switched off boilers because at night time there was nearly zero demand (kWh) for space heating or hot water in many buildings. This is done as a part of the campus policy for energy efficiency. The policy is also implemented during the holidays and weekends mostly Sundays. More information in this regard will be presented in the following sections.

Based on the volume of water associated with each boiler (i.e. volume of tanks), the heat losses were calculated. Equation (6.1) was used to calculate heat losses. The necessary information for calculation of heat losses is presented in Table 6.2 [7].

\[ Q = [c \times M \times (T_2 - T_1)] = cM \Delta T \quad \text{(Equation 6.1)} \]

Where \( Q \) is the amount of heat loss, \( c \) is the specific heat of water \((c=4.1868 \text{ Joule/gram } °C)\), \( M \) is mass (litre), \( T_2 - T_1=50 °C \), 1 litre of water \( \cong \) 1000 gram

<table>
<thead>
<tr>
<th>Boilers location</th>
<th>Tank Capacity (litre)</th>
<th>Fuel type</th>
<th>Flow-Return Temperature °C</th>
<th>Daily Heat Loss (Joule)</th>
<th>Heat Loss (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aras An Phismaigh</td>
<td>1,600</td>
<td>Gas</td>
<td>70-60</td>
<td>334,944,000</td>
<td>93</td>
</tr>
<tr>
<td>Samuel Beckett</td>
<td>1,100</td>
<td>Gas</td>
<td>70-61</td>
<td>230,274,000</td>
<td>64</td>
</tr>
<tr>
<td>200 Pearse St</td>
<td>800</td>
<td>Gas</td>
<td>70-60</td>
<td>167,472,000</td>
<td>47</td>
</tr>
<tr>
<td>199 Pearse St</td>
<td>1,100</td>
<td>Oil</td>
<td>70-60</td>
<td>230,274,000</td>
<td>64</td>
</tr>
<tr>
<td>190 Pearse St</td>
<td>700</td>
<td>Oil</td>
<td>70-60</td>
<td>146,538,000</td>
<td>41</td>
</tr>
<tr>
<td>193 Pearse St</td>
<td>300</td>
<td>Gas</td>
<td>70-60</td>
<td>62,802,000</td>
<td>17</td>
</tr>
<tr>
<td>194 Pearse St</td>
<td>700</td>
<td>Gas</td>
<td>70-60</td>
<td>146,538,000</td>
<td>41</td>
</tr>
<tr>
<td>Civil Engineering</td>
<td>2,000</td>
<td>Gas</td>
<td>70-60</td>
<td>418,680,000</td>
<td>116</td>
</tr>
<tr>
<td>Sports &amp; CRANN</td>
<td>12,000</td>
<td>Gas</td>
<td>70-60</td>
<td>2,512,080,000</td>
<td>698</td>
</tr>
<tr>
<td>O’Reilly Building</td>
<td>5,000</td>
<td>Gas</td>
<td>70-60</td>
<td>1,046,700,000</td>
<td>291</td>
</tr>
<tr>
<td>17-19 Westland Row</td>
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<td>Gas</td>
<td>70-60</td>
<td>272,142,000</td>
<td>76</td>
</tr>
<tr>
<td>Hamilton Building</td>
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<td>Gas</td>
<td>70-60</td>
<td>732,690,000</td>
<td>204</td>
</tr>
<tr>
<td>Biotechnology Building</td>
<td>5,750</td>
<td>Gas</td>
<td>70-60</td>
<td>1,203,705,000</td>
<td>334</td>
</tr>
<tr>
<td>East End</td>
<td>12,000</td>
<td>Gas</td>
<td>70-60</td>
<td>2,512,080,000</td>
<td>698</td>
</tr>
<tr>
<td>Parsons Building</td>
<td>3,800</td>
<td>Gas</td>
<td>70-60</td>
<td>795,492,000</td>
<td>221</td>
</tr>
<tr>
<td>Moyne Institute</td>
<td>3,200</td>
<td>Gas</td>
<td>70-60</td>
<td>669,888,000</td>
<td>186</td>
</tr>
<tr>
<td>Lloyd Building</td>
<td>6,000</td>
<td>Gas</td>
<td>70-60</td>
<td>1,256,040,000</td>
<td>349</td>
</tr>
<tr>
<td>SNIAMS</td>
<td>4,000</td>
<td>Gas</td>
<td>70-60</td>
<td>837,360,000</td>
<td>233</td>
</tr>
<tr>
<td>Physiology &amp; zoology</td>
<td>5,000</td>
<td>Gas</td>
<td>70-60</td>
<td>1,046,700,000</td>
<td>291</td>
</tr>
<tr>
<td>Anatomy</td>
<td>1,200</td>
<td>Gas</td>
<td>70-60</td>
<td>251,208,000</td>
<td>70</td>
</tr>
<tr>
<td>Chemistry</td>
<td>3,800</td>
<td>Gas</td>
<td>70-60</td>
<td>795,492,000</td>
<td>221</td>
</tr>
<tr>
<td>Berkeley Library</td>
<td>4,250</td>
<td>Gas</td>
<td>70-60</td>
<td>889,695,000</td>
<td>247</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>124,100</strong></td>
<td><strong>8</strong></td>
<td><strong>16,558,794,000</strong></td>
<td><strong>4,600</strong></td>
<td></td>
</tr>
</tbody>
</table>

Monthly heat losses (kWh) 138,000
Overall Annual heat losses (kWh) 1,679,000
According to the calculations the overall annual heat loss of TCD boilers was approximately 1,679,000 kWh. This is a huge heat loss and needs to be addressed properly. The DH system in the west of TCD did not follow the daily switching on/off strategy. The reason was that the DH system at night time serviced a group of buildings e.g., residential accommodations that need hot water continuously. So, it can be concluded that comparing with the individual boilers, the DH system is more efficient. The mixed use functions of buildings, such as residential which has continual heat demand caused the DH system to be independent from the daily on/off policy. To reduce the heat losses of individual boilers resulting from interrupted daily operation, a methodology will be presented in the next chapter.

### 6.3.1. Monthly Heat Maps for TCD Campus

DHB tool is a GIS based tool developed in this research for generating the monthly thermal energy maps. In ArcGIS, the DHB tool was linked with EBD (Energy Building Database) which includes all the energy data such as DEC information, Monthly Thermal Energy Models (MTEMs), Monthly Thermal Energy Benchmarks (MTEBs), and heat density. It also includes all the information obtained from Surveys A and B (see Chapter 3, Sections 3.2.2 & 3.3.1). The attribute table of DHB tool comprises of 120,000 data cells which were used to generate the monthly heat maps. HMs using CIBSE TM46 and MTEBs were developed for first time in this research. For calculation of monthly heat demand of typical college buildings, the methodology developed in Chapter 5 was used, however for Non-UC buildings a different methodology was applied. The average annual demand based on the CIBSE TM46:2008 benchmarks were used. The monthly heat demand of TCD in January 2012 was generated and shown in Figure 6.2.

In fact Non-UC building types comprise 28 categories as defined by CIBSE TM46 [99] (see Appendix 1). In Chapter 4, Section 4.3 (Table 4.5), it was discovered that 38% all issued DECs at four case study campuses belonged to Non-UC buildings. To calculate the amount of mean monthly thermal energy demand for Non-UC buildings, the benchmarks based on the dominant function (single function) of Non-UC buildings were derived from TM46 and divided by 12 (number of months in a year) and then the result multiplied by the total useful floor area (TUFA) of that building which was obtained by Surveys A and B. Using Equation (6.2) the mean monthly heat demand was calculated for Non-UC building types.

Mean monthly thermal energy demand for a Non-UC building \( (Q_i) \) with dominant function \((i)\):

\[
Q_i = \left(\frac{TM46\ benchmark\ (i)}{12}\right) \times A \quad \text{Equation (6.2)}
\]

where benchmark \((i)\) in kWh/m²/yr refers to dominant function of the building and \(A\) is total useful floor area (m²)
The weakness of this method is that it ignores mixed functions in the Non-UC buildings. For instance, a library building was considered as a single use building and it is categorised as ‘Cultural activities’ (CIBSE TM46, Table 1 and Row 10) with a thermal benchmark of 200 $kWh/m^2/yr$ [99]. Due to the lack of data to develop a robust monthly thermal energy demand model for Non-UC buildings the current CIBSE benchmarks were used. However, this gap could be investigated in future studies.

**Figure 6.2.** The heat demand (HM) map of TCD campus, January 2012, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) shows the unconditioned spaces.

The analysis of thermal energy map of TCD in January 2012 revealed that the highest thermal energy demand among the buildings on the campus was 330,748 kWh belonging to Arts Building followed by the Panoz Institute and Lloyd Building with 231,550 and 225,250 kWh respectively (illustrated in Figure 6.2). The lowest demand was approximately 6,500 kWh belonging to a storage facility building in the north of the campus behind the Simon Perry Building. On Figure 6.2 the dark colours show a higher thermal energy demand and lighter colours a lower thermal energy demand. NCC refers to ‘No Climate Control’ spaces or unconditioned spaces.

The key characters of a spatial thermal demand map such as the sample shown in Figure 6.2, are to identify the locations of potential anchor thermal energy loads. Anchor thermal energy loads are high heat demand buildings such as swimming pools. Besides the high density thermal energy load, the other parameter that should be considered in the identification of anchor loads is the
continuous demand pattern. For instance, a building with high thermal energy density during a short period such as a month or even a season is not a thermal anchor load.

The DHB tool developed in this research, is applicable to generate the monthly heat maps for case study universities. In addition, it can share a lot of valuable information about the buildings and energy analysis. If a user of the DHB tool clicks on a building in ArcGIS, for example on the Lloyd Building, a window will open and delivers valuable information in a table format as shown in Figure 6.3. The screenshot (Figure 6.3) shows that how by clicking on a building footprint, the table of information can be accessed. The information can be used by professionals for various purposes for instance, energy efficiency planning to reduce the fossil energy consumption at the neighbourhood e.g., university campus scale. The monthly heat demand, dominant & mixed activities in the building, gross heat density (H_UED_g), Footprint heat density (H_UED_f), and the annual and monthly fossil thermal energy demand of building can be found in the table. In addition, the table delivers the building information such as size and number of floors.

![Screenshot of DHB tool, Energy and building info, Lloyd Building, TCD](image)

Figure 6.3. Screenshot of DHB tool, Energy and building info, Lloyd Building, TCD
Detailed analyses of the monthly fossil thermal energy demand of TCD buildings were undertaken using DHB tool and a sample is shown in Table 6.3. The analyses were presented at the building level.

Table 6.3. The monthly fossil thermal energy data of TCD campus at the building level

<table>
<thead>
<tr>
<th>Building Name</th>
<th>January Heat Demand</th>
<th>February Heat Demand</th>
<th>March Heat Demand</th>
<th>April Heat Demand</th>
<th>May Heat Demand</th>
<th>June Heat Demand</th>
<th>July Heat Demand</th>
<th>August Heat Demand</th>
<th>September Heat Demand</th>
<th>October Heat Demand</th>
<th>November Heat Demand</th>
<th>December Heat Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
<td>21,343</td>
</tr>
<tr>
<td>Coffee shop cafe</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
<td>22,236</td>
</tr>
<tr>
<td>Accommodation library</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
<td>49,375</td>
</tr>
<tr>
<td>Library</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
<td>56,017</td>
</tr>
<tr>
<td>Library  3</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
<td>61,469</td>
</tr>
<tr>
<td>Library  6</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
<td>70,473</td>
</tr>
<tr>
<td>Library  7</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
</tr>
<tr>
<td>Library  8</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
<td>122,413</td>
</tr>
<tr>
<td>Library  9</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
<td>177,854</td>
</tr>
<tr>
<td>Dining hall</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
<td>186,384</td>
</tr>
</tbody>
</table>

The heat map (HM) of TCD in July 2012 is presented in Figure 6.4. According to the map, the thermal energy demands of UC buildings at TCD were zero, however Non-UC buildings with functions such as residential, sports centre (swimming pool), restaurants, and library needed thermal energy over this month. According to the HM of July, the highest thermal energy demand belonged to Dining Hall with 186,384 kWh followed by Sports Centre with 177,854 kWh.

According to the statistical analysis undertaken in ArcGIS, the overall thermal energy demand of Non-UC buildings in July 2012 was 1,529,438 kWh. In addition, the average daily thermal energy demand was approximately 51,000 kWh which showed the baseload (the lowest daily load) of the campus. On the other hand, the peak load (monthly and daily) can be derived from analysis of January heat map presented in Figure 6.2. Based on the statistical assessments in ArcGIS the thermal energy demand of TCD in January 2012 was approximately 3,944,680 kWh which showed an average daily demand of 131,000 kWh. The difference between baseload and peak load was 80,000 (kWh/day). This detailed information, i.e. baseload and peak load which obtained from analysis of the monthly heat map is crucial in designing a DH system. Such information is very valuable in an urban zone. For example, understanding the thermal density extracted from HM helps urban planners to choose the optimised location for energy plants nearby the anchor load. This strategy reduces energy loss of hot water in a DH system due to the short distance between energy plant and energy consumer, i.e. anchor load. In addition, knowing the base and peak heat loads is useful in the design of a DH system plant in terms of capacity (tank volume)
and power. For instance, such information could be used by mechanical engineers to calculate efficient plants.

![Heat demand map in July 2012, TCD. The graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.](image)

**Figure 6.4.** The heat demand map in July 2012, TCD. The graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.

By comparing both January and July maps in Figures 6.2 & 6.4 respectively, important information regarding the anchor loads of the campus was obtained. The maps revealed the location of both anchor loads, i.e. Dining Hall in the northwest of the campus and Sports Centre at the opposite side, northeast.

In addition, by analysis of the heat map of July in Figure 6.4, two classes of buildings were defined (i) Continual Thermal Consumers (CTC), all buildings on the map except blue coloured and NCC, and (ii) Periodical Thermal Consumers (PTC), blue coloured buildings identified. PTC needs very low or nearly zero thermal energy during the summer or at night time. Typical college buildings are an example of this class. CTC and PTC are used as a foundation for the energy balance analysis which will be presented in the next chapter.

The detailed analysis of thermal energy demand of both classes of buildings showed the footprint area of PTC was 28,234 $m^2$ and the footprint area of CTC was 21,835 $m^2$. The useful buildings area of PTC was 87,049 $m^2$ while, the useful buildings area of CTC was 60,852 $m^2$. Accordingly, the annual thermal energy consumption of PTC was 14,640,057 kWh, while the annual
consumption of CTC was 16,657,440 kWh. The monthly thermal energy consumption of PTC buildings at the campus scale is presented in Figure 6.5.

**Figure 6.5.** *The monthly thermal energy consumption of PTC buildings*

The thermal energy consumption pattern of PTC not only depends on the outdoor temperature and is modified through the year but also depends on the attendance timetable of students/staff. For example, at night time e.g., 8pm when there were few students the boilers at TCD were switched off. This strategy was observed at the weekends and holidays as shown in Figure 6.6. The consumption pattern of PTC buildings will be assessed in detail in the next chapter.

**Figure 6.6.** *The thermal energy consumption pattern of PTC buildings, Aras An Phiarasgaigh, December 2013* [174]

Further assessment of the HM maps revealed that the location of energy source of DH system at TCD is located beside an anchor load, i.e. Dining Hall (Figure 6.7) which was a successful decision in terms of reducing heat losses during hot water circulation between energy source and anchor load (Dining Hall). The shorter distance results in shorter piping, lower risk of repairing, water leaking and consequently lower heat losses and insulation. Closeness of heat source to anchor loads is a key criterion that should be considered in land development in future urban planning. Determining the best location for energy generators from the perspective of energy
efficiency in a DH system at the community/urban context is one of the important applications of heat energy maps. Assessing the criteria such as minimum heat loss and costs, maximum efficiency, as well as optimum land cost to determine the best location for thermal energy generators could be investigated in future studies.

**Figure 6.7.** Location of anchor load and DH energy source, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.

Based on the analyses of heat maps of May, June, (Figures 6.8.a and 6.8.b), July (Figure 6.4) August, September (figure 6.8.c), and October (Figure 6.8.d) it can be concluded that if the DH system at TCD develops further, an open space in the west of Sports Centre is the best location for a new thermal energy source as shown in Layout 1 in Figure 6.8.c. Based on the closeness to the anchor load of the Sports Centre and the availability of open space, the location was determined.
Based on the distance analysis presented in Layout 1 (Figure 6.8.c), the college map was divided into three sections with 241, 224, and 205 m intervals. The current DH system covers the first interval, i.e. 241 m at the west of campus. The new DH system can cover the rest of campus with maximum distance of 325 m as shown in the figure. The new location specified with a circle with an area of 415 m$^2$. 
The new DH source with maximum distance of 325 m can service buildings located in the southeast and east of the campus such as Parsons Building, Moyne Institute, Chemistry Building, Smurfit Institute, Panoz Institute, Hamilton Building and Lloyd Building. Likewise, it can also service another group of buildings located in the north of the campus with distance of 224 m.
Samuel Beckett Theatre, Aras An Phiarsaigh, and Simon Perry Building are examples of buildings in this group. In case of connecting both DH resources (the existing plant room near Dining Hall and the recommended source near Sports Centre) the maximum distance between them is approximately 480 m. Establishing a new DH system instead of individual boilers can save a heat loss of 1,679,000 kWh resulting from the daily on/off strategy.

Using the DHB tool, 7 monthly heat demand maps of TCD were generated and presented in Figure 6.9. Other examples are Figures 6.2, 6.4, and 6.8.
Figure 6.9. The monthly fossil heat map of TCD in 2012. The graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.
The amount of monthly thermal energy demand of TCD at the campus scale is presented in Table 6.4. The overall annual consumption of the campus was 31,297,497 kWh/yr. The lowest demand at the campus scale was in July with nearly 1,529,000 kWh, while the highest demand was in January with nearly 3,945,000 kWh. The heat demand of TCD in January was approximately 2.5 times greater than that in July.

Table 6.4. The monthly fossil thermal energy demand at the campus level, TCD

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCD</td>
<td>3,944,680</td>
<td>3,559,110</td>
<td>3,363,968</td>
<td>2,784,643</td>
<td>2,398,429</td>
<td>1,625,991</td>
<td>31,297,497</td>
</tr>
<tr>
<td>campus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>1,529,438</td>
<td>1,626,047</td>
<td>1,722,659</td>
<td>2,302,316</td>
<td>2,978,586</td>
<td>3,461,630</td>
<td></td>
</tr>
</tbody>
</table>

6.4. Generating Monthly Heat Maps for UCD

The Energy Building Database (EBD) was linked with the DHB tool and used for the generation of monthly heat demand maps of UCD in 2012 presented in Figures 6.10.a and b. The highest thermal energy demand at the building scale in January was 1,004,168 kWh and belonged to the Newman building complex (including Arts Café, School of Geography, School of history, and School of Archaeology). The lowest thermal energy demand in July was 810 kWh and belonged to a one floor office of Estate Services, at the north of UCD followed by Belfield Bike Shop with 898 kWh.
Figure 6.10.a. The monthly HM of UCD campus in 2012, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.
Figure 6.10.b. The monthly HM of UCD campus in 2012, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.
Chapter 6  

Heat Mapping

The thermal energy demand of PTC buildings in January 2012 was 3,750,916 and the details at the building scale are presented in Table 6.5.

Table 6.5. Thermal energy demand of PTC buildings in January (2012)

<table>
<thead>
<tr>
<th>Building Name</th>
<th>January (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humanities Institute of Ireland</td>
<td>14,718</td>
</tr>
<tr>
<td>Industrial Microbiology Annex</td>
<td>16,908</td>
</tr>
<tr>
<td>Urban Institute</td>
<td>17,776</td>
</tr>
<tr>
<td>UCD research</td>
<td>17,776</td>
</tr>
<tr>
<td>UCD Confucius Institute</td>
<td>20,328</td>
</tr>
<tr>
<td>Belfield House</td>
<td>21,252</td>
</tr>
<tr>
<td>William Jefferson Clinton Auditorium</td>
<td>26,752</td>
</tr>
<tr>
<td>Daedalus Building (Applied language centre)</td>
<td>49,368</td>
</tr>
<tr>
<td>Schools of Computer Science</td>
<td>51,209</td>
</tr>
<tr>
<td>School of Architecture</td>
<td>80,872</td>
</tr>
<tr>
<td>Hanna Sheely Skeffington</td>
<td>86,064</td>
</tr>
<tr>
<td>NOVA UCD</td>
<td>126,126</td>
</tr>
<tr>
<td>School of Mathematical Science</td>
<td>150,480</td>
</tr>
<tr>
<td>School of Earth Science</td>
<td>152,526</td>
</tr>
<tr>
<td>Charles Institute</td>
<td>152,680</td>
</tr>
<tr>
<td>School of law</td>
<td>192,522</td>
</tr>
<tr>
<td>National Institute for Bioprocessing Research Training</td>
<td>198,352</td>
</tr>
<tr>
<td>School of Veterinary Science</td>
<td>225,902</td>
</tr>
<tr>
<td>Conway Institute</td>
<td>240,711</td>
</tr>
<tr>
<td>Quinn School of Business</td>
<td>266,310</td>
</tr>
<tr>
<td>School of Civil, Structural and environmental Engineering</td>
<td>281,292</td>
</tr>
<tr>
<td>Centre for Synthesis and Chemical Biology</td>
<td>282,040</td>
</tr>
<tr>
<td>schools of Engineering and Material Science</td>
<td>322,262</td>
</tr>
<tr>
<td>Agriculture and food Science Centre</td>
<td>363,770</td>
</tr>
<tr>
<td>O’Brien Centre</td>
<td>392,920</td>
</tr>
<tr>
<td>Total</td>
<td>3,750,916</td>
</tr>
</tbody>
</table>

The overall annual demand of the UCD campus in 2012 was 89,987,993 kWh. Based on the energy maps, the monthly thermal energy demand of the campus was calculated and presented in Table 6.6. In 2012, the lowest demand of the campus was in July with 4,771,126 kWh, while the highest demand was in January with 11,041,434 kWh followed by February with 9,869,728 kWh and December with 9,626,937 kWh. The heat demand of UCD campus in January was approximately 2.3 times greater than that in July.

Table 6.6. The monthly thermal energy demand at the campus level in 2012, UCD

<table>
<thead>
<tr>
<th>UCD campus</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11,041,434</td>
<td>9,869,728</td>
<td>9,384,147</td>
<td>7,927,404</td>
<td>6,956,241</td>
<td>5,013,917</td>
<td>89,987,993 kWh/yr</td>
</tr>
<tr>
<td>March</td>
<td>4,771,126</td>
<td>5,013,917</td>
<td>5,256,707</td>
<td>6,713,450</td>
<td>8,412,985</td>
<td>9,626,937</td>
<td></td>
</tr>
</tbody>
</table>

Creating the thermal energy density maps is one of the other capabilities of DHB tool. Urban Energy Density (UED) is the total amount of end use energy demand (kWh) in a building normalized by the total building’s area or its footprint area during a year [47]. UED is a measure for analysing and understanding the density of end use energy in the buildings and it can be divided into two types (i) Gross Urban Energy Density (UED₉) and (ii) Footprint Urban Energy Density (UED₉).
Density (UED$_f$). If the amount of energy is divided by total building area, the result is UED$_g$. Accordingly, if the amount of energy is divided by footprint area of the building, the result is UED$_f$. Both UED$_g$ and UED$_f$ were calculated in ArcGIS and the results available in the EBD. The fossil thermal energy UED$_f$ and UED$_g$ of UCD campus are presented in Figures 6.11 and 6.12 respectively. For calculation of UED the overall annual thermal energy demand of the buildings was used.

Figure 6.11. UED$_f$ map of UCD campus in 2012, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.

The UED$_f$ map (figure 6.11) shows the thermal energy density of the UCD campus and revealed which building needed more energy and where they are located on the campus. The thermal energy density map is useful for determination of the best and most efficient location of central generators. The map also showed the distribution pattern of energy sinks for example, the buildings with larger UED$_f$ were in the centre of the campus which was named Zone 1.

The highest UED$_f$ was 2,218 kWh/m$^2$ and belonged to a residential complex in the south of the campus, while the lowest UED$_f$ was associated with a church in the centre of the site as illustrated in Figure 6.11 (yellow colour) with energy density of 92.4 kWh/m$^2$ per year.

Further analysis of the UED$_f$ map showed the location of the district heating generator (plant room) is not appropriate because of the large distance of 2,000 m from anchor load (residential
complex), while a land identified in Layout 2 is the best place for the plant room. The new location reduces the distance between the plant and highest UED building e.g., anchor load building to the half and therefore, the heat losses during water circulation could be decreased. In addition, the new location is closer to Zone 1 where the higher UED buildings are located.

The gross energy density map (Figure 6.12) of UCD campus showed that Swimming Pool building with highest gross thermal energy density of 1,130 kWh/m² needed approximately 4,560,318 kWh of thermal energy per year followed by the Fitness and Sports Centre with a gross density of 440 kWh/m² which needed approximately 4,699,834 kWh of fossil thermal energy per year.

![Figure 6.12. UED map of UCD campus in 2012, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.](image)

6.5. Generating the Monthly Heat Maps for DCU

The monthly thermal energy demand of DCU campus is presented in Figures 6.13.a and b. The diverse quantities of heat demand of buildings during a year (2014) were presented by colour codes in the maps. The same methodology that used for generating the heat maps at TCD and UCD was applied. The heating system in DCU is individual boilers; however, some buildings may be serviced by shared boilers. The best place to establish a generator space for a DH system is in the east part of the campus near O’Reilly Library.
Figure 6.13.a. Monthly HM of DCU campus in 2014, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.
Figure 6.13.b. Monthly HM of DCU campus in 2014, the graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand. NCC (No Climate Control) showed the unconditioned spaces.
The demand of typical college buildings changed significantly during the year and the differences were calculated and illustrated on the HMs. CTC (Continual Thermal Consumer) buildings such as student/staff residential, fitness and health centre needed thermal energy in all months over the year.

Table 6.7 shows the monthly fossil thermal energy demand of DCU extracted from the analysis of heat maps of the campus. The analysis showed that the DCU campus needed approximately 35,766,000 kWh of fossil thermal energy in 2014. The campus demand in January was approximately 4,500 MWh, while its demand in July was nearly 1,780 MWh.

Table 6.7. The monthly thermal energy demand at the campus level in 2014, DCU

<table>
<thead>
<tr>
<th>DCU campus</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4,467,478</td>
<td>4,037,517</td>
<td>3,822,536</td>
<td>3,177,595</td>
<td>2,747,634</td>
<td>1,887,712</td>
<td>35,766,355</td>
</tr>
<tr>
<td>Jul</td>
<td>1,780,222</td>
<td>1,887,712</td>
<td>1,995,202</td>
<td>2,640,144</td>
<td>3,392,576</td>
<td>3,930,027</td>
<td></td>
</tr>
</tbody>
</table>

The generated data using monthly heat maps was saved in EBD (Energy Building Database). Using DHB tool in ArcGIS the generated data was analysed and the monthly thermal energy demands (2014) of 11 PTC (Periodical Thermal Consumers) buildings at DCU were generated as shown in Figure 6.14. The School of Mathematical Sciences with total useful area of 12,632 m² had the greatest demand (monthly and annual), while the lowest demand belonged to National Institute for Digital Learning with total useful area of 1,152 m².
In Figure 6.15 the annual thermal energy demands of 14 CTC buildings including student residential, fitness and health care, library, entertainment hall (The Helix and Invent), office, operating theatre, and crèche were compared. Helix with annual (2014) thermal energy demand of 4,911,240 kWh had the greatest thermal energy demand, while the lowest demand was 48,312 kWh belonging to a crèche at the northeast of the campus.
The HM and the relevant analyses were not provided for DIT because it is a non-centralised campus. However, the amounts of heat demands of its individual campuses were provided in the EBD (Energy Building Database). The HMs for the developing centralised DIT campus as well as the relevant analysis are presented in Chapter 8.

6.6. Conclusion

The study of the heating systems of TCD showed that the Estates Office switched the boilers off in the evening and switched them on again in the morning over a year. Due to this policy, the water temperature in boiler’s tank cooled down from 70 °C to 20 °C which resulted in the daily decreasing of 50 °C of temperature. The decreasing of temperature resulted in a large heat loss in the tanks. The associated heat losses at the campus level were calculated and discovered that the overall annual heat losses were 1,679,000 kWh. Such heat losses were not observed in the DH system at TCD because it serviced various types of Non-UC buildings that needed heat energy even at night, summer months, and holidays.

Monthly heat maps (HM) for case study campuses of TCD, UCD, and DCU were generated and the associated thermal energy demand for each campus calculated. HM and the data analyses have shown a significant difference between the heat demand of buildings over a year. The study of HM also revealed that the heat demand patterns of buildings on a campus were different. So, based on the monthly heat demand patterns, the buildings on a university campus were classified into two classes (1), Continual Thermal Consumer (CTC) and (2), Periodical Thermal Consumer (PTC).

In addition, using the EBD and DHB tool the gross and footprint thermal energy density maps of UCD campus were generated and the patterns of low and high thermal energy demand density buildings were identified. In this context, the locations of thermal energy anchor loads were determined and the current location of the plant room was assessed.

Detailed information such as determining the location of anchor thermal loads, daily baseload and peak load, monthly heat demand at the campus or individual building level, and consumption patterns of heat demand is fundamental in management and planning of energy efficiency at the community scale. Such valuable information is also essential for smart design, visualisation, and management of DH system.

At TCD, the useful floor area of PTC buildings was 87,049 $m^2$ and the useful floor area of CTC was 60,852 $m^2$. Accordingly, the annual thermal energy consumption of PTC was 14,640,057 kWh, while the annual consumption of CTC was 16,657,440 kWh. Students residential, sports centres, restaurants, and entertainment halls are among examples of CTC class of buildings which
was assessed in detail. It was also found that the student attendance timetable was a key parameter affecting the thermal energy consumption of PTC. The assessments of CTC buildings revealed that further analyses could be conducted to develop an accurate thermal energy estimation model for them. Because of the lack of data, it was not covered in this study. However, the detailed information recorded in EBD can be used as a basis for future studies to fill this gap.

According to the analyses, the annual thermal energy demand at DCU was 35,766,355 kWh/yr. Among 11 PTC buildings, the greatest annual demand belonged to the School of Mathematical Sciences, while the lowest demand belonged to the National Institute for Digital Learning. On the other hand, among CTC buildings, the greatest thermal energy demand in 2014 was 4,911,240 kWh belonged to Helix Building.
Chapter 7

Creating a Smart Thermal Energy Campus Network
Chapter 7. Creating a Smart Thermal Energy Campus Network

7.1. Introduction

A new concept of sharing surplus thermal energy between adjacent buildings on a campus is developed as an alternative for thermal energy storage. Using the monthly thermal energy models generated in Chapters 4 and 5 and the heat mapping methodology presented in Chapter 6 as well as the solar thermal potential of the case study buildings, the amounts of monthly surplus thermal energy are determined. Sharing surplus thermal energy is more applicable and efficient than thermal energy storage. The concept can reduce the thermal energy consumption. In this chapter the concept and its advantages are discussed.

Thermal energy storage faces a series of barriers such as the large size of stores, specific technologies and equipment, limited time of storage, short-term stability (Phase Change Materials) properties, and the efficiency of method [166-168]. In addition, in most cases the conversion of energy is essential during the storage process which reduces the efficiency of the system. The efficiency of the energy storage process even without the necessity for energy conversion in the best systems is less than 80% [209, 210].

In comparison with individual boilers, a DH system is more efficient and produces less carbon dioxide [153]. A DH system is more efficient, greener, and cost-effective because it can use surplus heat from multiple sources such as renewables [146, 154, 155]. The basis of a DH system is a thermal network which connects all energy consumers (buildings).

Considering the 1,679 MWh of annual heat losses of Trinity College Dublin (TCD) boilers (Chapter 6, Section 6.3) and ever increasing role of renewable energy especially solar thermal technologies as well the high efficiency of a DH system, the concept of sharing surplus thermal energy between the campus buildings forms the structure of this chapter.

To do so, the DHB (District Heat Balance) tool was developed further by adding new information to enable the tool to be useful for smart managing of thermal demand-supply across a campus. In Chapters 4-6 the models and maps for better estimation of the demand side procedure were explained comprehensively. The current chapter involves the methods used for modelling and visualising the supply (waste heat from individual boilers and solar thermal potentials) side. It explains how by visualising and assessment of monthly or daily (average) thermal energy
demand-surplus can reduce fossil fuel consumption. The methodology, advantages, and the energy use reduction results of the concept are explained in this chapter.

7.2. Thermal Fossil Consumption Patterns at the Campus Scale

Based on the analysis of actual heat consumption data [174], the patterns of thermal fossil demand of the studied campuses were assessed in further detail e.g., hourly scale and it was found that they were very different. In addition, the amounts of thermal energy demand per unit area were also varied. For example, a swimming pool needed 1,130 kWh/m² during 24/7 (24 hours 7 days) over a year [14, 15] while a typical college building needed 1-2 kWh/m² (Monthly Thermal Energy Benchmarks (MTEBs), Section 5.7, Chapter 5) from June to September. Understanding these differences in terms of demand sizes (kWh) and patterns in the management of thermal efficiency at the community scale are vital.

In Chapter 6, based on the demand diversity of campus buildings they were classified into two classes, i.e. Continual Thermal Consumers (CTC) such as fitness, swimming pools, restaurants, and student accommodations and Periodical Thermal Consumers (PTC) such as typical college buildings.

This diversity is the starting point of the concept of sharing surplus thermal energy across a campus. The idea is similar to the smart electricity grid; however, it is limited to the community scale such as a campus. The heat loss during the transmission of hot water affects the size of a thermal network. For example, the distance between thermal energy plant and energy sinks (buildings) affects the heat losses during hot water transmission.

In the context of waste heat from individual boilers it was discovered that the decreasing of hot water temperature from 70 ºC in the evening to 20 ºC in the morning resulted in a 1,679,000 kWh/yr heat loss (Chapter 6, Table 6.2). Turning off boilers at night time was implemented as an energy efficiency policy which is more efficient than running boilers at night time when few occupants use the buildings. However, the efficient way is to use this waste heat and develop the strategy.

Alternatively, the waste or surplus heat energy can be shared across a DH system. Restaurants or residential accommodation are good candidates to utilise the surplus thermal energy of individual boilers. If the energy is shared across a campus thermal network with other buildings that have a thermal demand at that time, there will be no need to switch off the boilers and consequently 1,679 MWh of waste fossil heat energy can be used in case of TCD campus. Moreover, there is no need for thermal energy storage technologies.
The successful implementation of the idea of sharing surplus thermal energy requires a comprehensive understanding of the bilateral concept of thermal demand-supply. The patterns and monthly sizes of thermal demand of typical college buildings (PTC buildings) have been explained comprehensively. Nevertheless, the thermal demand patterns of CTC buildings need to be investigated further.

The actual fossil thermal energy consumption patterns [174] of a sports centre, a restaurant, and student accommodation belonging to case study universities in July 2016 are presented in Figures 7.1-4 respectively. The analyses confirmed the continual thermal demand of these buildings even during the night in July. Gas was the main fuel type in all the cases. These buildings are good samples of CTC. July was selected for assessment of thermal demand patterns in which the demand of PTC buildings is nearly zero. So, it is the best month that indicates the difference of heat patterns/size in PTC and CTC buildings. Accordingly, for hourly assessments 15th July 2016 was selected.

**Figure 7.1.** *The daily actual thermal consumption size and pattern of Sports Centre, July 2016, TCD* [174]

Figure 7.1 shows the daily heat consumption size and pattern of Sports Centre building at TCD which is a mixed use building (office, swimming pool, and fitness). The building needed 183,574 kWh fossil thermal energy in July 2016 [174]. The minimum consumption was approximately 4,000 kWh on Sunday 17th July. The 24-hour pattern of heat demand of the building at 15-minute intervals is presented in Figure 7.2 which shows the building consumed 5,369 kWh fossil thermal energy between 04:00 and 21:15 on the 15th of July 2016.
Figure 7.2. *The hourly actual thermal consumption size and pattern of Sports Centre on 15th of July 2016, TCD [174]*

Accordingly, the daily (July 2016) and hourly (15th of July 2016) fossil thermal energy consumption patterns of a restaurant at University College Dublin (UCD) are presented in Figures 7.3.a and 7.3.b respectively. It was found that the daily (15th July) and monthly gas consumption was 122 and 4,223 $m^3$ respectively. The $CO_2$ emissions in July was 9,375 $kgCO_2e$. The graph shows that the lowest consumption was on Sundays with mean consumption of 90 $m^3$. On Sundays, thermal energy was used from 7:00 to 21:30, while in other days it was used for longer period. The analysed restaurant needed thermal energy every day in July (Figures 7.3.a).

Figure 7.3.a. *The Daily fossil (gas) thermal demand size and pattern of a restaurant, July 2016, UCD [174]*
Figure 7.3.b. The hourly fossil thermal size and demand pattern of a restaurant, 15th July 2016, UCD [174]

The restaurant needed thermal energy between 03:45 and 24:00 on 15th of July 2016. At some points the consumption was zero; however, the graph shows a nearly continual demand. At lunch time (12:00-13:00) the maximum demand of 5 m$^3$ was observed followed by 3 m$^3$ in the morning (7:00-8:00) and evening (17:00-19:00).

Figures 7.4.a and b present the daily (July 2016) and hourly (15th of July 2016) fossil thermal energy consumption patterns of a student residential building at Dublin City University (DCU) respectively. According to the actual data [174] College Park Residences 11, 12 and 13 consumed heat energy every day in July (Figures 7.4.a). The overall gas consumption in July was 1,705 m$^3$ which produced 3,632 kgCO$_2$e.

Figure 7.4.a. The daily fossil thermal consumption size and pattern of a Residential complex, July 2016, DCU [174]
The continual hourly consumption patterns on 15th of July 2016 over 24 hours were also observed. The peak heat demand was observed between 06:00 and 07:00 which was also reported by other studies [11-13] in residential buildings. The peak consumption refers to showering and making breakfast. Furthermore, the daily analysis of College Park Residences indicated there was not a great difference (less than 12%) between thermal energy demand at weekend and weekdays.

Figures 7.1-7.4 show the thermal energy demand patterns of various types of CTC buildings in the studied campuses. The graphs show CTC buildings, for instance residential and restaurant, needed thermal energy during day and night time over the year even in July continually. While, the thermal demands of typical college buildings in July, holidays and night time were very low (nearly zero).

7.2.1. Assessment of Thermal Demand Size in CTC Buildings

To smartly manage the issue of thermal energy demand and supply at the campus community scale, further assessments of the issue at CTC building are required. Therefore, a group of CTC buildings usually found on a campus was analysed in detail. The group includes swimming pool, fitness, entertainment hall, restaurant, general accommodation, cultural activities, and general office. According to the analysis of mean monthly thermal demand as presented in Figure 7.5, swimming pool with mean monthly demand of 94 kWh/m² had the highest demand, while general office with 10 kWh/m² had the lowest demand. In the graph the monthly thermal energy benchmarks (MTEBs) were also presented. The thermal energy demand density (mean monthly) of fitness, entertainment hall, and restaurant were 37, 35, and 31 kWh/m² respectively. As shown
in the graph there was a significant difference of 61% between thermal density of swimming pool and fitness.

**Figure 7.5.** The mean monthly heat demand of CTC buildings vs. MTEBs
7.2.2. Further Assessment of Thermal Demand Patterns in CTC Buildings

As explained in Chapter 2, the paucity of data is a great barrier to energy studies in buildings in Ireland. The lack of data of CTC buildings was the main reason for failure in generation of monthly thermal models for this class of building. However, to prove that they need thermal energy even in summer, most of the available data was analysed and some examples are presented in the following sections.

The annual analysis of thermal demand of Sports Centre at TCD in 2016 (Figure 7.6) indicated approximately 41% difference between average demands in winter and summer which related to space heating in swimming pool and hot water demand for pool and showers. The demands in December, January and February were 311,471, 383,587, and 366,259 kWh respectively. The average demand in these months was 353,772 kWh. On the other hand, the demands in June, July, and August were 244,000, 183,574, 194,564 kWh respectively. The average demand in these months was 207,379 kWh.

![Figure 7.6. The monthly thermal demand, Sports Centre, 2016, TCD [174]](image)

The thermal energy demand of the swimming pool and houses 17-19 at DCU was nearly 26,159 m³ during June, July and August 2016 as shown in Figure 7.7. The consumption of buildings was not measured separately.
Figure 7.7. The monthly thermal demand, swimming pool and houses 17-19, 2016, DCU [174]

Figure 7.8. The monthly thermal demand, Library, 2016, UCD [174]

The thermal demand of the UCD library was approximately 234,950 kWh in June, July and August 2016 as shown in Figure 7.8. According to the assessments of thermal energy patterns shown in Figures 7.1-7.8, it can be concluded that the CTC buildings such as swimming pool, accommodation, sports centre, and library need thermal energy in all months of the year during day and night.

7.3. Sharing Surplus Thermal Energy

Solar thermal technology (such as evacuated tube collectors) with efficiency of 60-70% can play a significant role in mitigation of global warming [159-161] and many public buildings have started to apply such technology. The size of evacuated solar collectors for example, the number of tubes is calculated based on the average annual solar radiation and the amount of hot water demand [162]. Nevertheless, one of the limitations of such technology is the availability of enough space on the roof for installation of solar thermal panels especially in high buildings in densely populated cities. Sometimes roofs are not south facing to absorb solar energy or they may be occupied by HVAC equipment [211].
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The other limitation refers to the contrast between the availability of maximum solar radiation and thermal energy demand. For example, in summer the maximum solar thermal energy is available in Ireland, while the heat demand of a typical college building in July is nearly zero. In other words, maximum solar radiation is available when the thermal demand is minimum and vice versa.

Thermal energy storage is a method to store surplus energy for later usage. However, it faces a series of barriers [166-168] as explained comprehensively in Chapter 2, Section 2.10. Therefore, the current study presents the idea of sharing surplus thermal energy as an alternative.

Assuming that typical college buildings will apply solar thermal technology in the near future, smart managing of daily/monthly heat demand or surplus at the campus level was investigated and modelled in this chapter.

Due to maximum solar radiation being available during the summer months in Dublin [179], typical college buildings that have installed solar evacuated technology produce maximum surplus solar thermal energy (hot water) at this period. On the other hand, CTC buildings need thermal energy 24/7. So, across a local thermal network the surplus thermal (solar or waste heat) energy of typical college buildings can be shared with CTC buildings. Meanwhile, the waste heat from individual boilers can also be used across a thermal network.

Comparing the thermal energy storage method, sharing surplus heat energy is cheaper and applicable. The advantages of sharing thermal energy across a DH system at the community scale are as follows:

(i) DH system is more efficient [144] than individual boilers (also was proved in Chapter 6)
(ii) No need for store rooms, expensive equipment, specific materials compared with thermal energy storage method
(iii) No need for high level of insulation and air tightness compared with thermal energy storage method
(iv) Managing thermal energy efficiency at the community scale is more effective than an individual building
(v) Further number of buildings and people can benefit from sharing surplus energy compared with thermal energy storage method
(vi) Saving a significant amount of fossil fuel and reduction of CO₂ emissions

Managing thermal balance between demand and surplus was undertaken by a DHB (District Heat Balance) tool developed in the study.
7.3.1. Surplus Thermal Energy, Assessment and Analysis

For implementation of the concept of sharing surplus heat across a campus it is assumed that the individual boilers were connected to create a local thermal network and renewable energy sources particularly solar thermal technologies were also applied.

According to the Irish energy efficiency action plans [60, 182, 212], the renewable heat share has doubled in Ireland since 1990 and approximately 5.7% of all thermal energy use in 2013 was obtained from renewable heat sources. However, with the target of 12% for contribution of renewable energy for heating by 2020 [212] there is still some way to go.

To consider the role of renewable energy sources in thermal energy maps, data of solar thermal such as incident solar radiation, geothermal, and biomass was added into the DHB tool. The 22-year monthly average solar radiation on a horizontal surface (kWh/m²/day) in Dublin was obtained from NASA [179] and presented in Table 7.1. The maximum radiation was in June with 5.25 kWh/m²/day followed by 5.22 kWh/m²/day in May. The minimum radiation was 0.53 kWh/m²/day in December.

<table>
<thead>
<tr>
<th>Dublin</th>
<th>NASA Surface metrology and solar energy, Atmospheric Science Data Centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>53</td>
</tr>
<tr>
<td>Longitude</td>
<td>-6</td>
</tr>
<tr>
<td>Jan</td>
<td>Feb</td>
</tr>
<tr>
<td>0.72</td>
<td>1.40</td>
</tr>
</tbody>
</table>

NASA radiation data was input in the ArcGIS and joined with the attribute table of the DHB tool. Figure 7.9 presents the monthly solar radiation produced by the DHB tool to calculate the capability (potential) of monthly solar thermal energy in each building in the case study campuses.
Ireland has a reliable source of shallow geothermal energy reserves. The Irish shallow ground waters are a longstanding source of geothermal energy that may be applied to generate the heat energy with high level of efficiency. The effective returns of 4 to 6 $kW$ of heating energy for every 1 $kW$ of electrical energy input (heat pumps) can be obtained from shallow ground geothermal system [213].

The Geothermal data of Dublin obtained from The Geothermal Association of Ireland was also added as a new layer in the DHB tool as presented in Figure 7.10. The geothermal temperatures were presented at various depths; however, the shallow geothermal information at depths of 500 $m$ and 100 $m$ were only added into the DHB tool. The map shows that the geothermal temperature is 31°C at a depth of 1000 $m$ in Dublin, while it reduces to 18 °C at a depth of 500 $m$ as illustrated in Figure 7.11 and the geothermal temperature remains constant at 18 °C across the country at a depth of 100 $m$ as shown in Figure 7.12.
Figure 7.10. Ireland’s Geothermal map at a Depth of 1000 m

Figure 7.11. Ireland’s Geothermal map at a Depth of 500 m

Figure 7.12. Ireland’s Geothermal map at a Depth of 100 m
In order to enable the DHB tool to be used for calculating renewable thermal energy potential at the campus level, detailed information regarding the potential of renewable thermal energy sources in each building was added into the database. To achieve this goal, a form (Table 7.2) was designed to record all the required data which was necessary for managing surplus-demand thermal energy.

**Table 7.2. A sample form to collect the renewable energy data**

<table>
<thead>
<tr>
<th>FID</th>
<th>Gross Area (m²)</th>
<th>Useable Area (m²)</th>
<th>Opening</th>
<th>Useable</th>
<th>South facade</th>
<th>North facade</th>
<th>East facade</th>
<th>West facade</th>
<th>Gross Area (m²)</th>
<th>Location</th>
<th>Car access</th>
</tr>
</thead>
<tbody>
<tr>
<td>3782</td>
<td>1553 m²</td>
<td>1098</td>
<td></td>
<td></td>
<td>22.45*11.52</td>
<td>5.69*11.52</td>
<td>9.29*6.86</td>
<td>4.64*6.86</td>
<td>237 m²</td>
<td>North-West</td>
<td>Provided</td>
</tr>
</tbody>
</table>

**Calculation of monthly solar thermal potential**

<table>
<thead>
<tr>
<th>FID</th>
<th>Energy Systems</th>
<th>Ability to produce energy (kWh)</th>
<th>CO₂ emission per kWh</th>
<th>average annual Demand July kWh/month</th>
<th>Heat Balance (demand/surplus) kWh/month</th>
</tr>
</thead>
<tbody>
<tr>
<td>3782</td>
<td>Solar heating</td>
<td>5.03<em>30</em>918*0.70=95,968</td>
<td>0</td>
<td>0</td>
<td>95,968 − 0 = +95,968</td>
</tr>
</tbody>
</table>

(1) According to NASA Surface Meteorology and Solar Energy (https://eosweb.larc.nasa.gov/sse/), Latitude 53 & Longitude -6

(2) [Generated monthly solar energy – Monthly heat demanded], if “+” = surplus heat, and if “−” = demand

Table 7.2 presents data of O’Reilly Institute at TCD as a sample (Figures 7.14 and 7.15). The useable area (m²) of roof for installation of solar thermal panels was calculated using Google Earth Pro. Gross area equals to total roof area, while useable area is the area of the part of roof which suitable for installing solar thermal panels. So, the north-facing section was subtracted from the gross roof area. The useable areas of facades were also calculated, but only the useable roof area was considered in the calculation of solar thermal potential. The area as well as the location of any available yards and area of any green spaces adjacent to the building were recorded which may be used in terms of installation of horizontal shallow geothermal system. Car access information can be used in terms of biomass for delivery the biomass fuel.
In the study, only the potential of solar thermal energy was explained in detail, however the information regarding biomass and geothermal was added into the EBD which can be used in future studies.

7.3.2. Smart Management of Demand/Surplus Thermal Energy

The idea of sharing surplus thermal energy between a group of buildings (O’Reilly building, Sports Centre, SNIAM (Sami Nasr Institute of Advanced Materials), and Lloyd building at TCD campus (Figure 7.13) was explained in further detail. The information of two buildings (O’Reilly and Sports Centre) as an example is presented in Table 7.3.

![Diagram](image)

**Figure 7.13.** *Sharing surplus thermal energy between adjacent buildings at TCD*
Table 7.3. Monthly heat demand and surplus, O’Reilly building and Sports Centre, TCD

<table>
<thead>
<tr>
<th>FID</th>
<th>Building name</th>
<th>Building Class</th>
<th>Footprint Area (m²)</th>
<th>Building area (m²)</th>
<th>Useable roof area (m²)</th>
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<tr>
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<td>PTC</td>
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<td>4,100</td>
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<tr>
<td>1500</td>
<td>Sports Centre</td>
<td>CTC</td>
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<td>2,954</td>
<td>391</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>FID</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
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<th>Dec</th>
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<td>4.100</td>
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</table>

<table>
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<tbody>
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<td>58,991</td>
<td>33,351</td>
<td>16,965</td>
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<td>20,528</td>
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<td>43,108</td>
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<td>35,225</td>
<td>25,126</td>
<td>14,205</td>
<td>7,226</td>
<td>4,352</td>
</tr>
</tbody>
</table>

FID is a unique code in GIS which was allocated to each building
Periodical Thermal Consumers (PTC)
Continual Thermal Consumers (CTC)

The monthly solar thermal energy potential was calculated for evacuated solar thermal technology installed on the roof of above mentioned buildings. For calculation of the solar thermal energy potential the useable roof area of each building was calculated. The parts of roof such as north facing and voids were subtracted from the overall roof area. The detailed calculation of useable roof area of O’Reilly building is presented as an example. The information was recorded in Energy Building Dataset (EBD) and is used in the assessments.

In Figure 7.14 the useable area of the roof in terms of suitability for installation of solar evacuated panels is presented. The following calculations show how the useable area of roof was obtained.

Overall roof area = 1553 m²

Area of part (1) = 9.40 × 15.63 = 147 m², Area of part (2) = 7.10 × 34.27 = 243 m²

Area of part (3) = 8.75 × 12.23 = 107 m²

Area of part (4) = 6.35 × 21.71 = 138 m²

Useable roof area = The overall roof area – (area of useless parts, i.e. parts 1, 2, 3, and 4) = 1553 - (147 + 243 + 107 + 138) = 1553 - 635 = 918 m²

Useable roof area \( A_U \) = 918 m²
Chapter 7  Creating a Smart Thermal Energy Campus Network

Figure 7.14. Calculation of useable roof area, O’Reilly building

Figures 7.14.a &b show the picture and a schematic of existing heating system (boilers) of O’Reilly building respectively. The system uses gas for producing heat energy.

Figure 7.14.a. Boilers heating system, (b) Schematic of heating system, O’Reilly building

An efficiency of 70% was considered for evacuated solar thermal panels [214]. The 22-year monthly averaged solar radiation on a horizontal surface (kWh/m²/day) in Dublin [179] was used for calculation of solar thermal potential. Equation (7.1) was used to calculate the amount of solar thermal energy generation in the O’Reilly building.

Where the potential of solar thermal in a month is \( Q_2 \), the amount of solar radiation (kWh/m²/day) is \( R \), and useable roof area is \( A_U \), 30 is the average number of days in each month. \( Q_2 \) can be calculated as follows.

\[
Q_2 = R \times 30 \times 0.70 \times A_U \text{ (kWh/month)} \quad \text{Equation (7.1)}
\]

Using Equation (7.1) the monthly solar thermal energy potentials were calculated for each building and the data was added into DHB tool. A sample of the data is presented in Table 7.3.
For example, the $A_U$ of O’Reilly building was 918 $m^2$ therefore, the amount of solar thermal energy generation (potential) in July equals:

$$Q_2 = 5.03 \times 30 \times 0.70 \times 918 = 96,968 \text{ kWh/month} \quad \text{Equation (7.1)}$$

Based on the monthly heat demands and monthly solar thermal potentials, the balance of thermal energy in a building can be calculated as follows.

\[
\text{Monthly Thermal Energy Balance (MTEBa) = Monthly solar thermal potential - Monthly thermal demand} \quad \text{Equation (7.2)}
\]

If the results of calculations in Equation (7.2) is positive (+) it means in that month the building can share some surplus heat energy and if the result is negative (-) it means the building needs a back-up heating system or the lack of thermal energy can be obtained from nearby buildings via the local thermal network. The surplus heat energy could be shared via thermal network.

The Monthly Thermal Energy Balance (MTEBa) of O’Reilly building is visualised and presented in Figure 7.1. The MTEBa methodology compares the demand side with supply side, i.e. renewable energy potential (in this case solar thermal) in each month and calculates the balance. Then based on the calculations, the balance graph, such as Figure 7.15, can be generated which shows monthly thermal demand-surplus of the building.

The results of the analysis, summarised in Table 7.3, showed that the O’Reilly building heat demand in January was 102,500 kWh, while the solar thermal potential was 13,880 kWh. The MTEBa of January was -88,620 kWh. This means the building needs a back-up heating system in this month. It can be seen that between April and October the building could share approximately 410,000 kWh of surplus solar thermal energy. In addition, the graph shows in January, February, March, November, and December the solar thermal could not cover the thermal demand of the building and consequently the balance was negative.
Accordingly, the useable roof area ($A_u$) of Sports Centre at TCD campus (Figure 7.16.a) as well as MTEBa (Monthly Thermal Energy Balance) were calculated as shown in Figure 7.16.b. The useable area of roof for installation of the solar thermal evacuated system was $391m^2$. 

**Figure 7.15. The MTEBa model of O’Reilly building**
The MTEBa graph of Sports Centre (Figure 7.16.b) shows that the building with 391 m² of useable area can generate 283,772 kWh of solar thermal energy per year, while the annual thermal demand of the building was 2,134,000 kWh/yr. In all months, the thermal energy balance of the building was negative.
According to the analysis (Table 7.3 & Figure 7.16.b) the heat balance of the building between April and October was approximately -1,010,718 kWh (negative balance). On the other hand, the analysis of thermal energy balance of the adjacent building, i.e. O’Reilly building during this period showed approximately 410,601 kWh of surplus thermal energy. Based on the 30 m distance between O’Reilly and Sports Centre it may be possible to share this surplus clean energy with the Sports Centre. Consequently, the Sports Centre still needs nearly 600,000 kWh thermal energy.

The required thermal energy for the Sports Centre (600,117 kWh) can be shared by other adjacent college buildings such as Lloyd building or SNIAM with 57 and 85 m distance from Sports Centre. In some DH systems, the length of hot water pipes is more than 5 km. For example the length of pipes of Killarney Town, Kerry (Ireland) is 5,430 m [141]. The efficiency of DH system depends on the level of insulation of network, so the high temperature of flow hot water needs highly insulated pipes. Nevertheless, a short distance network is more efficient in terms of lower heat losses, and insulation costs. A new generation of DH using a supply temperature of 50 °C is more efficient than conventional system which uses a supply temperature of 80 °C [215, 216].

Using DHB tool, the surplus solar thermal energy of Lloyd building with 493 m² of useable roof area was calculated. The surplus thermal energy between June and September was 146,483 kWh.

Accordingly, the surplus thermal energy of SNIAM with 861 m² of useable roof area between June and September was 294,292 kWh. All in all, from 1,010,718 kWh of heat demand of Sports Centre during the summer months, nearly 851,376 kWh (410,601+146,483+294,292) can be shared by three mentioned adjacent buildings (Figure 7.13). Thus, the building still needed 159,342 kWh thermal energy.

The reduced fossil energy demand equals to the total solar thermal potential energy that could be shared by PTC buildings across a campus whenever the heat balance is positive such as summer months. In the sample buildings at TCD, the reduced fossil energy was 851,376 kWh. The results of sharing surplus energy are shown in Figure 7.17.
By sharing solar thermal energy during the summer months between Periodical Thermal Consumers (PTC) and Continual Thermal Consumers (CTC) buildings at TCD campus, the fossil thermal energy consumption of CTC buildings can be reduced significantly. In the assessed samples at TCD, the fossil thermal energy demand of Sports Centre was compensated by 851,376 kWh of solar thermal energy shared by adjacent buildings. In Figure 7.17 this amount was mentioned by reduced fossil thermal energy. The amount of reduced fossil thermal energy is equivalent with reduction of 161,000 kg of CO₂. All the analysis presented in this chapter can be applied automatically in a software such as DHB tool.

The methodology of sharing surplus energy is also applicable between the two building classes during the night time. As explained the boilers at TCD campus are switched off during the night time and this policy has resulted major heat losses (1,679,000 kWh) at the campus scale (see Chapter 6, Table 6.2). Using local thermal network, at the campus scale, the waste heat can be used by the CTC buildings. Sharing thermal energy across a local heat network can be extrapolated to the similar campuses such as DCU and UCD. The methodology of smart analysis of sharing thermal energy and controlling the balance could also extrapolate to an urban context.
7.4. Conclusion

In this chapter a new concept of sharing surplus thermal energy for reducing as well as smart management of thermal energy consumption, which mostly comes from fossil fuel (gas) was developed. The advantages of the concept were compared with the thermal energy storage method. To apply the concept, the thermal demand size and pattern of various buildings (CTC & PTC buildings) were studied in detail. As calibrated at the TCD campus as an example, applying the concept can reduce fossil fuel consumption and consequently CO₂ emissions. If the large scale of a campus is to be considered, the importance of sharing surplus thermal energy will be more significant. In addition, the method can be extrapolated to other campuses or an urban context.

Because of the barriers in front of thermal energy storage systems as well as the low efficiency of individual boilers, the concept of sharing surplus energy through a thermal energy network at campus scale has been presented as an alternative. The concept relied upon the assumption of applying solar thermal evacuated technologies and a DH system. The methodology of sharing surplus heat and smart managing of the thermal energy network across a campus were discussed in detail using a group of adjacent buildings at TCD campus as a sample.

The thermal patterns of two classes of buildings, i.e. Continual Thermal Consumers (CTC), and Periodical Thermal Consumers (PTC) were assessed in detail. The diversity of patterns of thermal energy demand in these two classes of buildings formed the foundation of the concept. The idea of smart managing of thermal energy at the campus scale included two sides, i.e. demand and supply (renewable potential and waste heat). Using monthly thermal energy models/maps and analysing the demand pattern in CTC buildings the demand side was calculated and explained comprehensively.

The other component of the concept is related to the applicability of renewable energy systems inclusion on a campus such as solar, biomass and geothermal systems. Based on the monthly solar radiation and useable roof area for installation of solar evacuated thermal technology, the potential of solar thermal energy for three buildings were calculated.

The difference between generated solar thermal and the thermal demand was calculated. The monthly thermal energy balance (MTEBa), negative or positive, was defined and calculated in the sample buildings. It was found that during the summer months, three typical college buildings which are located adjacent to the Sports Centre could share their surplus thermal energy through a local thermal network.

According to the MTEBa analysis, the three assessed buildings during the summer months could share approximately 851,376 kWh solar thermal energy with Sports Centre. While, the thermal
demand of Sport Centre during this period was 1,010,718 kWh. The shared clean energy covered 85% of thermal demand of Sports Centre and reduced 161,000 kg of CO₂.
Chapter 8

Validation of the Monthly Thermal Energy Models/Maps in DIT: Grangegorman Campus
Chapter 8. Validation of Monthly Thermal Energy Models/Maps in DIT: Grangegorman Campus

8.1. Introduction

In this chapter, the models and mapping methodology are applied to Dublin Institute of Technology (DIT) under development campus of Grangegorman. The developing centralised campus will accommodate more than 20,000 staff and students in 39 buildings. The objective of this chapter is to discover how the monthly thermal energy models (MTEMs), monthly thermal energy benchmarks (MTEBs), and heat maps (HM) can help architects, urban planners, and energy planning professionals to design a more thermally efficient campus. In other words, the chapter shows how the findings of the current research could be applied in practice and how the models can be used in future urban planning/design by adding some new layers into the current sustainable urban study methodology.

8.2. The Grangegorman Development Master Plan

Grangegorman is a suburb located in Dublin 7 at the north part of the city (Figure 8.1). Grangegorman Development Agency (GDA) aims to create a vibrant new city quarter with a diverse mixed of uses [217].

![Figure 8.1. The location of Grangegorman campus in Dublin](image)

Currently there are 22 existing buildings on the Grangegorman DIT campus. According to the master plan, 11 of them will be knocked down during the developing process as presented by yellow colour in Figure 8.2.a. However, 50% of the existing buildings such as Bradogue, St. Laurence, Glassmanogue, Clocktower, and Security Office are kept in the master plan (magenta coloured buildings). The current situation of the campus and its view are shown in the figure.
8.3. 2D Energy Modelling for Grangegorman

To generate the monthly heat map for the campus, two key data are necessary including building area and function. Since the campus is under study and the architectural maps (building plans & sections) are not available, the necessary information was derived from the master plan shared by GDA [218]. 15 PDF files explaining the master plan strategy and 27 PDF files presenting the details of master plan were reviewed and the key data (number of floors and buildings function) was derived from the files. In Figure 8.3 the sections of developing site are presented which show the skyline of the project. The skyline helped to understand the number of floors of some buildings.
In addition to the above mentioned sections (Height Diagram A-A, B-B), the number of floors of the rest of the buildings was derived from the master plan [218]. The number of floors was used to calculate the buildings total useful area. When the necessary data was collected, the next step was to generate the energy models and maps.

To generate the heat maps, a raster image of the developing campus, in PDF format [218], was inserted into AutoCAD. Then, in AutoCAD the roof plan (site plan) of new buildings was drawn, then a ‘DWG’ format file (AutoCAD file) was exported into ArcGIS using ‘Conversion’ tools such as ‘CAD to geodatabase tool’. In ArcGIS, to overlap the AutoCAD file and the raster image of the master plan with OpenStreetMap the ‘Georeferencing tool’ was applied.

Based on the imported maps (AutoCAD and master plan image), a GIS map was generated for the campus. In ArcGIS using ‘Editor’ in ‘Arc Toolbox’ and then the ‘Calculate Geometry’ command, the footprint area ($m^2$), footprint perimeter (m), X & Y coordinates of buildings were calculated as presented in Table 8.1.
The first version of the attribute table (Table 8.1) was exported into Excel and then in Excel, 20 new columns were added into the table such as number of floors, total useful floor area (TUFA), MTEBs, MTEMs (12 Columns), overall annual thermal demand, building height, building dominant function, CIBSE TM46 thermal benchmarks, and UCrb. All necessary data regarding energy demand and buildings size was calculated and recorded in Excel. Then the developed Excel file was imported into ArcGIS and joined with the table previously generated in ArcGIS, i.e. Table 8.1.

According to the ‘Neufert architects data’ [219] 20% of gross area of buildings is used for services such as stair cases, access ways, and toilets. So, 80% of gross area was considered in the final database as total useful floors area. In other words, 20% of the gross area (footprint multiplied by number of floors) which may allocate to the unconditioned spaces was excluded from the analyses. Similar method was also used in creating the energy map for New York City [150]. The exclusion of unconditioned area was also highlighted by the Sustainable Energy Authority of Ireland in definition of TUFA [100]. In Table 8.1, X and Y geographic coordinates for Ireland, generated based on IRENET95_IRISH_Transverse_Mercator, are presented. It was implemented jointly by the Ordnance Survey Ireland (OSI) and revised in April 2004. It is a CRS (Coordinate Reference System) for large and medium scale topographic mapping and engineering survey.
Using the MTEMs and MTEBs methodology for typical college buildings (developed in Chapter 5) and the average monthly method for Continual Thermal Consumer (CTC) buildings (developed in Chapters 6-7), the thermal demand of the Grangegorman campus was estimated and recorded in the energy building database (EBD). The mean monthly method used in CTC buildings relies on CIBSE TM46:2008. A sample of the advanced EBD for Grangegorman campus is presented in Table 8.2. The database has 24 columns and 160 rows.

**Table 8.2. A sample of EBD developed for Grangegorman campus**

When the essential database was prepared, then in ArcGIS the monthly thermal demand energy maps for Grangegorman campus were generated. Among the 12 monthly Heat Maps (HM) the heat map of January and July are more important because they indicate the peak and minimum thermal demand during a year. Discovering the maximum and minimum consumption of the campus for energy planners are crucial. To generate the heat maps, the heating degree days (HDD) of 2016 were used as presented in Table 8.3.

**Table 8.3. Monthly Heating Degree Days of 2016 [178]**

<p>| Weather station: Dublin Airport, IE (6.30W,53.42N), 2016 |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|</p>
<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>294</td>
<td>314</td>
<td>294</td>
<td>267</td>
<td>132</td>
<td>60</td>
<td>38</td>
<td>58</td>
<td>146</td>
<td>291</td>
<td>257</td>
<td>2,185</td>
<td></td>
</tr>
</tbody>
</table>

Celsius-based heating degree days for a base temperature of 15.5°C

The typical operation hours of heating systems in 2016 were calculated based on the data on AEM (Active Energy Management) [174] and presented in Table 8.4.

**Table 8.4. Monthly typical operation in 2016 [174]**

<p>| Typical operation (hours), 2016 |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|</p>
<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
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<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
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<td>300</td>
<td>270</td>
<td>286</td>
<td>240</td>
<td>85</td>
<td>47</td>
<td>23</td>
<td>60</td>
<td>231</td>
<td>277</td>
<td>206</td>
<td>2,325</td>
</tr>
</tbody>
</table>
Based on the data presented in Tables 8.3 and 8.4 and using Equations (3.5) and (3.7), the Monthly Thermal Energy Benchmarks (MTEBs) in 2016 for Grangegorman typical college buildings were calculated and presented in Table 8.5. The MTEBs were used in all thermal demand analysis as well as heat maps.

**Table 8.5. MTEBs of 2016**

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
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<th>Oct</th>
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<tbody>
<tr>
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<td>22</td>
<td>23</td>
<td>19</td>
<td>18</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>19</td>
<td>13</td>
<td>132</td>
</tr>
</tbody>
</table>

The main function and the list of developing buildings at Grangegorman campus is presented in Figure 8.4. This is the primary version of ArcGIS map of Grangegorman generated based on master plan. Most of these buildings will be built in near future.

![Figure 8.4. Grangegorman developing campus generated in ArcGIS](image)

HM for January 2016 of Grangegorman developing campus is presented in Figure 8.5. According to the analysis of energy map as well as the statistical analyses in ArcGIS, the campus area was 329,297 $m^2$ and the footprint area of buildings (land occupied) was 95,246 $m^2$. Accordingly, the overall buildings area (total useful floors area) was 318,844 $m^2$. 

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The analyses of HM of January 2016 indicated two anchor thermal loads (high thermal demand density) on the campus. The first thermal anchor load was the School of Business at the west of the site and just beside the space was considered for the district heat (DH) plant. The footprint area of the building was 2,368 m², while its TUFA was 11,365 m². The building thermal demand in January 2016 was estimated to be 284,133 kWh and accordingly its annual thermal demand was 1,522,955 kWh.

The second thermal anchor load was Science & Industry Centre building at the east of the campus with footprint and TUFA of 1,083 m² and 10,394 m² respectively. The thermal demand of this building in January 2016 was estimated to be 259,850 kWh, which forms approximately 20% of its annual demand, i.e. 1,392,798 kWh.

Figure 8.5 shows that the location of the thermal energy plant is very close to the first anchor load, i.e. School of Business which is the best location. However, the second location could be near to the second anchor load, i.e. Science & Industry building at the east of the campus.

The top 10 high thermal energy density buildings as well as their building size were compared in Table 8.6. The ranking was based on the higher thermal energy density in January (peak load).
The locations of the top 10 high thermal density buildings on the campus is presented in Figure 8.6.

Table 8.6. Top 10 thermal anchor loads at Grangegorman developing campus

<table>
<thead>
<tr>
<th>footprint area, m²</th>
<th>No of floors</th>
<th>Building area</th>
<th>Functions</th>
<th>January kWh</th>
<th>Total Annual kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,368</td>
<td>6</td>
<td>11,365</td>
<td>Business</td>
<td>284,133</td>
<td>1,923,954</td>
</tr>
<tr>
<td>1,083</td>
<td>12</td>
<td>10,194</td>
<td>Science &amp; Industry</td>
<td>259,850</td>
<td>1,392,798</td>
</tr>
<tr>
<td>1,120</td>
<td>8</td>
<td>7,168</td>
<td>Applied arts</td>
<td>179,209</td>
<td>960,562</td>
</tr>
<tr>
<td>2,638</td>
<td>5</td>
<td>10,553</td>
<td>DCC Library</td>
<td>175,880</td>
<td>2,110,563</td>
</tr>
<tr>
<td>945</td>
<td>8</td>
<td>6,045</td>
<td>Science &amp; Industry</td>
<td>151,132</td>
<td>810,068</td>
</tr>
<tr>
<td>1,403</td>
<td>5</td>
<td>5,613</td>
<td>Engineering</td>
<td>140,327</td>
<td>752,153</td>
</tr>
<tr>
<td>1,095</td>
<td>6</td>
<td>5,255</td>
<td>Residential Accomodation</td>
<td>131,880</td>
<td>1,576,557</td>
</tr>
<tr>
<td>1,041</td>
<td>6</td>
<td>5,092</td>
<td>Social, Legal &amp; Languages</td>
<td>127,207</td>
<td>682,368</td>
</tr>
<tr>
<td>647</td>
<td>9</td>
<td>4,660</td>
<td>Science &amp; Industry</td>
<td>116,511</td>
<td>624,497</td>
</tr>
<tr>
<td>831</td>
<td>7</td>
<td>4,632</td>
<td>Engineering phase 1</td>
<td>116,302</td>
<td>623,381</td>
</tr>
</tbody>
</table>

Figure 8.6. Location of top 10 high thermal density buildings on the campus

256
The overall thermal demand of these buildings in January 2016 was 1,682,031 kWh, while their annual thermal demand was 11,055,898 kWh which forms 18.8% of the Grangegorman’s annual demand. Moreover, the thermal demand of the campus in January 2016 was 6,808,575 kWh.

The heat demand pattern of the campus in July 2016 was generated and presented in Figure 8.7 which indicates both CTC (Continual Thermal demand) and PTC (Periodical Thermal Demand) classes of buildings. The overall TUFA of PTC (blue) was 138,500 m². On the other hand, CTC accounted for 168,060 m² of TUFA and needed approximately 3,346,160 kWh of thermal energy in July. The heat demand of PTC buildings in July was zero.

![Figure 8.7. Heat Map of July 2016, Grangegorman campus](image)

Based on the analysis of the thermal energy map of July, a smart heat efficiency strategy at the campus level could be used in designing of a District Heat (DH) network where part of the network which services the PTC buildings could be cut off from the DH supply during the summer. Some advantages of the cutting off strategy of the DH network are as follows:

1. Because of cutting a significant part of the DH network during the summer season, the hot water does not circulate in the pipes of that part (with TUFA of 138,500 m²). This could reduce heat losses and decrease the water circulation time. A short-cut connection should be used to service other buildings.
2. Temporary cutting off a considerable part of the DH network increase its life time.
3. The strategy also saves possible water leaks
4. The system could be controlled smartly based on hourly demand patterns. For example, even in April and August in the night time, part of the DH service could be switched off.

The thermal energy map analysis of July showed that the campus demand was 3,346,160 kWh comparing with 6,808,575 kWh of January showing nearly 51% reduction. Such detailed information, is useful for urban/energy planners or even for the Estates Office in terms of energy supply policy and financial optimisation. For example, the average daily demand (baseload) of the campus in July was 111,539 kWh, while in January it needs nearly 226,953 kWh per day (peak load). For instance, using this detailed information, the Estates Office will manage biomass storage more efficiently from a financial perspective if the heat source is biomass.

The monthly thermal demand of Grangegorman campus is presented in Figure 8.8. The average monthly demand of campus was 4,901,423 kWh. In May, June and July it needed 11,423,483 kWh, while in January, February, and December it needed 19,283,619 kWh.

![Figure 8.8. The monthly thermal demand at the campus level, Grangegorman, 2016](image1)

Figures 8.9. The monthly thermal demand of PTC buildings vs. mean monthly of CTC buildings
Figure 8.9 indicates the variation of thermal demand of PTC buildings at the campus scale vs. the mean monthly demand of CTC buildings. According to the analysis, the demands of PTC buildings varied from 3,462,505 kWh, 3,024,761 kWh, 2,770,004 kWh in January, February, and December respectively.

The demands of PTC class of buildings in May, June, and September were 1,246,502 kWh, 138,500 kWh, 277,000 kWh respectively. The demands in July and August were approximately zero. While, the mean monthly thermal demand of CTC buildings was constant during the year. This shows the modelling method in the CTC buildings was not sensitive to the outdoor temperature. The reason for this refers to the paucity of data for this class of buildings so that the monthly thermal energy benchmarks (MTEBs) was not generated for them and inevitably the mean monthly CIBSE TM46 benchmarks were used, this gap may be covered in futures studies.

### 8.4. 3D Energy Modelling for Grangegorman

To simulate the actual situation for building owners/users based on the EBD developed for Grangegorman, a 3D model of developing as well as existing buildings was generated. To do so, the height of buildings was calculated by multiplying the number of floors by floor-to-floor height derived from the master plan. The following guidance [218] was used to calculate the height of buildings:

- Laboratory and Research Buildings 4.5m floor-to-floor
- Administrative and Office Buildings 4.0m floor-to-floor
- General and Academic Buildings 4.0m floor-to-floor
- Housing 3.0m floor-to-floor

For generating 3D models, in AutoCAD the 2D plan was generated. Then the AutoCAD files were imported in SketchUp Make 2016. The first 3D model in SketchUp is shown in Figure 8.10 and Figure 8.11.
ArcScene, a GIS based application, is a 3D visualization software that is useful to overlay many layers of data in a 3D environment. In ArcScene, the height of buildings was added as a new field to the attribute table which facilitated to visualise features in 3D. The height field was used as an ‘Extrusion’ value. In the next stage the 3D buildings were converted into a real 3D database by making multipatch geometry, which models the external shell for 3D objects. Multipatch geometry generates a series of triangular faces to convert 2D shapes into real 3D volume which is similar to Triangulated Irregular Network (TIN) data model. In a geographic information system (GIS) for illustration of a surface a TIN which is a digital data is used. TIN is an artificial irregularly distributed nodes and lines with 3D coordinates (x, y, z) that are arranged in a network of non-overlapping triangles [220]. The real 3D volumes can be exported into 3DS Max, CityEngine, or SketchUp for further development.
In ArcScene ‘Multipatch To Collada’ tool was used to export multipatch features into Google Earth Pro as presented in Figure 8.12. In addition, The Collada (.dae) format files also were imported in SketchUp for further development. Figure 8.13 shows the real Thermal-3D features which georeferenced on the Grangegorman campus. Figure 8.13 shows an actual perspective of developing buildings exported from SketchUP into Google Earth Pro. A close-up perspective of buildings is presented in Figure 8.13. The angle and viewpoint of the close-up perspective is indicated in Figure 8.12. The Student Housing building with 15 floors and height of 45 m was targeted in Figure 8.13. The annual energy demand of the buildings was indicated by colour code values in kWh.

![Image](image_url)

**Figure 8.12. Georeferencing of developing buildings on the campus site**
The annual thermal energy demand of the developing campus in 2016 was visualised in 3D model and presented in Figure 8.14. The diversity of demands during a year can be seen in the 3D models. The results of the analyses showed that the overall annual demand of the campus was 58,817,074 kWh/yr.

Figure 8.13. Thermal-3D view to Student Housing and the sizes of thermal demands in kWh

The graduated colour code illustrates the thermal energy demand (kWh), where darker colours represent higher thermal energy demand and lighter colours a lower thermal energy demand.

Figure 8.14. 3D thermal demand visualising, 2016
The five highest annual thermal energy density at the campus level is presented in Table 8.7. The highest demand in 2016 was 2,110,565 kWh and belonged to DCC library, followed by a residential accommodation, School of Business, Science & Industry, and Student Hub. On the other hand, the lowest annual demand was 5,931 kWh and belonged to an existing security office.

<table>
<thead>
<tr>
<th>Functions</th>
<th>NO of Floors</th>
<th>Height (m)</th>
<th>Total annual thermal (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCC Library</td>
<td>5</td>
<td>20</td>
<td>2,110,565</td>
</tr>
<tr>
<td>Residential Accommodation</td>
<td>6</td>
<td>18</td>
<td>1,576,557</td>
</tr>
<tr>
<td>School of Business</td>
<td>6</td>
<td>24</td>
<td>1,522,954</td>
</tr>
<tr>
<td>Science &amp; industry</td>
<td>12</td>
<td>48</td>
<td>1,392,798</td>
</tr>
<tr>
<td>Student Hub</td>
<td>2</td>
<td>8</td>
<td>1,190,386</td>
</tr>
</tbody>
</table>

### 8.5. The Importance of Monthly Thermal Models/Maps for Future Urban Design

Sustainability is a fundamental component of urban studies. Based on similarity of university campuses in terms of building function diversity, it could be considered as an urban context pilot. In the current study the thermal energy demand was studied at the campus level. It has also been shown by several examples, how the models can be used for smarter management of DH systems and how they were applicable for analysing of multiple energy sources such as solar thermal technologies. Furthermore, the models were used for Grangegorman campus as an example of future campuses.

In this section, it is indicated how the models/maps and their results can merge with current urban design criteria especially in developing and future lands. MTEBs and monthly HMs can play a significant role in sustainable urban development and planning, since they share fundamental information and indices with the potential of providing the assessments at individual buildings or community scale. Reducing fossil fuel consumption in buildings and consequently relevant CO₂ emissions are key parameters in sustainable cities.

Currently much effort has been devoted to innovate or develop tools for visualising, assessing and analysing the urban environment [221, 222]. Various criteria were used in the urban environment to address the multidimensional aspects of sustainability. However, this section focused on lack of information in urban planning which can be supported by MTEMs, MTEBs, and monthly HMs.
The models and methodology developed in this study can be applied for both existing, as used for TCD, and developing/future campuses as used for Grangegorman. Moreover, the models present an integrated method which can be used at individual building and the community scale at the same time. Accordingly, the models can assess a group of selected buildings for example, 5, 10, or 25 top thermal consumers in further detail.

This section aimed to show how the model can be used in urban planning and design studies. Cities are the focal point of studies concentrating on the carbon footprint. Urban planners might apply mitigation and adaptation measures to enhance the cities resilience against CO₂ emissions. The methodology developed in this study has the potential to support the assessments of thermal fossil demand with high level of accuracy. It can provide useful information for urban planners, architects, energy managers and decision makers. The impact of MTEBs method for operational urban planning and management is significant, because they provide a framework of spatial tools, easily retrievable from general/typical information, e.g., DECs and building area.

The developed methodology for benchmarking, estimating and mapping of thermal energy, can link the results of the assessment of an individual building with a group of them such as a campus community as shown in Figure 8.15. The aim of the methodology was to reduce fossil thermal consumption firstly by presenting more accurate monthly benchmarks and secondly by studying the thermal demand in a group of buildings. The ability of exporting the results of analysis, particularly 3D models into SketchUp, Google Earth, BIM (building information modelling) and 3D MAX, facilitated the simulation of models in virtual three-dimensional space.

Despite current urban study methods that assess the thermal demand at individual buildings scale (mostly) or at community scale independently, the developed methodology is a dual-purpose methodology which can assess the energy demand at either scale.
Considering the abilities of the developed methodology, it was possible to add some new layers into the current sustainable urban study (Figure 8.16). Three new layers were added into the current urban studies to get more information about how to design a developing/future community with respect to fossil fuel efficiency.

1. The first layer was Geovisualisation of thermal energy demand of buildings at the community level. This layer can be generated using thermal energy maps. It presents useful information such as the location of thermal energy anchor loads or presents the thermal energy density. Such an information layer helps to manage a DH system smartly. For example, the thermal energy maps show where is the best location for an energy generator on a campus. Figure 8.16 shows the new layers (layer 1-3) that can be added into the current urban studies. Monthly thermal benchmarks and monthly energy demands estimation with high level of accuracy share valuable information which is necessary in urban/energy planning. For example, monthly HM in January showed the location of anchor loads which is useful in land development planning and management of DH systems.
The second layer presents the feasibility of integrating renewable energy sources such as solar thermal with current thermal fossil energy sources. An example of this approach was applied in TCD campus in Chapter 7. Sharing surplus thermal energy was explained in further detail in Chapter 6. In addition, saving CO\textsubscript{2} emissions was also calculated. Such a method can be used in sustainable urban development studies. It was suggested that the Grangegorman Development Agency (GDA) consider the feasibility of using several renewable energy sources, while the backup source may rely on fossil fuels.

The third layer explains the importance and impact of thermal end use energy density. In current urban studies the population density and land use density are considered as key parameters in land use planning and functions. So, from now on, the thermal energy density i.e., UEDf (Urban Energy density footprint) and UEDg (Urban Energy Density gross) should also be considered as significant indices in future urban planning [47].
8.6. Conclusion

Using Grangegorman as a sample of future/developing campuses, the methodology of monthly thermal energy benchmarks was used to assess the thermal energy in future buildings. Based on the assessments it was found that the Grangegorman campus area was 329,297 m², while the overall TUFA of buildings was 318,844 m². The land occupation (footprint area of buildings) was approximately 95,000 m².

HMs for January and July 2016 at the campus scale were generated and analysed. According to the analyses, the campus in July needed 3,346,160 kWh of thermal energy, while its demand in January was nearly a twofold increase.

Based on the assessment of July HM, it was recommended for more energy efficiency a part of the DH system which services PTC buildings could be cut off from the network. This strategy reduces heat losses of the network.

The monthly and consequently overall annual thermal demands of the campus were calculated. Based on the analyses the developing campus needed 58,817,074 kWh of thermal energy in 2016. Relying on the thermal energy assessment of HM of January, two anchor loads at the campus were identified and it was also found that the location of the recommended thermal energy plant on the west of the campus was correct because of closeness to the anchor loads.

To visualise 3D thermal demand, 3D thermal energy maps were generated. The 3D maps using SketchUp and Google Earth Pro were georeferenced on the current campus map. Such visualisations were very similar to the actual situation and therefore, the maps and perspectives are user friendly and understandable for architects and energy planers.

Finally, it was shown how the developed methodology could be applied for future campuses and additionally, it was indicated how the results of the study can be merged to develop current sustainable urban studies by adding three new layers into the field.

The three new layers were recommended which can be used by urban planners, architects, and energy professionals including, (1) Geovisualisation of energy demand at the community scale, (2) integrating renewables energy potentials with current energy source, and (3) energy density layer. Finally, the presented methodology by adding new information to current urban studies such as monthly benchmarking and sharing surplus thermal energy as well as monthly HMs can improve sustainable campus analysis by providing more detailed information than CIBSE TM46 methodology.
Chapter 9

Conclusions
Chapter 9. Conclusions

9.1. Key Conclusions and Findings of Thesis

Ireland uses the Chartered Institution of Building Services Engineer (CIBSE) TM46 benchmarks to generate Display Energy Certificates (DECs). The majority of energy action plans in Ireland at the building or national scale rely on DECs as authentic documents. The CIBSE TM46 methodology was originally developed in the UK in 2008. The accuracy of the benchmarks directly affects the successfullness of energy action plans. However, no study has focused on the accuracy of CIBSE TM46 at university campuses in Ireland.

This thesis analysed the accuracy of the CIBSE TM46 University Campus (UC) benchmark and found a significant gap between the DEC measurements and the benchmark in four universities in Ireland. The current TM46 UC benchmark was revised and a new benchmark (UCrb) presented which the revised benchmark significantly increases the efficiency of typical college buildings and consequently reduces fossil thermal energy consumption. The impact of UCrb on reduction of CO₂ emissions is crucial to mitigate global warming and save money. The difference between UCrb and CIBSE UC benchmark was 110 kWh/m²/yr which is a significant improvement. The discussion and statistical analysis were explained in detail in Chapter 4. Since the energy benchmarks are used at the national scale, therefore, applying an accurate and updated benchmark forces to reduce the fossil fuel consumptions as well as CO₂ emissions in a large number of buildings.

The thesis presented a new generation of monthly thermal energy benchmarks (Chapter 5) which shares more detailed heat demand information. The data could be used to provide successful energy action plans. Architects, urban planners, and mechanical engineers may use this detailed information to design more thermal energy efficient urban regions and university campuses. The models are also important for energy suppliers to discover the amount of monthly heat demand at an urban regional scale.

By presenting an applicable and advantageous alternative for thermal energy storage, i.e. sharing surplus thermal energy, the thermal energy consumption could be reduced significantly at the university campus scale. In addition, a new methodology for generating Heat Maps (HM) was presented. The HMs were applied to estimate heat demand at the campus level. They show the base and peak heat loads at an individual building as well as the campus scale. HM is a fundamental document that could be used to calculate the capacity of heat generators and they also indicate the optimised location for generators in terms of the minimum heat loss. HM is also
useful to develop and manage District Heating (DH) systems more efficiently and smartly. The detailed discussions were presented in Chapters 6 and 7.

Three new layers were suggested to add into the process of studies of sustainable urban planning, including Geovisualisation of heat demand, Integrating renewable energy potential, and Energy density index. These information layers increase the environmental quality (air quality) by reducing fossil fuel consumption and consequently CO₂ emissions.

The thesis developed the boundary of knowledge in the field of thermal energy benchmarking and modelling including key points (UCrb, sharing surplus heat, and HMs) which can be used by energy and urban planning professionals. The findings of the research are important to design and manage a university campus more efficiently in terms of thermal energy consumption.

9.2. Contributions to Knowledge

The primary aim of this thesis, was to discover a method for reducing fossil thermal energy in campus university buildings. However, this involved diverse investigations into current and theoretical performance of buildings located on four case study university campuses. Based on the methodology, a multidimensional plan including surveys, comparative analysis, Display Energy Certificate (DEC) data assessment, analysis of actual consumption data at daily/hourly/monthly/annual scale, typical operational hours of heating systems, building maps, mixed activities, various tools and software such as SketchUP, AutoCAD, and GIS, heating degree days, and statistical assessments were used to develop the models for the study.

The study discovered significant gaps between current CIBSE TM46 UC benchmark (240 kWh/m²/yr) and the mean and median of 52 UC DEC values belonging to Trinity College Dublin (TCD), Dublin Institute of Technology (DIT), University College Dublin (UCD), and Dublin City University (DCU) campuses. Based on the analysis, 110 kWh/m²/yr difference between the median of DEC values and the benchmark was observed which is a critical gap.

Using statistical analyses, the performance of 50% of UC DEC samples was defined as a revised benchmark which was called UCrb (University Campus revised benchmark). Additionally, the performance of 25% of analysed samples was calculated and recommended as ‘good practice’ index (95 kWh/m²/yr) which is not displayed on DEC. A new benchmark of 130 kWh/m²/yr (UCrb) was recommended instead of 240 kWh/m²/yr suggested by CIBSE TM46 which is an important improvement in the field. Using Descriptive Statistics, the accuracy of UCrb was assessed and it was discovered that the revised benchmark was located between lower and upper confidence intervals which indicated robustness of the new benchmark. In addition, further statistical analysis
using Bootstrapping method was conducted and the results showed that the UCrb is an accurate up-to-date description of typical performance of college buildings in Dublin.

UCrb of 130 kWh/m²/yr if applied instead of the current benchmark (240 kWh/m²/yr), will force an increase in thermal energy efficiency of peer buildings and consequently will reduce fossil fuel consumption as well as CO₂ emissions. Compared to the current CIBSE TM46 UC benchmark, the revised benchmark (UCrb) can save approximately 55 million kWh fossil thermal energy as well as more than 10,500 tonnes of CO₂ emissions per year in analysed samples which is a significant reduction.

Although the reviewed studies in the literature have found a discrepancy between CIBSE TM46 benchmarks and DEC values in educational buildings, this study, in addition to discovering a similar discrepancy between the benchmark and DEC values, has progressed the knowledge in the field by creating the monthly thermal energy benchmarks (MTEBs). MTEBs are novel and demonstrate the monthly thermal energy demand of typical college buildings per unit area, while the current CIBSE UC benchmark presents a single annual value. The monthly thermal energy models/benchmarks were created using five key factors including (i) mixed use method; (ii) CIBSE UC revised benchmark (UCrb); (iii) impact of mixed activities (composite benchmark); (iv) heating degree days; and (v) typical operation hours of heating systems. The methodology, up to now, is unique especially monthly thermal energy benchmarks.

Compared with approximately a 100% error of CIBSE UC heat estimation in the analysed buildings, maximum 21% error of monthly thermal models is an important contribution. Despite the fixed annual benchmark of CIBSE, MTEBs altered from 24 kWh/m²/yr in January to one and zero kWh/m²/yr in June and July respectively. In this regard the difference of CIBSE TM46 UC benchmark with DEC values was 46%.

Since MTEBs present effective and accurate thermal demand information compared with the current CIBSE benchmark, energy suppliers and planners can provide more detailed action plans in future. Knowing monthly thermal demand increases the accuracy of energy planning which is crucial for both suppliers and building owners.

The Energy Building Database (EBD) is another fundamental achievement of this research for generating thermal energy maps and related assessments. It includes all thermal energy demand data such as DEC values, MTEMs, MTEBs, and heat density. It also includes all the information obtained from surveys during the research. Both energy and the buildings size data were linked to the District Heat Balance (DHB) tool in ArcGIS. The attribute table of the DHB tool comprised of 120,000 data cells. Such a dataset fills the gap of the paucity of thermal energy consumption
data in Ireland which is the main barrier for research in this area. This dataset is available for future research.

Monthly heat maps (HM) were generated at the campus scale and provide further information for example, the thermal energy demand density. They show thermal anchor loads (high thermal energy users). These assessments facilitated energy planning in a group of buildings rather than at an individual building level. HM also revealed that the thermal energy demand patterns of buildings on a campus were different and the buildings were classified into two classes (i) Continual Thermal Consumer (CTC) and (ii) Periodical Thermal Consumer (PTC) buildings. These types of classifications at the campus level, as an urban pilot, presented for first time in this study which has paved the way toward new ideas in terms of thermal energy planning in communities. Such analysis could be used in DH (District Heating) systems.

The study also discovered that the individual boilers because of their operation patterns, i.e. daily switching on/off were not efficient for example, at TCD it resulted in 1,656 MWh of heat loss per year. In contrast the TCD’s District Heating (DH) system was more efficient. Based on thermal energy patterns, i.e. CTC and PTC buildings, the concept of sharing surplus energy at the campus scale has been presented as an advantageous alternative to thermal energy storage.

Using the monthly thermal demand and solar thermal potential, the heat balance index was defined and calculated. The index has facilitated the implementation of sharing surplus thermal energy across a local thermal energy network as shown for TCD campus as an example. Sharing surplus thermal energy is an efficient approach to reduce thermal fossil energy and prevent the heat loss at individual boilers.

Merging the thermal energy analysis data with site plan characteristics is another advantage of the method. For instance, the users can discover the scattering pattern of high thermal energy demand buildings on the site. From this perspective, the HM is essential for study of DH systems. The ability to add many analysis layers based on the scale of output data is applicable using DHB tool. As a sample of the methodology, the analysis of potential solar thermal energy at TCD campus was added in to the models and the capability and usefulness of output data was discussed in detail in Chapter 7.

The current research has proposed 3 layers of information which can be linked with sustainable urban planning/design knowledge to improve the sustainability of communities such as a university campus. The proposed knowledge can be used by urban planners, architects, and energy professionals. The layers include, (1) Geovisualisation of energy demand at the community scale, (2) integrating renewables energy potential with current energy source, and (3) energy density layer.
A summary of the contributions to knowledge of this PhD thesis are presented as follows:

1. Discovering a significant gap of 110 kWh/m²/yr between CIBSE UC benchmark and UC DECs values of four famous universities in Dublin
2. Recommending an alternative (UCrb) benchmark of 130 kWh/m²/yr instead of 240 kWh/m²/yr
3. Development of a fundamental database was called EBD (energy building database) comprised of 120,000 data cells
4. Presenting a new generation of benchmarks called monthly thermal energy benchmarks (MTEBs).
5. Development of heat models to predict the quantity of monthly thermal energy demand in typical college buildings, i.e. MTEMs
6. Defining two classes of buildings on a university campus based on thermal energy demand patterns, i.e. CTC and PTC buildings
7. Presenting the novel concept of sharing surplus thermal energy across a local thermal network such as DH
8. Defining the heat balance measure to manage thermal energy demand-surplus at the campus level
9. Generating monthly heat maps (HM) which give detailed information at a campus level such as the heat map developed for Grangegorman developing campus at DIT.

9.3. Action Points and Recommendations for Each Campus

The thesis recommends the following key action points to reduce and manage thermal energy consumption more efficiently and smartly in each campus.

1. At TCD campus, the Estates Office switches off the individual boilers at night time, weekends, and holidays in typical college buildings to reduce thermal energy consumption. This strategy as a primary step to reduce fossil fuel consumption is recommended for other campuses, i.e. UCD, DCU, and DIT. However, as indicated in Chapter 6, Section 6.3 this strategy can be developed by connecting individual boilers to make a DH system which is more efficient. It is recommended that all campuses use DH systems.
2. The location of the heat generator (in central heating systems) in UCD campus is not optimised in terms of heat losses. It is recommended to establish a new location when developing the heating system. The optimised location was indicated in Figure 6.11 (Page 210).
3. It is recommended the energy consumption data of DIT university to be recorded in AEM (Active Energy Management) website at a quarter hour scale.
4. It is recommended all universities to develop their heating systems and connect the individual boilers to establish a DH system which is more efficient. This issue, particularly at TCD that has many individual boilers is important.

5. The study recommends that Universities provide DEC for all buildings.

6. There were two miscategorised DECs, i.e. CRANN & Sports Centre at TCD and Science Centre Hub at UCD that need to be corrected in future.

7. It is strongly recommended to use the accurate thermal benchmark of UCrb (130 kWh/m²/yr) instead of the CIBSE TM46 UC benchmark of 240 kWh/m²/yr in future DECs for typical college buildings.

8. The monthly thermal energy demand models could be used to calibrate the amount of heat demand in developing and future campuses.

9.4. Recommendations and Future Work

The ideas and concepts presented in this study offer interesting opportunities for supplementary studies and future investigations. Some of these possibilities are identified and listed as follows:

- Developing the EBD dataset so that it could cover other university campuses in Ireland
- Due to the small number of CTC buildings, for instance cultural activities, sport centres, entertainment halls, and restaurants it was not possible to investigate the discrepancy between CIBSE TM46 and DEC values of these types of buildings. A supplementary study may include further samples and will discover the accuracy of the CIBSE benchmark for these types of buildings.
- The methodology of monthly benchmarking can extrapolate to other EU countries with different weather conditions.
- The similar study may be conducted in the UK to calculate the monthly thermal energy benchmarks.
- In this study, only the typical college buildings were assessed as mixed use buildings. This refers to the paucity of data and the limited time of the PhD. However, in future studies the impact of mixed use (functions) may be assessed in other types of building on a campus. Due to the lack of data and DECs this thesis only focused on typical college buildings to generate monthly benchmarks. However, extrapolating the methodology into other building types such as swimming pool, fitness, library, and entertainment hall are important and was recommended to discover in the future.
- The thermal energy analyses, monthly benchmarks, energy models, and maps were conducted at the campus level. Since a university campus is a pilot of urban context, the methodology can generalise into the urban context. Monthly thermal energy benchmarks
and sharing surplus thermal energy need further investigation to discover the capability of concept at an urban context.

- The sharing surplus thermal energy may be possible even between campus buildings and adjacent buildings in the urban context. This needs more investigation.
- The study recommends to extrapolate the methodology to Dublin city, particularly the International Financial Services Centre (IFSC) which is an important urban zone in the city and its building data (the main function and number of floors) was collected.
- Considering the possibility of releasing the DEC dataset of public buildings in close future by the Sustainable Energy Authority of Ireland (SEAI) the study can be conducted using further DEC samples.
- Further investigation into the use of thermal energy density during developing urban areas may help to improve the energy efficiency. For example, if the heat sources are located near the high density thermal energy demand buildings this reduces the heat losses during the thermal energy transfer and distribution across the local thermal network.
- Considering the thermal energy demand density as a key factor in urban planning, it may impact on urban land use and distribution patterns of building in an urban context. This may rearrange the design of developing urban areas during the urban design process.
- In the study, only the potential of generating of solar thermal energy was explained in detail; however, the information regarding biomass and geothermal were added into the EBD which can be used in future studies in further detail.
- Assessing the criteria such as minimum heat loss and expenses, maximum efficiency, as well as the optimum land cost to determine the best location for thermal energy generators could be investigated in future studies.

The role of occupant behaviour as a parameter that affects thermal energy consumption needs to investigate in public buildings.
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Publications

Journals


Conferences


## Appendix 1: CIBSE TM46:2008 Benchmarks

Table A1, CIBSE TM46:2008, benchmark categories and values [99]

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<th>Illustrative Fossil Thermal typical benchmark kgCO₂/m²</th>
<th>Illustrative Total typical benchmark kgCO₂/m²</th>
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<td>75.1</td>
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<td>77</td>
<td>0</td>
<td>77</td>
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<td>General Retail</td>
<td>0</td>
<td>90.8</td>
<td>0</td>
<td>90.8</td>
</tr>
<tr>
<td>Row4</td>
<td>Large Non-food shop</td>
<td>170</td>
<td>38.5</td>
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</table>
Appendix 2: Architectural Plans of Case Study Buildings

2.1. Hamilton plans, Ground floor plan
2.1.1. Hamilton plans, First floor plan
2.1.2. Hamilton plans, Second floor plan
2.2. Aras an Phiarsaigh, Ground floor plan
2.2.1. Aras an Phiarasaigh, First floor plan

FIRST FLOOR
FLOOR AREA = 1003 SQ.M
PLANT AREA = 4.5 SQ.M
2.2.2. Aras an Phiarsaigh, Second floor plan

SECOND FLOOR
FLOOR AREA = 1003 SQ.M
PLANT AREA = 45 SQ.M
2.2.3. Aras an Phiarsaigh, Third floor plan
2.2.4. Aras an Phiarsaigh, Fourth floor plan

FLOOR AREA = 629 SQ.M
PLANT AREA = 4.5 SQ.M
2.2.5. Aras an Phiarsaigh, Fifth floor plan

FIFTH FLOOR
FLOOR AREA = 44 SQ.M
PLANT AREA = 106 SQ.M
2.3. Museum building, Basement plan
2.3.1. Museum building, Ground floor plan
2.3.2. Museum building, First floor plan
2.3.3. Museum building, Second floor plan
2.4. School of Engineering and Research (DCU), Basement plan
2.4.1. School of Engineering and Research (DCU), Ground floor plan
2.4.2. School of Engineering and Research (DCU), First floor plan
2.4.3. School of Engineering and Research (DCU), Second floor plan
2.4.4. School of Engineering and Research (DCU), Third floor plan

2.4.5. School of Engineering and Research (DCU), Fourth floor plan
Appendix 3: DEC Samples

3.1. Hamilton Building, Trinity College Dublin
3.2. Aras An Phiarsaigh, Trinity College Dublin
3.3. Engineering and Research, Dublin City University
3.4. Bolton St, Dublin Institute of Technology
3.5. NovaUCD