Department of Mechanical and Aerospace Engineering

Investigating building stock modelling using individual building geometry and dynamic energy simulation

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Abstract

It has been established from various studies in the literature that EPC ratings are inept at predicting the true energy consumption of individual buildings and of a given building stock. However, many building stock models, including the most recent and ambitious projects still use the same data acquisition and calculation methods that are used to create EPCs. Energy mapping using EPC methods is the norm for governmental work and thus policy-makers run a high risk of misinformation. Many models have been developed that use dynamic simulation to better predict energy consumption however these are always tailored to a specific site or situation and lack transferability.

This project aims to improve the methods used by current practice in building stock modelling for energy mapping. This is to be done by using a dynamic simulation engine for calculation, publicly available satellite images to provide building geometry and aerial images to estimate the glazed surface area and solar absorption of each building façade. Not only is this new method attempting to improve accuracy in prediction of energy consumption but also encourage the utilisation of publicly available data sources in building stock modelling.

First EPC and measured data were compared for the building stock under study. The mean bias error (MBE) for individual buildings was found to be 110kWh.m^{-2} per year with an average percentage difference of 66.5%. It was only possible for 10 out of 14 buildings in the stock to be modelled due to data availability. Using the project method, the MBE reduced to 86kWh.m^{-2} per year for individual buildings with a constant underestimation of the measured data. There was an average percentage difference of 35% for the individual buildings. Amending the results for EPC and measured data comparison, the project method led to an improved accuracy in estimating energy consumption of 46% compared to EPC methods for individual buildings.

These results are significant in that they promise a shifting paradigm of building stock modelling which will utilise a wider spread of data sources. These data sources are publicly available and therefore easily accessed. With further research it is hoped that a tool can be created to utilise these data sources to generate an accurate energy map of any desired urban area. Such a tool would greatly benefit practitioners and policy makers in improving the energy performance and

health effects of buildings, much more so than current best practice.

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1. Introduction

1.1. Motivation

It is well established that buildings contribute a very significant proportion to the world's final energy use [1] as well as also being responsible for over a third of worldwide greenhouse gas emissions [2–8]. Additionally, buildings are ultimately responsible for the quality of the indoor environment which greatly affects the health, productivity, safety and finances of the occupiers. The interconnectivity between energy efficiency, emissions, health and fuel poverty are therefore unavoidable [9–16]. These problems have been a driver towards the emergence of international policies designed to improve building energy performance, such as the European Union's (EU) Energy Performance of Buildings Directive (EPBD) [17] and the Smart Cities and Communities Directive (SCCI) [18]. Energy mapping via stock modelling is used to support such policies as an alternative to empirical data for high numbers of residential, public and/or commercial buildings. Building stock modelling for energy mapping allows for the evaluation of possible future scenarios such as retrofitting or energy system installation whereas empirical data does not [19–22]. Building stock modelling is therefore extremely useful to energy policy makers in developing strategies to reduce building energy consumption [22–35].

Many approaches have been developed for energy in building stock modelling, however they are all limited by their uncertainties, assumptions and validation to varying degrees [29]. Uncertainties relate to the building stock model input data for geometry, construction materials, glazing area, building type and orientation, shading, occupant use, heating, ventilating and air conditioning (HVAC), lighting efficiency, operations and climate [36–39]. This is as well as any assumptions and simplifications that the model adopts for its calculation method. Such uncertainties are even more pronounced when applied to energy systems which are dynamic, systematic, variable and non-linear [40]. For building stock models to accurately represent energy consumption, data input for the above parameters ought to be as accurate as possible and accessible.

The geometry for buildings is relatively accessible through tools such as geographic information systems (GIS) and readily available historical records and surveys [41–45]. Obtaining information on the other aspects affecting energy performance, as listed above, is less straightforward with the most common way of acquiring input data being from surveys and audits. In EU countries, such surveys are used to create energy performance certificates (EPCs) which are a requirement of the EPBD and are created using a national calculation methodology (NCM). The time consuming, expensive and subjective process in producing EPCs is detailed in section 2.3.2. Various studies have highlighted the inability of EPCs to accurately predict energy consumption for individual buildings and the whole stock due to the combination of poor quality input data and the simplified calculation method [44, 46–55].

Despite this evidence, EPC methods are still the default for governments and other regulatory framework [8, 17, 56–59]. Models and projects which have attempted to improve current practice often use the same assumptions and use very site-specific data. This greatly limits their transferability and does not improve the ease of data acquisition [29, 60]. The greatest problem in creating accurate building stock models is limited data availability [29, 61, 62]. This project introduces the notion of using publicly available aerial and satellite images for extraction of building dimensions and surface attributes such as glazed area and absorptivity of the façade. This data is to be combined with EPC data to define the inputs to an individual building model. As such, the project method compensates accuracy for availability. To atone for the reduction in accuracy, dynamic simulation is used rather than the simplified calculation models for producing EPCs, which can better capture the complicated nature of energy systems.

The new modelling method proposed in this project is hoped to lead to overall more accurate energy predictions for individual buildings which can then be applied to the whole building stock. The data acquisition in particular is aimed at provoking a new direction in more accessible model inputs which is traded for accuracy. It is of interest to see whether less accurate but publicly available data sources combined with other EPC data and dynamic modelling can offer better predictions of energy consumption than current practices. A prediction method with improved overall accuracy which uses easily accessible data for energy mapping of buildings could provide the means for policy to be more effective in addressing the issues associated with high energy use and inefficiency of buildings.

1.2. Aim

This project aims to improve current practice for energy in building stock modelling. By using a dynamic simulation tool with high resolution (ESP-r in this case) a more accurate representation of energy consumption can be achieved compared to the NCMs widely used by governments and industry today. The data sources for this model will be comprised primarily of data from EPC surveys but also publicly available aerial and satellite images where possible. These satellite and aerial images offer a less precise description of the geometry and fenestration of buildings but greatly improves the transferability of the method. Ultimately, with further work and research, it is hoped that useful stock modelling tools can be derived from wider and more accessible data sources. Such tools would be generic in nature and so could, in principle, determine the energy map of any given urban environment.

1.3. Objectives

In order for the above aim to be achieved. the following objectives have been identified:

1. Quantify the difference in energy consumption between EPC ratings and real data, as reported in literature, for a selection of University of Strathclyde campus buildings and hence confirm the project motivation

2. Select buildings for which EPC and real data is available and model them in ESP-r using a combination of EPC, aerial and satellite images and assumptions as data sources.

3. Evaluate the models' accuracy in determining energy performance compared to its EPC equivalent

4. Discuss and account for any discrepancies between model output and metered data

5. Identify areas for further model improvement and research

1.4. Overview of Methodology

The methodology undertaken in this project is concerned with successfully achieving the objectives. This section describes the high level methodology used for the project. More detailed accounts in methodology for the individual objectives can be found in their respective sections.

Real utility data is available along with EPCs for a number of University of Strathclyde (UoS) buildings. Therefore, the first objective can be fulfilled. Once the difference in energy usage between EPC and real data for the building stock has been quantified, buildings can then be modelled using ESP-r, a dynamic simulation tool. A smaller number of buildings were chosen for simulation compared to the original stock. These buildings were chosen based on the available data that would make objectives 1 and 2 achievable. Data input for these models came from three principle sources. Publicly accessible satellite images were used for determining the geometry and aerial images for glazed surface area and surface absorption. Information on building fabric, HVAC systems, occupancy and lighting were taken from the EPC survey whilst IT equipment and ventilation rates were assumed from inferred EPC information and the literature. The weather file was sourced from the UoS ESRU database.

The chosen buildings are to be first modelled as a single zone in ESP-r as such a description may be sufficient in showcasing a marked improvement in energy consumption prediction. After the chosen models have been simulated, a comparison can be made between measured data and results for energy consumption supplied by the ESP-r model. A final comparison in results for energy usage between a NCM approach (in the form of EPCs) and that of an ESP-r dynamic simulation model using different data sources is to be made. After analysing these results, assumptions and limitations in data input will be addressed and a recommendation can be made as to whether single zone models with a range of data sources would be more beneficial to policy-makers and stakeholders than current best practice. Figure 1 is a simple schematic of the overall methodology process that is to be implemented in carrying out this project. It also importantly states the data source for the various model elements.

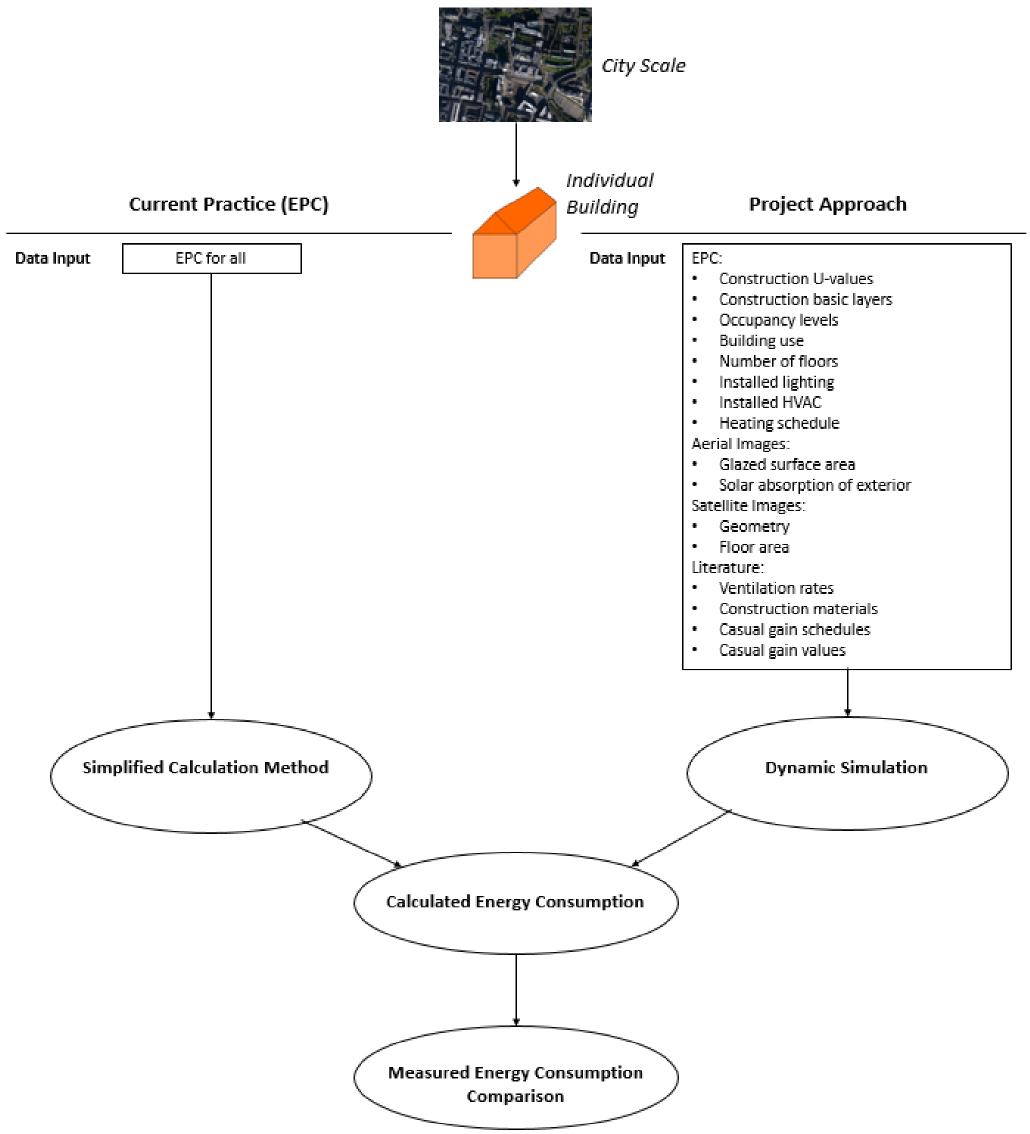


Figure 1: Overview of Project Methodology

1.5. Structure of Dissertation

The first section sets the case for why this project is being undertaken and how it can have a positive influence in the field of building stock modelling for energy mapping. As well as this, the project's aim and objectives are set out along with the project methodology adopted in order to achieve these. Section 2 gives an in-depth context to the challenges faced pertaining to building stock modelling, energy consumption and energy efficiency in the form of a literature review. An overview of energy and buildings is detailed followed by a review of building stock models. This review includes descriptions of both the simplified calculation method used by NCMs in producing EPCs and of dynamic simulation. Current practice in building stock modelling and common deficiencies are highlighted and the section concludes with closing remarks on how limitations could be challenged and overcome.

Section 3 quantifies the difference in predicted energy consumption from EPC ratings and utility data for a number of UoS buildings. These 14 buildings comprise this project's building stock and a brief overview of the variability in usage and physical characteristics is given in section 3.2. The method for quantifying the mismatch in energy consumption is next described followed by the subsequent results. These results are analysed, discussed and compared to examples from the literature to finally draw some concluding comments on the suitability of EPCs for predicting energy consumption.

In section 4, the project methodology (see figure 1) is invoked. A general method for modelling buildings is described including details for data extraction and manipulation from EPC, aerial, satellite and literature sources. This general method is then applied to 10 buildings within the stock. In a similar way to section 3, the difference between predicted and measured energy consumption is then quantified. The quantification of results is discussed along with the various assumptions in deriving the models in section 5. Section 5 also discusses the relative effectiveness of EPCs and the project method at predicting energy consumption and offers reasons as to why the observed differences occur for this case study and in general. Section 6 concludes the overall findings from the study and discussion and contemplates the significance of results in the overall context of building stock modelling for energy mapping research. Limitations to the project and any future work are presented in sections 7 and 8 respectively.

2. Literature Review

2.1. Overview of Literature Review

It is important to establish a context for why a project such as the one presented exists. In section 2.2, the high level issues associated with the energy efficiency of buildings is discussed along with what attempts have been undertaken to tackle those exposed issues. The positive impacts of energy efficiency measures are presented along with their associated problems.

With the context of energy and buildings established, an overview of building stock modelling is next explored. Section 2.3 highlights the wealth and variety of worldwide research on the topic of building stock modelling. Common methods of ascertaining energy demands within building stock modelling are discussed in addition to prevalent deficiencies exhibited by a multitude of models. Attention is drawn to how these models and their data are used in projects and how their inadequacies call for improved energy prediction methods.

2.2. Energy and Buildings

2.2.1. Introduction to Energy and Buildings

The International Energy Agency [1] have estimated that heating and cooling in buildings account for approximately 40-50% of global energy demand and, as section 1.1 mentions, buildings also contribute to over a third of total greenhouse gas emissions and can greatly affect the health and well-being of its occupants. Often, the energy performance of a building is only considered during its operational phase. However, the embodied carbon during raw material extraction and manufacturing, transportation of materials, construction and demolition phases of a building's life also significantly contribute to the world's energy and resource demand problems [63–65]. Carefully constructed town and city planning strategies incorporating a life-cycle approach are therefore vital for any sustainable development initiatives to be realised [66–69].

The problems relating to energy, resource and pollution from buildings is set to become amplified over the 21st century. This is due to two major factors - climate change and population increase. The expected demographic transition that will take place will not only see an overall rise in the number of humans but also a shift in balance of population distribution from rural to urban dwellings [62, 70–72]. The rise in population and urbanisation will not only lead to greater energy consumption but also further strain on the planet's natural resources, including construction materials for building homes [72–77]. With an average rise in temperatures from climate change (anthropogenic or otherwise), heating demands are predicted to decrease [78–81]. However, studies have shown that the predicted rise in cooling loads can offset this and lead to an overall increase in HVAC energy requirements [79, 81–87]. More extreme weather events as a result of climate change [88] will lead to peak power demands which will threaten the security of supply [89]. Another adverse outcome is related to the urban heat island (UHI) effect which is an artificial rise in temperature within cities due to buildings trapping heat, industry, heat from machines, vehicles, people and pollution. This urban microclimate has an effect on energy demands, thermal comfort and health of the urban population [90]. Increased urbanisation and rising temperatures will intensify the UHI effect with the waste heat emissions from an increased use of cooling systems strengthening it further still [4, 31, 90–93].

It is clear that buildings pose many problems relating to energy use, anthropogenic global warming and resource depletion and that these will only be exacerbated without wide-scale intervention. Improving the energy efficiency of buildings and encouraging smart urban planning can therefore aid in the curbing of greenhouse gas emissions and fossil fuel reliance. In fact, the Intergovernmental Panel on Climate Change (IPCC) have highlighted buildings as having the greatest potential for carbon abatement [88]. Increased urbanisation could even act as a positive driver in reducing carbon emissions if certain measures are taken [7, 88, 94, 95].

2.2.2. Nearly-Zero and Zero Energy Buildings

Nearly-zero energy buildings (NZEBs) are targeted to become the norm in buildings occupied by public authorities from 2018, as stipulated in the EPBD 2010 recast (see section 2.2.5). Additionally, new buildings are also to become NZEBs by 2020 irrespective of their primary function [96].

Indicators for building energy performance in EU countries do not take the life-cycle of the buildings into consideration. An approach involving the life-cycle of the buildings would incorporate the materials used, construction, transport, operation, maintenance and recycling. This comprehensive view is necessary if the environmental impacts of the construction sector in general is to be improved, rather than simply focusing on the operational phase [63, 67, 97]. Evidence suggests, and it is intuitive that, there is a financial restriction on being able to effectively establish (N)ZEBs. A study by [98] involved simulating refurbished schools within the UK and assessing the effects on carbon emissions and cost across the entire life-cycle. In all cases, the carbon payback period was shorter than that of the financial. The study suggests that when considering a building system in its entirety, from sourcing materials to destruction and potential recycling, there is a compromise between the monetary input and carbon emission abatement.

The question must also be raised as to whether significant adoption of ZEBs is actually sustainable, particularly in the medium term before materials in a life-cycle approach could be re-used. The Earth's carrying capacity may limit the construction materials available to facilitate such a large urban population. Prior to the operational phase of a building, the embodied energy in highly energy efficient materials will actually be higher than normal. The greater the energy efficiency of the building, the higher the embodied energy, use of natural resources and environmental degradation. A life-cycle approach is therefore crucial in ensuring that there is an overall positive and sustainable outcome from improving buildings [64].

2.2.3. Passive Solar Techniques

One way to improve the energy efficiency of buildings and create (N)ZEBs is to incorporate passive solar techniques. This involves utilising incoming solar radiation for heating and lighting and does not rely on any electrical or mechanical input [99]. Typical passive solar designs include trombe walls, solar chimneys, evaporative cooling and unglazed transpired solar façades. All of these involve the building storing heat throughout the day then distributing it to the indoor environment later on. Ventilation ducts then allow for the passage of hot air for cooling during summer [100].

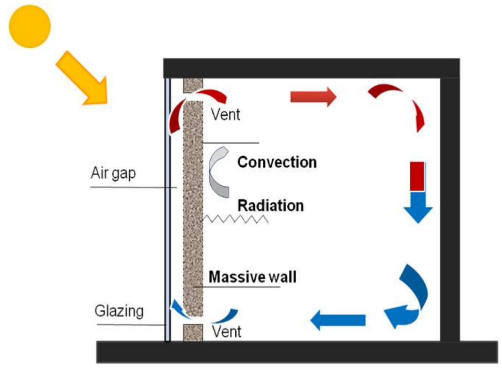


Figure 2: Working principle of a traditional trombe wall
[101]

Successful projects have been demonstrated such as the Self-Sufficient Solar House (SSSH) in 1992 where the building was entirely energy self-sufficient and exhibited no reliance on fossil fuels in providing its power [102]. Another study found that passive solar techniques greatly improved thermal comfort levels and reduced the need for air conditioning in Brazilian social housing [2]. As well as the façade and layout, insulation, air vents and glazing are essential to a building's energy performance and all must be considered for realising effective passive solar techniques.

Figure 3: The Self-Sufficient Solar House created at the Fraunhofer Institute for Solar Energy Systems in 1992
[103]

2.2.4. Renewable Energy Integration

Renewable energy technologies present a clean alternative to fossil fuels and take many forms. Typical examples in the context of buildings include photovoltaic (PV) and wind turbines for electricity generation along with biomass boilers, heat pumps and solar thermal devices for heating. Heat pumps can use renewable electricity to provide space and hot water heating.

Reliance on carbon based fuel sources and their associated emissions will reduce with greater renewable energy system penetration. However, they are fraught with problems concerning reliability and cost-effectiveness. The problems stem from the performance of wind, solar and photovoltaics (the three most common renewable microgeneration sources) being determined by underlying meteorological factors which are stochastic by nature [104]. This problem is exacerbated in dense urban areas where exposure to high winds and direct sunlight is limited. The Warwick Wind Trials highlighted this fact as the findings found urban small-scale wind turbines produced negligible power and in some instances even generated less power than they consumed to power their electronics [105].

Despite these problems, renewable energy systems are still increasing in capacity, including on a local scale. It is becoming more and more common for individual buildings or a group of buildings to have on-site renewable generation - distributed renewable energy resources. In 2011, distributive energy resources took up 9% of the UK's total generation capacity. It has been estimated that this will rise to 14% by 2030 with an installed capacity of 17GW [106]. One of many examples is the West Whitlawburn district heating scheme which has a 740kW biomass boiler to supply heating to over 500 homes [107].

Microgrids incorporate distributed generation, loads, storage devices and control operations. Due to storage being small scale, renewable energies can also be more easily integrated, particularly those supplying heat. Microgrids can be operated in stand-alone or grid-connected mode and offer a higher security of supply. In addition, the more autonomous control of end users can help to influence demand management and relieve pressure on energy supplies. The emergence of microgrids can therefore help to alleviate the issues associated with renewable energy systems. However, there are still issues with managing and building a suitable infrastructure to realise these on a large scale [108].

(a) West Whitlawburn residential high rises

(b) The 740kW biomass boiler being installed for district heating

Figure 4: West Whitlawburn district heating scheme
[107]

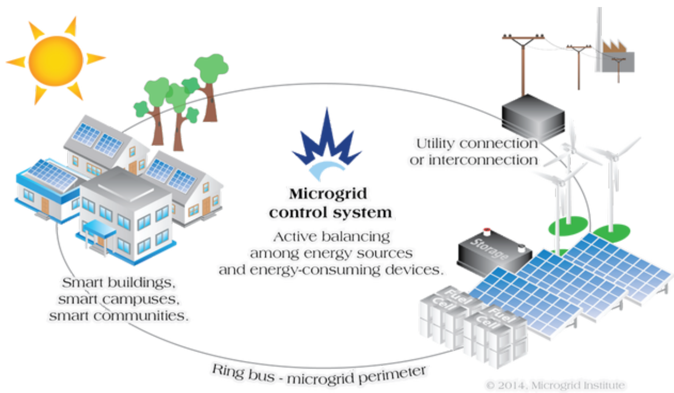


Figure 5: A simple schematic of a typical microgrid
[109]

2.2.5. Policy Relating to Energy in Buildings

The aforementioned problems concerning the energy efficiency of buildings, both present and future, have driven towards the emergence of international policies designed to improve building energy performance. National energy efficiency standards for the use of thermal insulation have been developed since the 1950s with revisions and more strict policies generally being enforced in the decades after [110]. This is part of the reason why nearly-zero and ZEBs have become more commonplace as well as microgeneration in the form of renewable energy systems.

In order to create a more homogeneous set of policies among EU countries, the Energy Performance of Buildings Directive (EPBD) was published in 2002 by the European Council on the Energy Performance of Buildings and came into effect in 2003. This directive provides the basis for the majority of policies that have since been implemented by EU states to improve their buildings' energy efficiency. As part of the EPBD, all member countries are required to develop a method for calculating the energy performance of buildings which then define the criteria for EPC ratings in each EU country. In 2010 there was a recast of the EPBD which extended the scope of the directive to include cost effectiveness. This is to ensure that the capital required for sufficient upgrades balances the savings in energy throughout the life-cycle of the building [111].

Another policy that runs parallel to the EPBD is that of the Smart Cities and Communities Initiative, both of which strive to realise the EU's 20/20/20 sustainability targets - that is a 20% reduction in EU greenhouse gas emissions from 1990 levels by 2020. This Initiative strives to find affordable and sustainable retrofit solutions along with energy efficient and low carbon solutions for new buildings and districts [112]. It aims to encourage citizen and industry involvement through interconnectivity using the Internet of Things (IoT) which is hoped to optimise the management of the city and its residents' resources whilst providing a high quality of life [66, 113].

In section 2.2.2, it was mentioned that there is a strive towards a high uptake of NZEBs. Part of the EPBD stipulates that new buildings from 2021 will have to be NZEBs [9]. There is evident progress in some EU member states, such as Germany and Austria, in adopting NZEBs but there is a failing in the EPBD in not providing a clear and concise definition of how such a building ought to be made and implemented. Part of the problem is that member states can decide for themselves what a high level of energy performance entails [96].

2.3. Building Stock Modelling for Energy Mapping

2.3.1. Introduction

In order for policy to be effective and make any difference, decision-makers must be informed with high quality data. Data can then be used to identify which buildings or areas perform most poorly and what strategies can be put in place to improve their energy efficiency and reduce consumption. In order to rate and prioritise buildings, the energy performance of buildings must be quantified.

Modelling energy systems for building stocks offers greater insight into the possibility and effectiveness of retrofitting than empirical data but also carry a significant level of uncertainty. A model is only as good as the data put into it but acquiring real or extremely accurate data is often challenging, expensive and time consuming. Uncertainties arise due to assumptions and simplifications used within the model and, sometimes, limitations in the model's validation. Uncertainties and assumptions pertain to occupancy schedules, equipment and HVAC use, schedules and set-points and thermophysical construction properties. These uncertainties and assumptions in building stock models are rarely communicated to policy and decision-makers which can lead to poor investment decisions [29].

2.3.2. Energy Performance Certificates and the National Calculation Methodology

As part of the EPBD, each country is invited to adopt its own energy performance grading system. Part of this is to provide a valid methodology for calculating the energy performance of buildings - the NCM. The EPBD also requires each nation to have a grading system in place to inform owners and occupiers of the energy efficiency of a building - the EPC. A comprehensive overview of EPCs and the NCM is given by [114] and is used extensively for the rest of this section.

A 'building' may be defined as either the whole or part of a structure. Therefore, different floors with different owners/tenants and different HVAC systems would require their own EPC. Conversely, the opposite is true whereby a complex that consists of several buildings sharing a core heating system only requires one EPC. EPCs are required when a building is constructed, sold or let. Existing occupiers and tenants do not require an EPC unless they sell or sublet the property. Places of worship, temporary buildings (used for less than two years), stand-alone buildings with less than 50m^2 of floor area, low energy demand buildings eg. barns and buildings due for demolition are also exempt from needing an EPC.

It is important to understand that the EPC is an asset rating and is based upon a building's fabric and services. Crucially, it is not a measure of how much energy is actually consumed. Therefore, any energy saving management scheme reducing usage will not improve the EPC rating. To produce an EPC, a NCM has been developed for non-domestic buildings and a Standard Assessment Procedure

(SAP) for dwellings. In the UK, these were both developed for the Department for Communities and Local Government (DCLG) by the Building Research Establishment (BRE). The NCM takes form as the Simplified Building Energy Model (SBEM). In order for a building to be assessed using SBEM the following information must be provided [58, 114, 115]:

- Address, owner and climate (14 climate options)*
- Position, geometry and orientation
- Indoor conditions
- Fabric performance including materials, glazing and infiltration rates
- HVAC and hot water
- Lighting and daylight
- Passive design
- Renewable and combined heat and power (CHP) technologies
- Controls

**Glasgow is one of these 14 climate options which is important for comparison in section 3.*

Once all the necessary data has been collected, SBEM calculates the required levels of heating, ventilation, cooling, lighting and hot water whilst electrical appliance use is omitted. In order to calculate the required heating and cooling of a building, it is split up into several thermal zones. These are all regarded as isolated single zone calculations with no accounting for thermal coupling between the zones, therefore any heat transfer by thermal conduction or air movement between adjacent zones is not taken into account. When zones share the same heating and/or cooling system then the zones are aggregated. For zones that do not share the same heating or cooling systems, the energy use is simply the sum of the individual calculation zones [59].

The thesis presented here is concerned with energy demand for space heating and hot water. The reasons for which are given in section 3. SBEM attempts to quantify the heating and cooling energy balance by finding the following values for every calculation period (monthly) for each zone, as in the official SBEM Technical Manual [59]:

- Calculate the characteristics for the heat transfer by transmission
- Calculate the characteristics for heat transfer by ventilation
- Calculate the casual and solar heat gains
- Calculate the dynamic parameters - 'gain utilisation factor' for heating, 'loss utilisation factor' for cooling
- Calculate the building energy demand for heating and cooling

The energy demand for space heating for each month in each zone is then given by:

$$Q_{NH} = Q_{LH} - \eta_{GH} . Q_{GH} \tag{1}$$

Where Q_{NH} is the building zone heating energy demand, Q_{LH} is the total heat transfer losses, Q_{GH} is the total heat source gain and η_{GH} is the gain utilisation factor. The gain utilisation factor is a dimensionless value that quantifies the capability of a building to utilise incoming solar radiation and internal gains so as to reduce the mechanical heating load. A description of how it is calculated can be found in [59].

The energy use is then converted to CO_2 emissions using the carbon footprint of fuels used. The resulting number is known as the building emission rate (BER) which is given in units of $kgCO_2.m^{-2}$. To then calculate the EPC, the BER must be compared with a standardised emission rate (SER) (again in units of $kgCO_2.m^{-2}$) which is based on the 'notional' building. The notional building is almost identical to that being assessed except all constructional elements are replaced with those satisfying 2002 U-value standards. The notional building has the same geometry, orientation, location and systems as the real one and is assumed to have standard occupancy and operational patterns. The fuel type is assumed to be gas for heating and electricity for cooling and lighting. The assumed fuel type used and CO_2 emissions from the calculated energy consumption are reduced by 23.5%. This value is somewhat arbitrary in nature yet is used as a standardised improvement factor for all buildings in calculating the SER value [114]. Equation 2 is then used to give the EPC 'rate' as a dimensionless value:

$$EPC = \frac{BER}{SER} \times 50 \tag{2}$$

The '50' is simply there to convert the rate to a number between 1 and 100 [114]. Figure 6 is of a template for an EPC in Scotland [116]. The EPC rating as calculated by equation 2 is used to give the value denoted by the arrow on the right (E+ in this case).

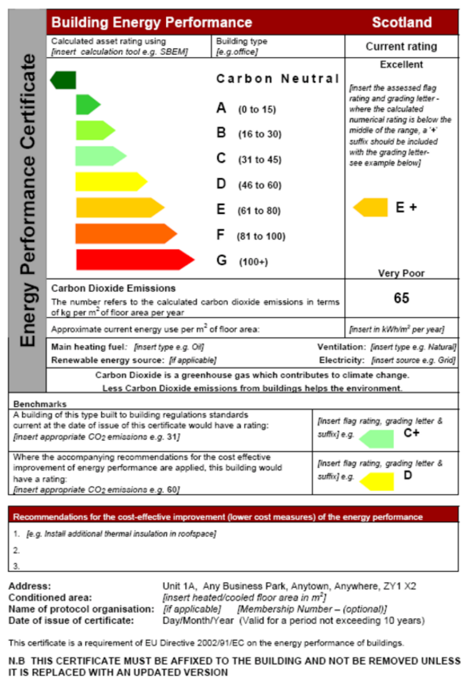


Figure 6: EPC template for buildings in Scotland [116]

Standardised assumptions for the behaviour of occupants and estimates of annual energy consumption are used to create an EPC and there is therefore a high level of uncertainty in the displayed energy consumption and carbon emissions [58]. An energy assessor is needed to provide the information to feed the NCM software calculation tool which then calculates the energy performance [117]. This process suffers from errors within the survey [117], access to data with many countries not having the resources to perform the necessary surveys [33, 60, 117–119] and from using a simplified heat transfer mechanism [44, 58, 59, 114, 115, 120]. Additionally, the process to produce an EPC and recommendations report is very time consuming [114].

The culmination of EU member states being able to decide their own grading system, define energy performance categories and none taking a life-cycle approach means there are clear inconsistencies across nations and a limited scope with regards to the sustainability of buildings. These factors somewhat diminish the integrity of the information supplied to policy and decision makers who are ultimately responsible for improving the energy efficiency of the built environment.

2.3.3. Dynamic Simulation of Energy in Buildings

An alternative to the NCM and EPC ratings for calculating energy consumption in buildings is using dynamic simulation. Dynamic simulation can provide more accurate predictions and is more useful for assessing design options. It offers a valuable and fast response to design parameter alteration and is therefore better equipped to tackle the health and energy efficiency problems related to buildings as introduced in section 1.1.

Rather than simplifying energy calculations as is used for generating EPCs, dynamic simulation represents every possible energy flowpath and every variable's interaction with every state of every other [40]. Figure 7 shows these energy flowpaths in a building and all the interactions that affects its overall energy characteristics. Dynamic simulation can offer insight into the intricate relationships between variables as shown in figure 7 whereas simplified EPC models cannot.

A wealth of literature exists on the subject of dynamic simulation for energy in buildings. Rather than reproducing previous authoritative and comprehensive work on the subject, this section gives a high level overview of the calculation process used in dynamic simulation and particularly for ESP-r which was the tool of choice for this thesis. Much of this section is indebted to [40] which provides a far more in-depth appraisal and explanation of dynamic building simulation tools than is presented here.

Every flowpath for heating, air, moisture, light and electricity in a building is defined in a dynamic simulation model. These are then exposed to a climate as well as system controls and human

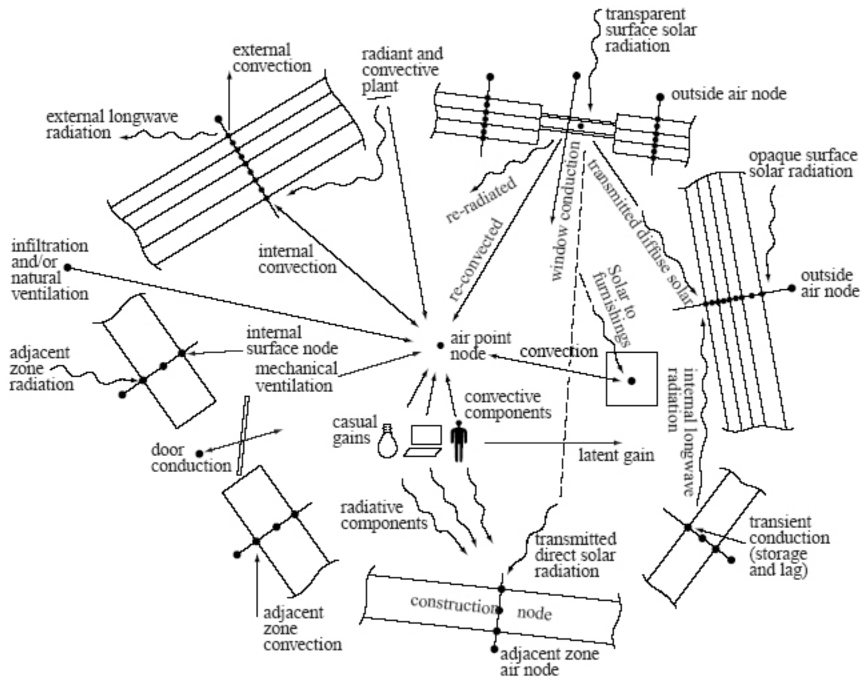


Figure 7: Flowpaths of energy in buildings
[40]

interaction which combine to form a universal model representing the whole building and its interactions with its systems and environment. For the dynamic simulation tool used in this thesis, the user must define the weather, location, exposure, orientation, geometry, construction (including glazing), casual gains, HVAC systems and controls. Energy flowpaths for all these separate elements are represented by independent equations which are attributed to a nodal point for every model variant [40].

Nodal points are a product of the discretisation of the building system. This discretisation is necessary for the numerical methods that are commonly used for energy calculations in dynamic simulation. Numerical methods couple the independent equations at each system node for combined solving and can thus simultaneously solve the entire energy system at each iterative time step. Numerical methods can handle problems of great complexity by allowing time-varying parameters to be handled at different frequencies to the modeller's desire. Numerical methods are based on underlying partial differential equations which are often based on truncated Taylor Series expansions which represent derivatives of a finite difference method, which itself is representing a continuous function. The total system of equations can be expressed as in equation 3 [40].

$$\mathbf{A}.\theta_{n+1} = \mathbf{B}.\theta_n + \mathbf{C} = \mathbf{Z} \tag{3}$$

Where **A** is a matrix of future time-row coefficients of temperature or thermal energy terms at a node and **B** is its equivalent for the present time. **C** is a column matrix which contains entries of boundary excitations which relate to the present and future time. Column matrices θ_n and θ_{n+1} are also of temperatures and heat injections at each node where 'n' refers to the present time and 'n+1' the future time row. **Z** is the resultant column matrix [40]. The equation can therefore be derived iteratively for a succession of time-steps which derive state variables for future times as a function of those at the present with respect to the imposed boundary conditions [76].

Equation 3 can be established for any building system with multiple zones. The simplest of these, as mentioned previously in section 2.3.2 is a single zone. The project method (see figure 1) is to model single zone representations of buildings using dynamic simulation. As well as simplifying the layout and internal heat transfers, glazing can be further simplified for a single zone. It matters not where in the zone that insolation occurs as the energy consumption is to be analysed for the whole zone not one part. As such, any glazing on a given façade can be aggregated into one area representing all fenestration.

Another simplification in dynamic simulation, with regards to this thesis, involves ventilation and infiltration. Regulations specify standard air supply rates based on occupancy and activity [121, 122]. The dynamic simulation tool used for this investigation accommodates the need for ventilation rate design by allowing the user to impose desired ventilation and infiltration rates on the building. Using approximate estimates for ventilation is often acceptable practice for studies wishing to gain a general insight into the overall energy impact of ventilation [122]. Infiltration is simply modelled as a conservation of mass through the single zone. As such, for a given zone, an airflow network must adhere to equation 4.

$$\sum_{i=1}^{i=j} Q_i = 0 \tag{4}$$

Where Q_i is the air flow rate due to different sources, typically driven by the wind or temperature differences or mechanically supplied. In all cases it is a pressure difference between air nodes outside and inside the zone that defines Q_i where j is the number of flow paths that penetrate the zone [122].

Dynamic simulation for assessing energy flows in buildings offers a far more accurate representation of the physical processes that occur in reality than the simplified calculation methods described in section 2.3.2. The use of dynamic simulation however is currently confined to private and research vocations and rarely affects public policy decisions. Policy is the best driver towards successful solutions in addressing energy consumption, efficiency, health and air quality issues associated with the built environment. Dynamic simulation is able to assess the effectiveness and robustness of various design measures such as those mentioned in sections 2.2.2, 2.2.3 and 2.2.4. Based on the immediate feedback from simulation, policy-makers are better equipped to determine the most effective and positive course of action.

2.3.4. Current Building Stock Models for Energy Mapping

Hundreds of tools and applications have been developed for energy quantification in building stock modelling, all of which can be split into two distinct categories: top-down (TD) and bottom-up (BU). BU models are technocentric in their approach and are thus able to assess different technological options and energy trends within specific sectors of society. This is achieved by extrapolating the energy performance of a set of representative buildings to a regional or national level. A TD model, on the other hand, focuses upon the macro-economic consequences of policy or investment decisions and are widely used at a national level. It does this by using historical aggregate energy data to estimate the energy consumption of the building stock as a function of high level variables [29, 30, 123, 124]. TD models are insufficient in analysing the effects of individual energy efficiency measures, hence BU models are more widely used and receive greater attention in building stock modelling research [125].

BU modelling techniques can be further split into two sub-categories: statistical methods (SM) and engineering methods (EM). A comprehensive overview of these two methods is given by [124]. SM relies on historical data to attribute dwelling energy consumption to certain end-uses whereas EMs are based upon the physics of thermodynamic energy flows. In more recent years, other categories of BU modelling have arisen, namely agent based models (ABM) [126, 127] and artificial intelligence (AI) methods. AI methods are similar to SM as they use historical data as input but use neural networks to describe the nonlinear relationships between energy inputs and outputs [39]. BU modelling consists of three main steps in the simulation process: data input; thermal modelling; validation [119].

There are three principle techniques to EM BU modelling. Firstly, there is sampling which uses true data as input information. This helps to capture the wide variety of building stock but is very data intensive so is limited in its application. Next, there are distribution techniques which use demographic and lifestyle data combined with appliance engineering data to establish an overall energy ratings profile for appliances. Finally, there is the use of archetypes. Archetypes are a broad classification of building stock based on size, age and type. Three principal components exist in defining archetypes according to [128]:

- Geometric configurations
- Thermal characteristics
- Operating parameters

The energy consumption estimates of modelled archetypes are extrapolated to represent the entire building stock of a region or nation [124]. Models that use archetypes include (but is certainly not limited to) BREDEM, BREHOMES, SAP, DOE-2.1, BEAM, UKCDM, INVESTIMMO, EPIQR, DECarb and CDEM [20, 29, 31, 110, 124, 129, 130].

Two separate buildings belonging to the same archetype may have significantly different energy consumption profiles due to energy efficiency and/or occupant use. Similarly, two buildings categorised by different archetypes may exhibit very similar energy consumption patterns as the thermodynamics relating to the building envelope may be the same. According to [131], studies have even shown that there can be more variety between buildings of the same archetype than between archetypes. In order to address the limitations of using archetypes in building stock modelling, [28] develop and describe categorising buildings using a thermodynamic class (TC) instead. The TC classes can incorporate different archetypes and the energy performance of a building would be based upon real, representative weather data. Any change in parameters on account of energy efficiency measures will then improve the TC of the building. This forms the basis of Strathclyde University's Energy Systems Research Unit (ESRU) Domestic Home Energy Model (EDEM), developed by the authors to simulate the housing stock for both present and future by inputting climate, exposure, occupancy and system control assumptions. Altering these assumptions allows the user to investigate future scenarios such as climate change and increased appliance ownership. Using TCs instead of archetypes is a view shared by [132] and [133].

The inclusion of temporal changes is not exclusive to EDEM. The Energy, Carbon and Cost Assessment for Building Stocks (ECCABS) developed by Chalmers University of Technology in Sweden takes changes in occupancy, appliances and solar radiation gains into account as well as outputting information on energy, CO_2 and cost. However, as with all models, there are limitations as a result of assumptions. Unlike EDEM, ECCABS assumes that the climate of the future will be the same as it is now and does not allow for alteration. It also makes unrealistic assumptions on U-values, ventilation rates and glazing [30].

As previously alluded to, many countries have developed their own models for representing building stocks with varying degrees of resolution and using various assumptions. For instance, the North Karelia model from Finland is a static model so does not consider changes in occupancy, appliance usage or solar gains over time. It is also greatly limited by its supporting data related to fuel use which leads to many assumptions. The Hens model, developed in Belgium, suffers from a too simplistic approach by neglecting cooling loads and only evaluating energy efficiency measures involving fabric upgrades. Then there is the UK's BREDEM (The Building Research Establishment's Housing Model for Energy Studies) which uses 47 archetypes. As previously discussed, this technique leads to erroneous assumptions of the true building stock energy map [29].

The simplest models assume a single zone and a static energy model [29, 30, 124]. The Housing Upgrading Evaluation (HUE) tool is an example of a static model that analyses the affect of retrofitting and fuel types on the EPC ratings for different building types [134]. To improve the accuracy of such models, various levels of complexity have been added in numerous examples. Dynamic simulation involving energy flows and differing occupancy, climate, exposure and system control assumptions have become more commonplace [28, 30, 135] and some models have incorporated a life-cycle approach as well as considering the urban surrounding [42, 119]. One example of a life-cycle approach is given by [42] which merges building information modelling (BIM) with GIS to create urban information modelling (UIM). With increasing complexity, the greater the computer power and time necessary to perform simulations [119]. The final step of BU modelling for energy building stocks, as highlighted by [119] is validation. The critique by [119] showed that over a large building stock, aggregated survey data generally correlates well with modelled. However, upon focusing on a single building, the accuracy drastically falls away due to peak energy periods.

2.3.5. Current Best Practice in Building Stock Modelling for Energy Mapping

Most modern building stock models use a geographic information system (GIS) to obtain the geometry and topography of the urban setting under study. One widely used tool is CitySIM which not only defines the physicality of the urban setting but also models urban resource flows [135]. The most widely used tool however is City Geography Markup Language (CityGML). It consists of different levels of detail (LoD) so can adapt to the availability and form of data [69, 119, 136]. In 2014, an alliance of building stock energy simulation developers established an application domain extension (ADE) to CityGML. With this modification, a 3D model of a city with building energy flows can be created. It can interact with utility networks using nodes and defines building objects using thermal zones [69, 136].

A core limitation to previous models is that they are very country or region specific which gives narrow scope for transferability. Each urban simulation model has its own database structure to collect, manage, interpret and distribute information. This is not particularly helpful to practitioners who must make decisions based on outputs from different models. The CityGML Energy ADE is able to convert and exchange information from other building energy tools and

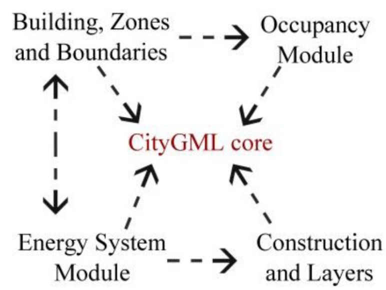


Figure 8: Data structure of CityGML Energy ADE
[69]

display simulations on a unified platform. This not only aids in the transferability of different building energy models developed in different countries but also leads to a greater sharing of knowledge [69]. Recently, the Tool for Energy Analysis and Simulation for Efficient Retrofit (TEASER) has been developed. This tool is open source and allows for multiple data sources and data enrichment [137]. This is immensely useful as different models have separate database structures to collect, manage, interpret and distribute information which is not particularly helpful for policy or decision-makers.

The Smart UrbaN ServIces for Higher eNergy Efficiency (SUNSHINE) project is the latest example of a collaboration between nations for energy in buildings stock modelling. It is an EU project involving numerous institutions from industry and universities, the aim of which is to support and encourage improved energy efficiency in buildings. To do this, the SUNSHINE project has developed three innovative web-serviced digital tools which can be used by the public as well as commercial and national institutions for analysing building energy performance data. The objectives of the three web-services are, respectively [138]:

1. Assess the energy behaviours of buildings on a large scale and create an energy map of the urban area
2. Optimise the energy consumption of heating and cooling systems using weather forecasting
3. Ensure the interoperable control of public lighting systems

The thesis presented here is ultimately concerned with only the first of these objectives. The aim of this first scenario is to deliver an automated large-scale assessment of building energy efficiency and present the information in the form of an energy map. This will then allow for the planning of large scale urban renewal projects, especially in opportunity mapping for district heating networks and (renewable) energy generation. This could lead to a knock-on effect of work creation, increased community involvement and improved air quality [27].

The fundamental layer in the SUNSHINE system architecture is that of the data layer which is based on the aforementioned CityGML, using LoD to structure the buildings. The geospatial model has to then be combined with energy performance data to prescribe the building with an energy class which can then be assimilated to form the city-wide energy map. The energy performance estimation procedure undertaken in the SUNSHINE project is described by [27].

The SUNSHINE Project gathers data using another latest tool in building stock modelling - the Typology Approach for Building Stock Energy Assessment (TABULA). TABULA is able to classify buildings into archetypes based on geometry, climate and thermophysical properties [57], though only the latter was exploited in the SUNSHINE project. From the geometric properties and set of estimated U-values, an energy class can be assigned to the building(s) by using EPC calculation methods, very similar to NCM. To validate the SUNSHINE project model, simulated results for energy performance were compared with EPC data.

The SUNSHINE project is the state of the art in terms of building energy stock modelling and offers an exciting premise for the sharing of information on energy efficiency in the urban environment. However, there are a number of shortcomings in the modelling procedure in delivering the energy map. These are indicative of many other preceding models such as those mentioned in section 2.3.4. There are three principle limitations in the SUNSHINE methodology, all of which are salient with respect to this thesis. Notably:

1. Real data used is survey data. Not all countries will have the resources available to retrieve such data and it also may not be wholly accurate

2. Comparison data used to validate the model is from EPCs which do not accurately represent the true energy performance of buildings. The methods used in the SUNSHINE model to

calculate energy efficiency are the same as those used for EPCs. As such, the validity of the project's results must be called into question

3. The modelling tool uses single zone simulation and considers them as isolated. No difference in aspect, shading or where windows and HVAC systems are placed within the building are taken account of. Extrapolating archetypes will also inevitably lead to a degree of uncertainty in the building stock model

Problems regarding the calculation method and its validation along with data input are not unique to the SUNSHINE Project. The various issues associated with energy in building stock modelling, as discussed in section 2.3.4 are widespread and are the default method adopted by governments and official agencies today. This presents a challenge in the field of building stock modelling that should be attempted to overcome.

2.4. Conclusion

Various motivations exist for improving building stock modelling for energy mapping. Consequently, there are a number of options available to help in reducing energy consumption and improving energy efficiency in buildings, such as passive solar techniques and installing renewable energy systems. Policy designed to affect positive changes suffers from a lack of detailed information about the true energy profiles of buildings. As such, building stock modelling incorporating energy profiling is an expanding and increasingly important area of research. A great numbers of models exist with varying levels of sophistication and applicability.

Despite the high number of models and the ever-advancing nature of the research field, there is clear scope for significant improvement. Even the most recent, collaborative and innovative projects such as the SUNSHINE Project and TEASER suffer from common deficiencies in the modelling process. Replacing standard NCMs with dynamic energy modelling may help eradicate a number of assumptions and greatly improve the accuracy of energy consumption predictions. Additionally, any change in HVAC or building design can be tested in a dynamic simulator to better ascertain how implementing them affects the energy flows. Results from such studies can indicate in what direction policy should strive to improve health and energy standards in buildings. There is also scope for research in improving the methods in obtaining information about buildings that affect their energy performance. Developing a sophisticated tool that can effectively extract necessary data from eg. a satellite image would greatly benefit transferability in building stock modelling research.

3. Comparison of EPC and Utility Data for Selected University of Strathclyde Buildings

3.1. Introduction

The first objective of this investigation is to 'quantify the difference in energy consumption between EPC ratings and real data...' (see section 1.3). This is in order to clarify the suggestion that there is a significant difference in results between actual and predicted energy consumption as calculated using SBEM. In the following section, the EPC ratings for selected University of Strathclyde (UoS) buildings is compared with real utility data. This exercise is necessary to establish the level of inaccuracy of EPC ratings for energy consumption and acts as a precursor to the rest of the project.

3.2. Context of University of Strathclyde Campus Case Study

The UoS was founded in 1796 by Professor John Anderson. His name lends itself to the present day Glasgow city centre campus which is comprised of around 34 buildings. The building stock is varied in nature ranging from the Victorian style Royal College Building completed in 1903 through to the 'brutalist' style new buildings eg. McCance (1964) and Architecture (1966) and modern constructions such as the Technology and Innovation Centre (2015). There are also a wide range of uses across the numerous buildings. Offices, laboratories, servers, workshops, cafeterias, halls of residence and sports facilities are all represented on the campus. Due to the varied age and use of the buildings, broad differences in energy consumption and efficiency are expected.

EPC ratings, calculated using SBEM (see section 2.3.2), from 2009 are available for numerous buildings across the campus. The collected data including floor plans, assumptions in construction and details on systems to generate the EPC is also available to the university's researchers. Utility data for electricity and gas consumption was collected from August 2012 - July 2015 by [139] using meters and this data was also made available for this project. It is therefore advantageous to the project's aims and objectives to use the UoS John Anderson campus as a case study for this project. The availability of dynamic energy simulation software provided by the university also makes this choice a logical one.

Due to only a few buildings having both sufficient EPC and utility data, the number of buildings initially under investigation was cut to 14. These are displayed in figure 9 along with a satellite image of the campus in figure 10. The James Weir building is annotated to act as a reference point.

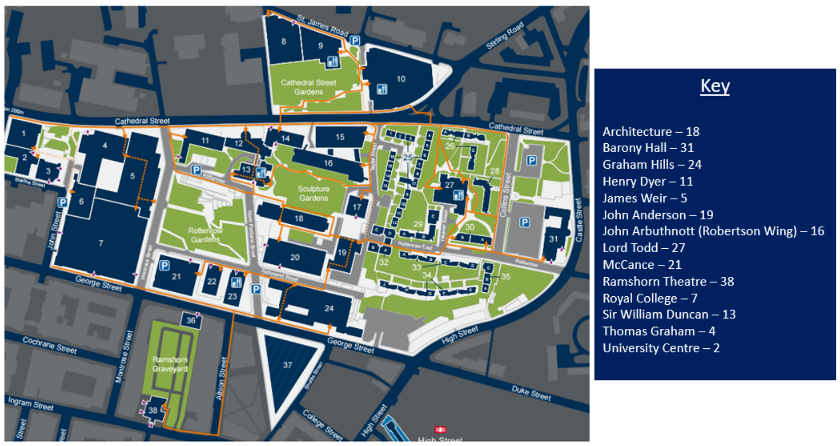


Figure 9: The University of Strathclyde John Anderson Campus [140]

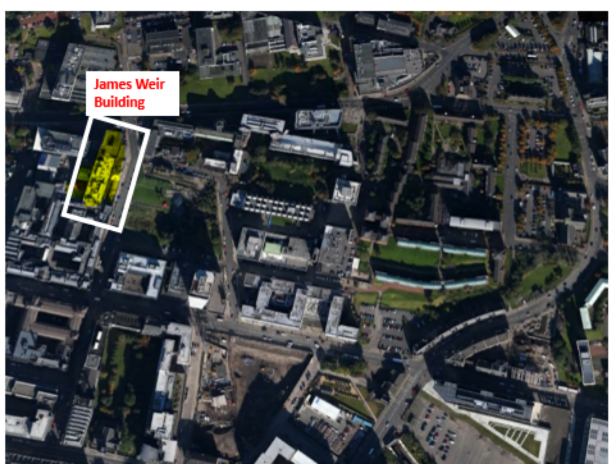


Figure 10: Satellite image of the University of Strathclyde's John Anderson Campus

EPC survey data was used to produce table 1 which gives some basic information on a handful of buildings. Data for the Barony Hall, Lord Todd, Ramshorn Theatre and University Centre was deemed insufficient to warrant inclusion. There is a range of mechanical systems and fabric properties that exist across the different buildings however some elements are standard throughout:

- The mains heating network is supplied by natural gas
- Boilers have manual on/off control as well as thermostat settings
- Hot water is heated via a centralised system in each building, sometimes between buildings
- Electricity is supplied by the national grid
- There are no on-site renewable sources for the buildings studied

Building	Use	Orientation (°N)	Floors	Total Floor Area (m²)	Year Built	EPC Rating
Architecture	Offices and Workshops	11	4	5325.29	1966	F+
Graham Hills	Offices, Workshops and Lecture Theatres	16	9	19972.5	1959	E+
Henry Dyer	Offices, Workshops and Lecture Theatres	11	3	2620.42	1970	E
James Weir	Offices, Workshops and Lecture Theatres	281	9	21067.4	1958	E+
John Anderson	Offices, Workshops and Lecture Theatres	11	9	10656.6	1971	E
John Arbuthnott (Robertson Wing)	Offices, Workshops and Lecture Theatres	10	6	8944.87	1998	D
McCance	Offices	12	5	6914.37	1963	F+
Royal College	Offices, Workshops and Lecture Theatres	12	12	35090.5	1903	G
Sir William Duncan	Offices, Workshops and Lecture Theatres	10	7	3721.02	1977	D+
Thomas Graham	Offices, Workshops and Lecture Theatres	12	9	13932.8	1962	D

Table 1: Basic information for various buildings on the University of Strathclyde John Anderson Campus

3.3. Method for Comparing EPC and Utility Data

As previously mentioned, utility data for electricity and gas was made available for the research requirements of this project along with EPCs of certain UoS buildings. The EPC for the James Weir building is shown below in figure 11. The approximate energy use per floor area is the most relevant piece of information to be taken from the EPC with regards to this project. So in this example it is 250kWh.m^{-2} which refers to space and hot water heating, lighting, ventilation and cooling [58].

Ideally, a comparison in energy consumption for all loads would be undertaken. However, the utility data only supplies information on total electricity and gas consumption with no further breakdown on what each is used for. Electricity consumption in an EPC does not take account of electrical appliance use and, as displayed by figure 12, space heating makes up the greatest proportion of energy use. Hence, the decision was taken to only compare energy consumption in terms of gas between the EPCs and real data. It is therefore necessary to then convert the value for annual energy consumption as given by the EPC to that only providing space heating and hot water, for which natural gas supplies.

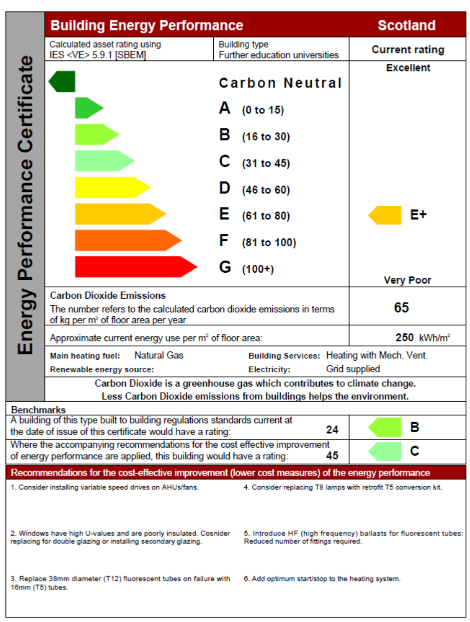


Figure 11: EPC for the James Weir Building

Accompanying EPC survey documents detail the energy consumption by use, as calculated by

SBEM, to go along with the EPC. As an example, figure 12 depicts the energy breakdown for the James Weir building. Where:

- H = Heating
- L = Lighting
- HW = Hot Water
- A = Auxiliary
- C = Cooling

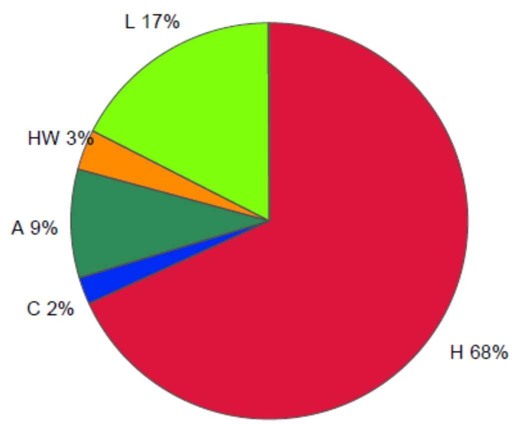


Figure 12: Pie chart of the James Weir Building's energy use as calculated by SBEM

The term 'auxiliary' refers to the energy required to transport delivered energy such as fans, pumps and electronics [141] and is thus not required for analysis of gas consumption. To completely alter the value of EPC energy consumption to that for only space and water heating, a simple formula is used as given by equation 5. Where G refers to the energy consumption per floor area purely from gas, EPC the total consumption, H and HW as above.

$$G = EPC \times (H + HW) \tag{5}$$

Taking the example of the James Weir, equation 5 becomes:

$$G = 250kWh.m^{-2} \times (0.68 + 0.03) \tag{6}$$

Giving the value:

$$G = \mathbf{177.5} kWh.m^{-2} \tag{7}$$

This value now has to be compared with the real annual gas consumption provided for by the Estate Management at UoS. The data provided has monthly totals from August 2012 until July 2015 totaling three years exactly. A minimum, mean and maximum annual gas consumption value could then be extracted for each building. Total floor areas from the EPC survey were then used to calculate the average annual energy consumption per floor area for each building in $kWh.m^{-2}$ so that a direct comparison between EPC and real energy usage could then be made.

The James Weir Building was used as an example in this section to illustrate the process in determining the annual gas consumption in terms of $kWh.m^{-2}$ for both EPCs and utility data. The equivalent figures 11 and 12 for the remaining 13 buildings under investigation can be found in appendices A - L.

3.4. Results from Comparing EPC and Utility Data

After collecting and modifying all the necessary data for the 14 buildings, figure 13 could be created for gas consumption. The dotted black line running through the origin is that which runs through all points where EPC and real data agree exactly. In other words, where the EPC is completely accurate. The various points relating to individual buildings then show the deviation in measured energy consumption from that predicted by the EPC.

The clearest result from figure 13 is that over the building stock, the EPC and measured energy consumptions do not agree. The average absolute difference, also known as the mean bias error (MBE), between EPC and measured values is **±110kWh.m**$^{-2}$ over a year. It is important to give context to any results in order to quantify and discuss their relevance. As such, [142] provides a gauge for typical energy densities associated with buildings and generation. Some of these are shown below for comparison with any results presented in this thesis:

- Passivhaus heating standard = $15kWh.m^{-2}.year^{-1}$

- Average European house energy consumption = 290kWh.m^{-2}.year^{-1}
- Typical Northern European solar farm = 44kWh.m^{-2}.year^{-1}
- London Array offshore wind farm = 22kWh.m^{-2}.year^{-1}

The mismatch between predicted and measured energy consumption is over seven times the standard for an A-rated dwelling and is the equivalent of five offshore wind farms. Such a difference is therefore very significant within the context of energy usage.

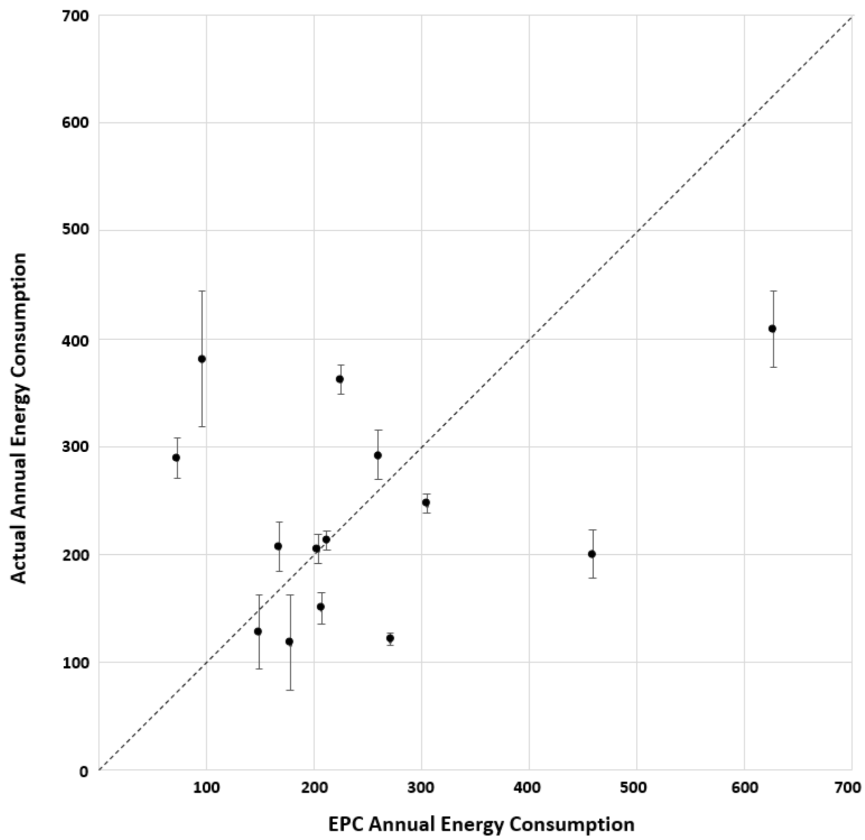


Figure 13: Annual consumption of natural gas (kWh/m^2) for 14 University of Strathclyde Campus buildings: EPC vs utility data

The average figure of 110kWh.m^{-2} does not account for the large disparity in how much the EPC differs from reality between individual buildings. A general trend can be observed whereby those buildings estimated to have very low or very high heating demands by the EPC, have very different actual consumption levels. Those with very low EPCs have had their heating demands underestimated whilst the opposite is true for those with particularly high EPCs. The buildings with average EPC energy consumption have their true loads more accurately predicted. The reason for this observation is due to the overestimated range of energy consumption between buildings as predicted by the EPCs. EPC ratings range from 73-627kWh.m^{-2}.annum^{-1} but the buildings actually consume more similar heating than their archetypes would suggest. The actual range is 118-409kWh.m^{-2}.annum^{-1}.

Another general trend regards the standard deviation (SD) of each building's actual energy consumption. The value for energy consumption fluctuates year by year and is illustrated by the error bars attached to each data point. Those buildings with a higher SD generally have a more inaccurate EPC. A useful metric is the 'specific percentage difference' (SPD) which is calculated using equation 8 where EPC and $Real$ refer to the energy consumption for space and hot water heating predicted by the EPC and the measured value as supplied by metering records respectively.

$$SPD = \frac{|EPC - Real|}{EPC} \times 100 \tag{8}$$

A breakdown of SPD values for individual buildings, as well as the absolute difference between measured and EPC energy consumption, is given by table 2. The average gas usage per building as calculated by SBEM is 245.3kWh.m^{-2}.annum^{-1} whereas the real value is found to be 237.3kWh.m^{-2}.annum^{-1}. This means that the EPC, averaged over the building stock, overestimates the gas energy consumption by only **3.3%**. Looking at such a statistic may give the false impression that the EPC is therefore very accurate however there is a range of values when comparing individual buildings. The Thomas Graham Building's EPC underestimates its space and hot water heating by almost four times whilst the Royal College Building's EPC overestimates by over twice the real value. The average SPD between true energy consumption and that predicted by the EPC for the UoS buildings under investigation is **66.5%**.

Figure 14 indicates that there is no apparent relationship between the floor area (as a proxy for overall size) of the studied buildings and their SPD. The majority of buildings have a reasonably small SPD as indicated by the cluster of points to the bottom left of figure 14. This is to be expected judging from the EPC and actual energy consumption comparison as illustrated by figure 13. Those buildings that have particularly extreme SPD values are indicated on figure 14. The John Arbuthnott and Thomas Graham buildings are denoted 'JArB' and 'TGB' respectively. These two buildings have by far the largest SPD but also the lowest EPC rating. It may be possible that there is a correlation between EPC rating and SPD value. An inversely proportional relationship as implied by these two data sets does not, however, occur when comparing the whole building stock.

Building	SPD (%)	Absolute Difference (kWh.m^{-2})
Architecture	18.9	58
Barony Hall	34.8	218
Graham Hills	27.6	57
Henry Dyer	0.3	1
James Weir	33.5	60
John Anderson	14.3	21
John Arbuthnott	296.1	216
Lord Todd	61.0	137
McCance	55.5	150
Ramshorn Theatre	12.2	32
Royal College	56.4	259
Sir William Duncan	23.3	39
Thomas Graham	296.7	285
University Centre	0.7	1

Table 2: SPD and absolute difference between EPC and measured energy consumption for selected University of Strathclyde buildings

Figure 15 shows the relationship between the floor area and absolute difference between EPC and true energy consumption values. Similarly to figure 14, no clear association between the area of the building and the inaccuracy of the EPC is indicated. Figure 15 also further emphasises the findings from figure 13. Those buildings with particularly low or high EPC ratings exhibit a greater disparity from their actual energy consumption. The John Arbuthnott ('JArB') and Thomas Graham ('TGB') buildings are once again indicated but also so too are the Barony Hall ('BH') and Royal College ('RCB') buildings. The latter two have the highest EPC heating requirement of all buildings studied and, just like those with the smallest EPC, display a large discrepancy in absolute energy consumption.

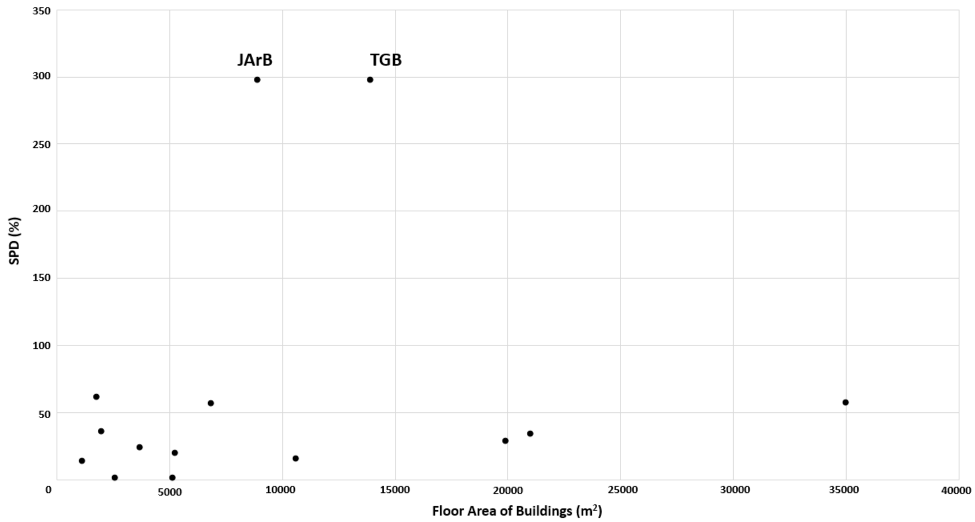


Figure 14: Relationship between the floor area of buildings and the SPD between their measured energy consumption and that predicted by the EPC

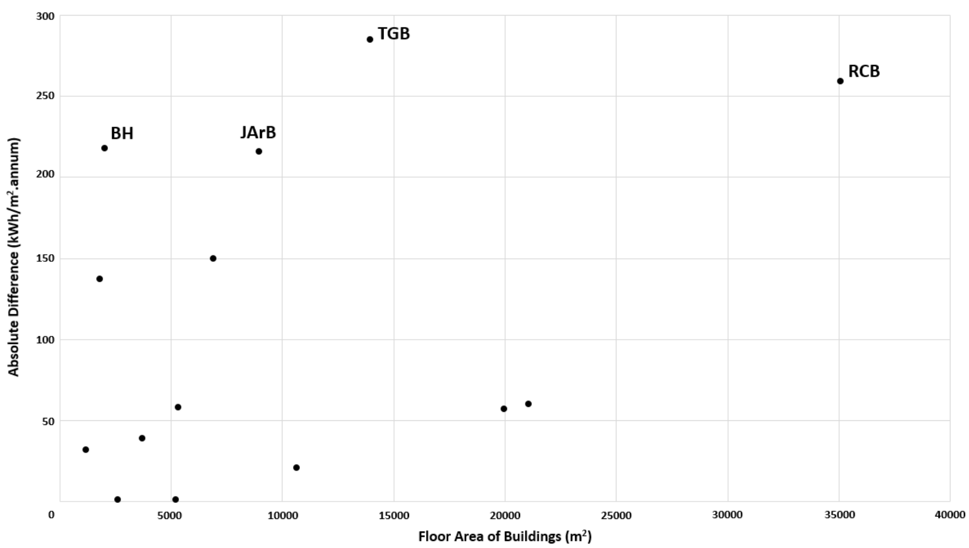


Figure 15: Relationship between the floor area of buildings and the absolute difference between their measured energy consumption and that predicted by the EPC

Figure 16 examines the relationship between the age of the buildings within the stock and their SPD. Most buildings are roughly the same age at around 50 years old. The exceptions are the Royal College Building ('RCB'), Ramshorn Theatre ('RT') and Barony Hall ('BH'). The John Arbuthnott and Thomas Graham belong in the former category of mid-20th century build so it is not apparent as to why their SPD is so large. Those clustered buildings share similar archetypes and so various assumptions will have been made for all when assessing their EPC. Both the JArB and TGB have been assigned a 'D' rating (see table 1) which is higher than the other buildings within their broad age group.

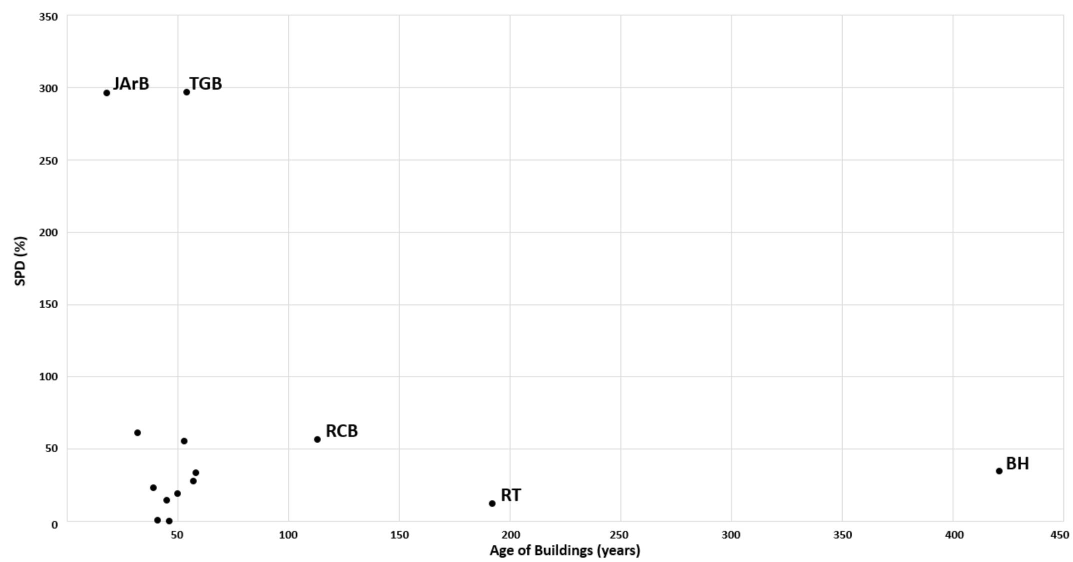


Figure 16: Relationship between the age of buildings and the SPD between their measured energy consumption and that predicted by the EPC

Figure 17 shows that the youngest (JArB) and oldest (BH) buildings have some of the highest absolute differences between EPC and actual energy consumption. There may then be a weak correlation between age and EPC accuracy. However, the Ramshorn Theatre ('RT') is far older than the majority of buildings but has a significantly more accurate EPC rating and the TGB has the highest overall difference between actual and predicted energy consumption. Overall, it must be concluded that there is a lack of substantial evidence to support a causal link between the age of the building and the disparity between calculated and measured energy for space heating consumption.

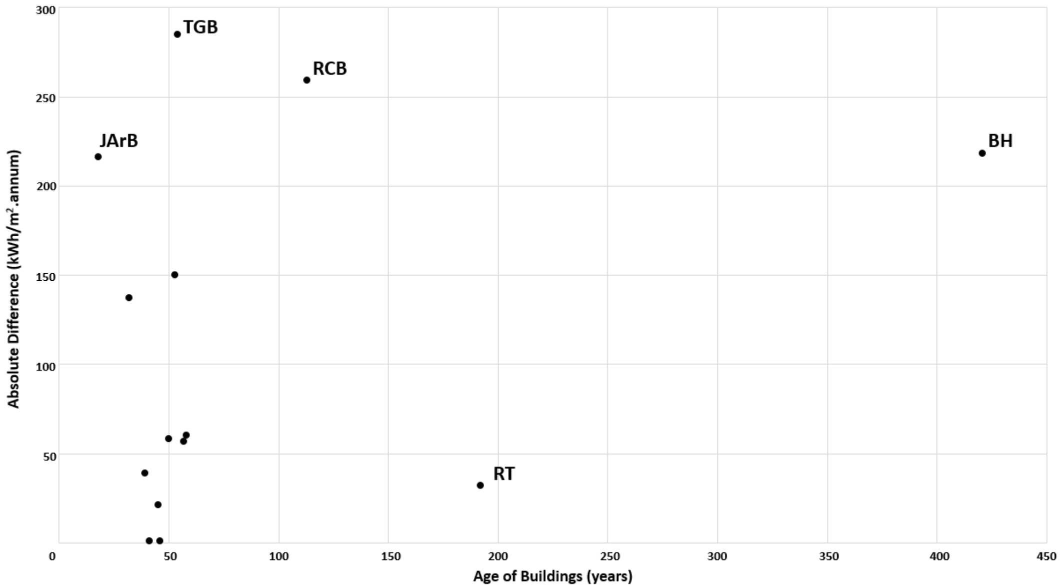


Figure 17: Relationship between the age of buildings and the absolute difference between their measured energy consumption and that predicted by the EPC

3.5. Discussion on the Comparison of EPC and Utility Data for Selected University of Strathclyde Buildings

It is stated widely in documentation from BRE that SBEM is not to be used as a design tool and its aim is not to predict actual energy consumption. Rather, it exists as a means for compliance with legislation [58]. It would therefore be naïve to expect a strong correlation between energy consumption as predicted by EPC and the true value for a given building.

The above statement is indeed found to be true from the small study detailed in this section with some buildings having a far greater EPC than others but significantly less actual gas consumption. Two buildings (University Centre and Henry Dyer) have their gas consumption predicted almost exactly by their EPC, as shown by the two points interested by the dotted line on figure 13. However, generally there is a poor match between EPC and measured energy consumption. The average difference was calculated to be 110kWh.m^{-2} per year across all 14 buildings which can also be presented as a 66.5% average difference for an individual building.

These findings are consistent with previous studies such as [46–53] which all compared EPC and true energy consumption for various types of buildings. At the core of why such differences are observed is the fact that there are a great many factors that affect actual energy performance other than just the buildings' archetype [46] which is the primary determination of EPC ratings [58].

Other reasons for differences between EPC and actual energy consumption include [111]:

- Uncertainties in modelling inputs
- Limitations in the simulation tool
- The built quality such as gaps in insulation and thermal bridges
- Usage involving the equipment and its effectiveness
- User behaviour

For the studies also comparing EPC and real data [46–53], the last of these points is most prevalent and affects the outcome the most. NCMs used to calculate EPCs assume constant occupancy profiles throughout the year [48] and ignore electrical appliance use [52], however a survey by the Better Buildings Partnership (BBP) found that occupiers can be responsible for up to 80-90% of final consumption [46]. This is particularly relevant to this project as it refers to an office environment of which all the UoS buildings studied are (see table 1).

The case study performed in this section used only 14 buildings and compared only the energy required for space and hot water heating. Other studies include electricity consumption and often analysed many more buildings, offering more conclusive results. Investigations by [43, 48, 51, 52, 54] all found that the EPC underestimated total energy usage by approximately 30% once averaged over all buildings whereas [49] found the actual energy consumption to be twice that as predicted for an office building. A survey by the Carbon Trust even found that the energy use of buildings was underestimated by a factor of 5 [50]. A very similar study to this section analysed university buildings in Zaragoza, Spain and includes electricity usage. Of the 21 university campus buildings studied, 18 had their total energy usage underestimated [48].

Although both the results presented in section 3.4 and the literature highlight an inaccuracy in EPC estimation, there are a few variations which warrant mentioning. Notably, the EPCs for the UoS buildings were split evenly between over and under-estimation (7 each) which averaged out at only a slight EPC overestimation of 3.3%. However, the average SPD across the building stock was a far higher value at 66.5% which greater captures the inaccuracy of EPC predictions. As mentioned previously, the largest reason for discrepancy in actual and calculated energy usage is the failure of NCMs to properly reflect the random nature of occupancy use. Occupancy patterns correlate strongly with electrical appliance usage which NCMs do not take account of [49]. The highlighted studies [46–52] all consider true electricity consumption and this may be the reason why the EPCs more consistently underestimate the true value. In this project, the concern is only for the differences in heating and so the occupancy assumptions used in NCMs have less of an effect on the overall result. It is also worth mentioning that the climate profiles used in this project are of course very different to that used for the Zaragoza University study [48] which ultimately drives heating consumption. The heating needs of the Zaragoza University campus would be far less than those of Strathclyde and so the difference in observed results is to be expected and this study is not ideal for comparison.

Not all studies however show strong trends towards underestimation of actual energy consumption. Indeed, the opposite is shown in [45, 143]. In [143] the measured heating consumption for Belgian residences was found to be less than that which was calculated using NCM. The reason for this was put down to the 'rebound' effect - the phenomenon of improved energy efficiency leading to increased consumption. Again, it is occupancy that is the driving force behind these differences. As [143] focuses upon residential buildings, the rebound effect is unlikely to be as potent when applied to work spaces such as the UoS buildings under study here.

The study described in [53] managed to show that SBEM could simulate a good agreement between calculation and measurement for intermittent heating for standard Cyprus dwellings. However, the heating load in such a climate only amassed to less than 25% of the total energy demand. The average for the UoS campus is a lot greater with heating demands accounting for over 72 ±12% of the total, averaged over the 14 buildings. Another study by [52] also found a good agreement between statically calculated and actual energy consumption for a Danish office block. However, this was only after various data corrections. The true space heating energy consumption was 43% higher than that calculated using initial NCM assumptions before such corrections took place.

A study by [131] showed that there was a strong relationship between the age of buildings and their energy consumption in Basel, Switzerland. Those built between 1947 and 1979, which comprised the majority of buildings, exhibited a higher average gas consumption than those built before or after. The study surmises that gas consumption has a strong correlation to age, volume and floor area. Similar findings are discussed in [144] and [145]. However, analysis of figures 14, 15, 16 and 17 revealed no clear indication of age and/or floor area being a proxy for EPC inaccuracy. It may be insightful to analyse the volume and/or compactness of the buildings as well as floor area and age. However, this information was not available from the EPC survey and was not possible to extract from aerial and satellite images. Future work would therefore possibly entail image processing of publicly available aerial and satellite images in order to determine building volume and areas and hence, compactness. Additionally, having a larger sample of building stock would aid in establishing any relationships between EPC inaccuracy and building characteristics.

3.6. Conclusion of EPC and Utility Data Comparison

A difference in results between those calculated using NCM and those supplied via utility data was expected and is the primary motivation for this project. It was found that, on average, there is a ±**110kWh.m**$^{-2}$ difference between the energy consumption (gas) as predicted by EPC and metered data. This translates as an average **66.5%** difference for individual buildings.

These results agree with that found in the literature in so much as there is a definite deficiency in EPCs accurately calculating real energy consumption. However, there are noticeable differences in the results in section 3.4 and those from previous studies. The main reason for this is the fact that this study neglects electricity consumption and thus negates the presence of severe occupancy errors. This was cited in the literature as the principle reason EPCs and measured data did not correlate well. Other key factors are that the heating loads for the UoS are far greater than those pertaining to the various literature studies, many studies examine the domestic building stock rather than commercial buildings such as the UoS campus and finally, most other studies use a far greater number of buildings in their analysis. This study is prohibited by the relatively small building stock of 14 individuals which does not allow for clear patterns or relationships to be observed.

There are some buildings (Henry Dyer and University Centre) whose calculated and measured energy consumption match almost perfectly. It is unclear as to why these buildings in particular have such matching results when other, similar buildings do not. There are too few buildings that were studied to draw any reasonable conclusions as to why certain buildings have a larger SPD than others. Examining the age and floor area did not expose any causal link in the accuracy of EPC prediction either absolute or proportional. For the purposes of this project, it is not too pertinent. There is enough evidence from this small section to conclude that the NCM is generally unsatisfactory in predicting the energy consumption of buildings.

Leading projects in building stock modelling for energy labelling (see section 2.3.5) still use NCM data acquisition and modelling practices to compute energy demands in order to inform policies and urban developments. Figure 13 indicates that even if such projects were perfect in all other aspects, the final results would likely still be poor. Dynamic simulation, even with a lower quality of input data may give more accurate results than the NCM which the following sections will investigate.

4. Dynamic Simulation for Determining Individual Building Energy Consumption

4.1. Introduction

NCMs use simplified, quasi-steady state, single-zone physics models in order to predict the energy consumption of buildings. Occupancy schedules along with lighting and equipment use are given standard usage profiles along with monthly averaged weather conditions [44]. Such models are therefore unable to adequately address temporal changes in heating demand as a result of HVAC and appliance use, occupants and solar gains and are thus incapable of reflecting the dynamism and stochastic nature of energy flows.

Section 3 highlighted how simple simulation models such as SBEM are generally inadequate in describing the complexity of energy consumption in buildings. Instead of static energy modelling, dynamic simulation can be used to predict energy performance of buildings. Within the context of energy performance, buildings should be viewed as systemic (made up of many parts), dynamic (each part evolves with time at a different rate), non-linear (conditions are determined by different thermodynamic properties) and complex in nature (a plethora of inter and intra-connected interactions) [40].

Dynamic simulation models are therefore more suitable than NCMs in accounting for functional complexities. They also allow more detailed input options and contain extensive databases of construction materials and systems [49, 120]. Additionally, NCMs use an averaged monthly calculation procedure whilst dynamic simulation can perform hourly or sub-hourly calculations, hence better capturing the true nature and profile of buildings' energy flows [120].

In the following section, the second project objective (see section 1.3) is addressed. The dynamic building simulation software ESP-r (Environmental Systems Performance - Research version) is used to model intermediate floors of a selection of UoS buildings to see whether dynamic modelling can achieve more accurate results compared to EPC estimates. Various versions of

ESP-r have been developed and improved upon since its first numerical engine was originally researched between 1974 and 1977. It is controlled by ESRU at UoS and is widely used today in industry and other research centres as a platform for exploring building system design and provides solutions for dynamic thermophysical interactions within the built environment [146, 147]. It uses the dynamic energy simulation outlined in section 2.3.3 and was thus deemed an appropriate tool for investigation.

Section 4.2 describes how different buildings were modelled. Results for the energy consumption of buildings as calculated using the project method is then presented in section 4.3. These are then compared to measured data and EPC ratings. Due to a lack of EPC information, four of the buildings that were used for results in section 3.4 could not be modelled. Results are therefore altered accordingly for the 10 remaining buildings so that a fair comparison can be made.

4.2. Methodology for Modelling Individual Building Floors Using A Combination of Data Sources

4.2.1. Introduction

The simplest means of modelling a building is to approximate it as a single thermal zone. It is important to bear in mind that the purpose of building simulation is not to exactly represent the building physically but rather to provide a mathematical description of the factors that will affect final energy consumption. In this case, those factors will only be those that affect the heat energy flows. Various simplifications with respect to the true building can hence be made.

As well as being a logical starting point in attempting to quantify the energy performance of a building, the single zone approximation is used in many energy simulation tools. Different EU counties' NCMs, for instance Denmark's, represent buildings using one thermal zone [52] whilst in the UK buildings are often modelled as several single thermal zones but take no account of thermal coupling between zones [59]. See section 2.3.2 for more details. There are many other software tools that have been developed for research and commercial uses that use one thermal zone, satisfying the needs of the specific project [30, 110, 129, 148].

Using a single thermal zone saves computation time as does limiting the temporal resolution, particularly when dealing with large building stocks. It is often due to a lack of data and information about the building stock that single zone simulation is performed [29, 30]. A method of ascribing certain accurate energy performance characteristics from façade features, courtesy of satellite images would be hugely beneficial in improving data input to building stock models.

This project is concerned with improving the data input to building stock modelling as well as the energy calculation method. The proposal is to utilise publicly available aerial and satellite images in order to extract useful information that will determine the buildings' energy efficiency. Image processing was deemed out of scope and so the extractable information was limited to the estimation of glazed area, building geometry and the solar absorption of the façade. All other information was taken from the EPC survey. If data from the EPC survey was missing or incomplete then the literature was used to make reasonable estimates. Section 4.2.2 showcases the project method for the 6th floor of the James Weir building (JWB). Sections 4.2.6 - 4.2.11 detail any deviations from the method and input parameters applied to the JWB building for the rest of the building stock. These buildings are presented in alphabetical order. An explanation of how the energy consumption for each building is calculated is then given in section 4.2.12 in order for the models to then be compared with EPC and measured data.

4.2.2. The 6th Floor of the James Weir Building as an Example of the Project Method to Individual Building Modelling

The first question that must be addressed in creating the first model is what building or part of a building should be modelled? In this instance the 6th floor of the James Weir building (JWB) was chosen. Strictly speaking the 6th floor is actually the 8th level as the building is also comprised of the basement and ground floors.

The JWB was chosen as a first model primarily on account of its simplistic physicality. The geometry of the JWB is relatively simple, being a cuboid structure. The 6th floor was chosen due to it conforming to this cuboid structure and exhibiting a rather homogeneous floor plan. The floor plan consists of mainly offices which align the outer perimeter of the floor with a corridor intersecting them. Rooms for other uses are present such as kitchens, stores, toilets, common rooms, plant rooms, meeting rooms and copier and printer rooms. Figure 18 was supplied by UoS/AECOM from the official EPC survey - the same that has provided EPC information for UoS buildings throughout this document. The colour scheme identifies where different HVAC systems are being used in each room. The combination of different HVAC elements are indicative of typical UK offices - another reason for choosing the 6th floor of the JWB.

Now that a building floor has been identified for modelling, the following building elements must be defined, which are described in the rest of this section:

- Building geometry
- Building construction
- Casual gains
- Heating and cooling systems
- Ventilation and Infiltration

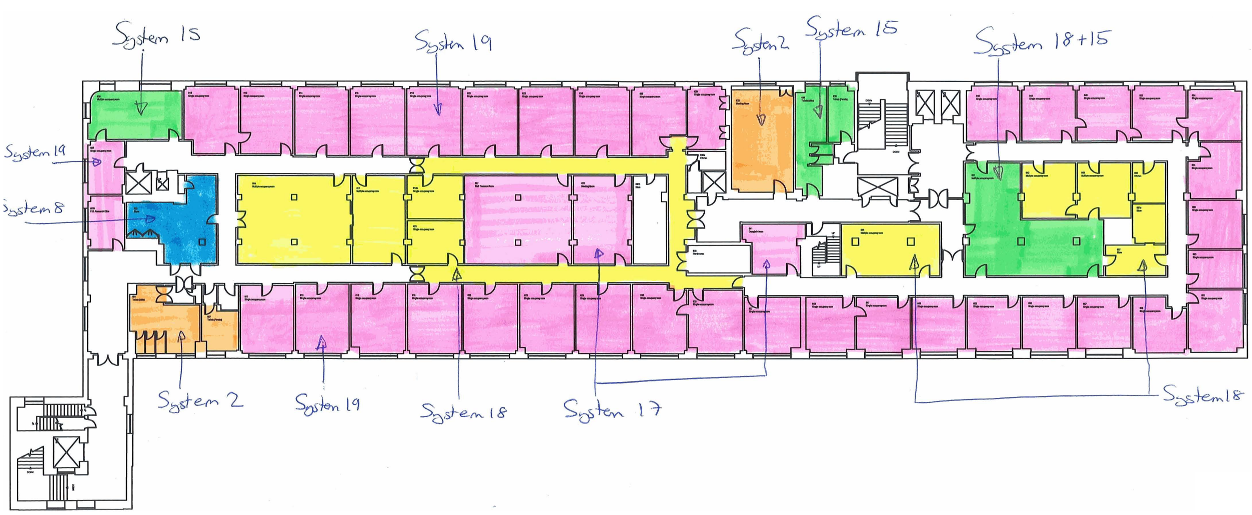


Figure 18: Floor plan of the James Weir Building, 6th floor

Geometry

The first task was to define the geometry of the floor. In order to do this, a satellite image of the James Weir was used to extract the dimensions of the building area. Figure 18 already provides knowledge about the expected rectangular shape and so only two simple measurements - length and width, were required to calculate the floor area. The stairwell shown to the bottom left of figure 18 was omitted as it added extra complications to the building model. It is well insulated against with two sets of double doors separating it from the main corridor and thus its inclusion was deemed unnecessary.

Figure 19 displays these dimensions on a satellite image of the JWB, courtesy of Google Maps. It was not possible to extract the height of the building using satellite or aerial images for this project, however this could constitute further work in the future. Instead, inside knowledge of the building floor was used to estimate the 6th floor height as being 3.5m. Looking at figures 20 and 21 of the eastern and western façades respectively, this seems a reasonable estimate. The geometry of the floor can be very simply inputted to ESP-r. The resultant input data using this method is not as accurate as using detailed floor plans as would be the case in an EPC survey. As mentioned in the project motivation though (section 1.1), this method can be used for any urban landscape where publicly accessible satellite images exist and avoids the highly precise and time-consuming process of determining the exact dimensions and geometry of a building.

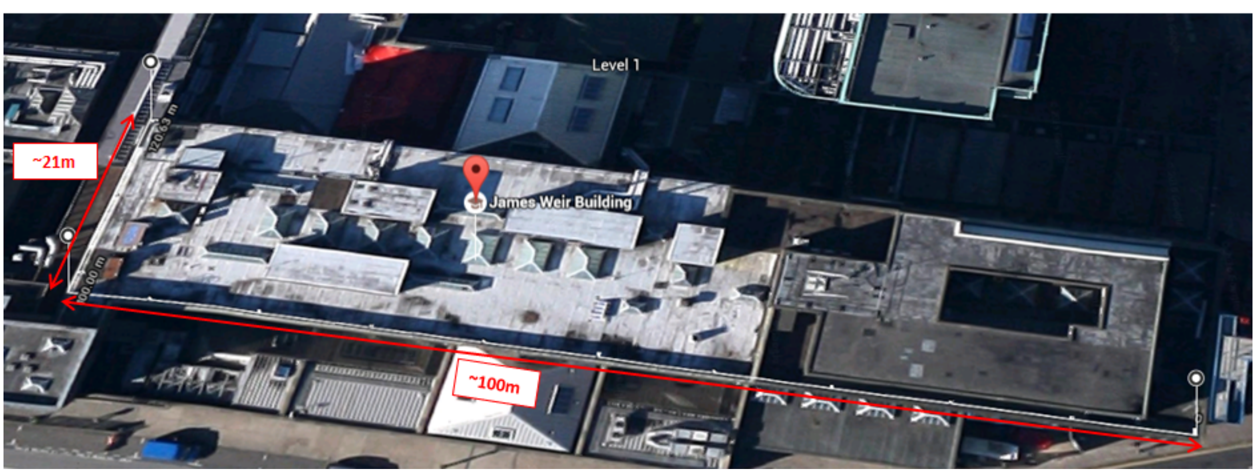


Figure 19: Satellite image annotated with James Weir Building dimensions

Construction

A building's fabric is crucial to how a building interacts with its indoor and outdoor environment. It moderates the thermal losses and gains with the external environment with much of the energy exchange between buildings and the outdoor environment taking place at the envelope interface [149]. This will affect how much heating, cooling, ventilation and lighting is required to maintain suitable health and comfort levels. The EPC survey did not include any more detailed data on the building fabric other than what is displayed in table 3. Data on insulation thickness, insulation type and the area of the fabric elements are all documented as 'unknown'.

Fabric Element	Assumed U-Value ($W.m^{-2}.K^{-1}$)	Description
External Walls	1	Cavity brick to 1966, '75, '82 building regulations
Internal Walls	1.69	Plaster – block – plaster
Window Glazing	2	Double glazed metal frame to 2002 building regulations
External Doors	2.2	Entrance and personnel doors
Internal Ceiling/Floor	2.28	Separates floors and thus ceiling and floor are equivalent. Ceiling tiles – slab - carpet

Table 3: Table of information on the James Weir Building fabric

However, ESP-r requires explicit thermodynamic properties and thicknesses of each layer of material in walls, windows, roofs and floors, including any air gaps [146]. For the single zone approximation, no wall partitions are necessary and so only the floor envelope has to be modelled. This also means that no internal windows or doors need included. This is in keeping with SBEM which also ignores internal windows and doors [115]. As the stairwell was omitted and the model is describing the 6th floor, no external door was included.

ESP-r includes a very comprehensive database for construction materials and common combinations which was used to best mirror those properties provided by the EPC survey in table 3. Despite the wealth of standard construction files made available by ESP-r, none were exactly suitable for the external walls or the ceiling/floor partition. A process of modifying standard files to better represent EPC data was undertaken using educated guesswork and information from the literature.

The EPC survey informs us that the external walls are of cavity brick construction (see table 3) and that the JWB was constructed in 1958 (table 1). The construction is concrete based however concrete has gone through some major development over the 20th century so it is important that the correct variety is selected. Aerated concrete blocks are now commonplace but not until the 1980s. Fiber reinforcement and insulation were also not regular until post-1970 and 1990 respectively. By the late 1950s, concrete technology had moved away from heavyweight and poorly insulating masses and it is therefore most likely that the concrete used for the JWB is a mediumweight block and the construction is of the form (from outdoor to indoor environments) [150, 151]:

Brick - Cavity - Mineral Fibre - Mediumweight Concrete Block - Light Plaster

This construction was based on a combination of ESP-r's common construction files and literature [152–155]. The next step was to assign thicknesses to the various layers. The thicknesses ought to be realistic and be as close as reasonably possible to the EPC assumed U-value of $1 W.m^{-2}.K^{-1}$. Various thicknesses for each wall element were trialled until the overall U-value and thicknesses appeared sensible. Equation 9 was used to calculate the overall U-value (U) where x_i and k_i are the thickness and thermal conductivity of the ith layer respectively where there are n layers. The terms h_o and h_i are the heat transfer coefficients at the outside and inside of the wall respectively. These are relatively large numbers and so their inverse becomes more or less negligible [156].

$$\frac{1}{U} = \frac{1}{h_o} + \sum_{i=1}^{n} \frac{x_i}{k_i} + \frac{1}{h_i} \tag{9}$$

The final thicknesses and other physical parameters for the external wall can be found in table 4 after the description of floor/ceiling and window constructions. Figures 20, 21 and 22 were used to assume the brickwork as being quite dark in colour. The absorptivity and emissivity could therefore be estimated. The values in table 4 are the averages between minimum and maximum absorptivities and emissivities corresponding to dark brick.

The process for defining the ceiling/floor was very similar to that for the external walls. The 6th floor is sandwiched between two similar floors and thus the ceiling acts as the foundation to the 7th. Hence, the floor and ceiling in the model could be assigned the same construction. The ESP-r databases were browsed until a construction similar to the EPC description was found. The EPC assumes the U-value of the floor to be 2.28W.m^{-2}.K^{-1} and consisting of ceiling tiles with a concrete slab and carpet above. From browsing and studying similar structures in the ESP-r database, the following construction was decided upon:

Ceiling Tiles - Concrete Slab - Cellular Rub Underlay - Carpet

These layers are ordered for the ceiling with the tiles being internal to the model. The opposite ordering was inputted for the floor. The slab was assumed to be of the same concrete as the external walls ie. mediumweight block. The thicknesses were again estimated using equation 9, the details of which along with the thermophysical properties of each layer can be viewed in table 4.

External windows are an extremely important factor in the thermodynamic character of a building. As section 2.3.3 explains, the windows for a given façade can be simply described by a single glazed area which is the sum of all the individual windows. Again, this is consistent with the methodology used by SBEM which asks for a percentage value of the wall that is glazed [59]. Aerial images of each façade (courtesy of Bing Maps) were used to estimate the glazed area of each external wall which would then be modelled as a single glazed area for each.

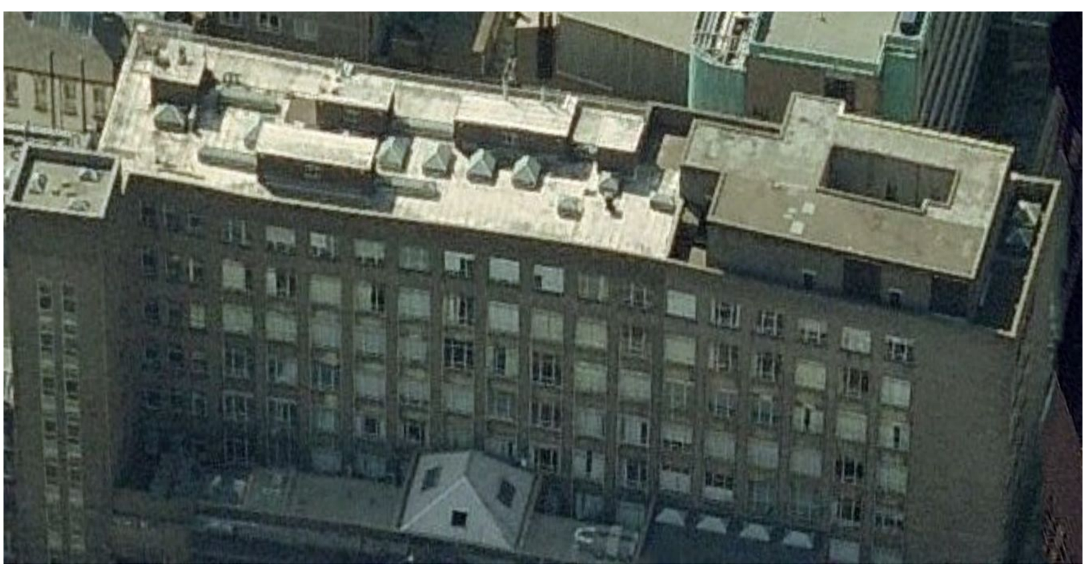


Figure 20: Aerial image of the eastern façade of the James Weir Building

Figure 21: Aerial image of the western façade of the James Weir Building

Figure 20 shows the eastern façade of the JWB. In this case, the glazed area is approximated to be 50% of the wall area. This approximation is consistent with floor plan from the EPC survey (figure 18). The aerial image of the western façade in figure 21 was used to also approximate the western fenestration as being half the façde area. The aerial images and floor plans are in decent agreement with each other for the east and west façades but there is a definite difference when analysing the southern and northern walls. According to the floor plans, roughly half the north and south walls are again glazed. However, figure 22 shows a different picture. Approximately a third of the wall surface in this case in covered by glass rather than half. The benefit of using aerial images for construction data is clear here as the source of data is more accessible and actually more accurate than that from the EPC survey. It should be noted that the large windowless tower to the right hand side of the southern façade (figure 22b) is not included in the definition of the JWB with regards to this project. This constitutes the aforementioned stairwell that was omitted from the building geometry.

The glazed area was made to originate within the centre of each wall and its length would then correspond to what proportion of the façade is glazed. A schematic of glazed area position for the east and west façades is shown in figure 23. Metal frames around the windows were specified in the EPC survey although these are rather unlikely to have any great thermophysical impact given their negligible surface area and so it was decided not to include them in the model. The EPC survey also specified the windows as having double glazing which was duly entered into ESP-r without any need for modification. The window construction was therefore:

Glass Plate - Air Gap - Glass Plate

(a) Northern façade **(b)** Southern façade

Figure 22: Aerial images of (a) northern and (b) southern façades of the James Weir Building

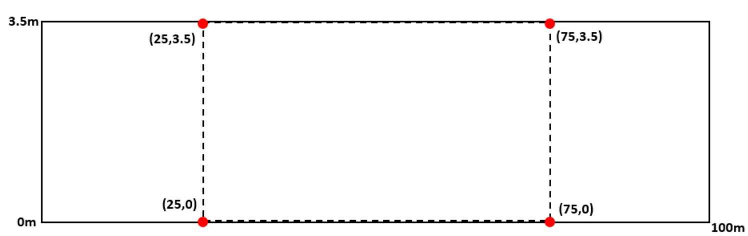


Figure 23: Schematic of modelled window area

As well as providing information on geometry and glazed surface, publicly available aerial and satellite images are immensely useful in estimating absoptivity, emissivity and albedo without the need for a survey such as one for EPCs. The absorptivity and emissivity for dark brick as estimated from figures 20, 21 and 22 were used as inputs to the ESP-r model. This is a further aspect for which image processing of public aerial and satellite images would be beneficial in building stock modelling. All values for absorptivity, emissivity, thermal conductivity, specific heat and density were taken from [157], many of which are also quoted in [40] and are readily available from the ESP-r database. Table 4 gives the thermophysical properties of each layer of the building fabric for the single zone approximation.

NB: The absorptivity and emissivity of intermediate layers are not quoted as they are not exposed to the external or internal environment.

Layer	Material	Thickness (cm)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Density ($kg.m^{-3}$)	Specific Heat Capacity ($J.kg^{-1}.K^{-1}$)	Absorptivity	Emissivity
External Wall, U-value = 0.95$W.m^{-2}.K^{-1}$, Thickness = 46cm							
1	Brick	20	0.77	1700	1000	0.7	0.9
2	Air	2	0	0	0	N/A	N/A
3	Mineral fibre	2	0.04	105	1800	N/A	N/A
4	Mediumweight concrete block	20	0.86	1970	840	N/A	N/A
5	Light plaster	2	0.16	600	1000	0.5	0.91
Ceiling/Floor, U-value = 2.29$W.m^{-2}.K^{-1}$, Thickness = 20cm							
1	Ceiling tile (white gypboard)	2	0.19	950	840	0.85	0.9
2	Mediumweight concrete slab	17	0.86	1970	840	N/A	N/A
3	Cellular rub underlay	0.5	0.1	400	1360	N/A	N/A
4	Carpet (synthetic)	0.5	0.06	186	1360	0.22	0.91
Window Glazing, U-value = 2.81$W.m^{-2}.K^{-1}$, Thickness = 2.4cm							
1	Glass plate	0.6	0.76	2710	8373	0.05	0.83
2	Air	1.2	0	0	0	N/A	N/A
3	Glass plate	0.6	0.76	2710	8373	0.05	0.83

Table 4: Table of thermophysical properties for the single zone James Weir construction

The referenced data is the best available but the quoted properties are by no means immune to scrutiny. The range of values are often limited to steady state scenarios with a lack of information supplied about the experimental conditions, equipment, procedure, assumptions and validation in acquiring the values [40, 158].

Once the geometry, construction and fenestration have been defined, a model representing the physicality and thermal mass of the building floor can be created. Figure 24 shows how the model looks once created in ESP-r.

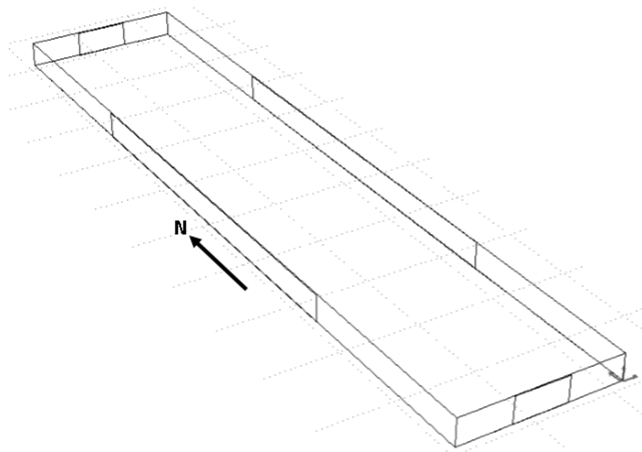


Figure 24: Wireframe view of the James Weir Building, 6th floor as modelled as a single zone in ESP-r

Casual Gains

Casual gains are an important factor in a building's energy consumption. They are a significant source of heat in addition to performing their primary task [99]. Radiation and convection from people, lighting and small power and IT equipment can act to significantly reduce the heating load and/or increase cooling requirements. These effects can be particularly potent in non-domestic environments where there is a high density of people, lighting and IT equipment [40].

Casual gains are very temporally dependent and so in order to acknowledge this, a variety of schedules must be included in the ESP-r model. The behaviour of building occupants can be simplified into two distinct aspects: when and how many people occupy the zone and how they interact with building devices such as the lighting and IT equipment [159]. The 6th floor of the JWB is an office environment with regular working patterns and so it was assumed that people would only be in the building between the hours of 09:00 and 17:00 on weekdays (Monday - Friday) and there would be zero occupancy outwith these times. The lighting and IT equipment exist to serve the needs of the occupants and so it was further assumed that their respective heat gains would be in keeping with the occupancy schedule. In effect, the stochastic nature of occupancy behaviour has been eliminated in a very crude manner. This is obviously not an entirely accurate representation of the casual gain regimes but is a necessary and justifiable simplification based on the available information. The technique of using constant occupancy profiles throughout the year was also used in related studies [48, 49]. More sophisticated means of eliminating occupancy diversity is given by [159–161] and an overview of such models is given by [162].

Figure 25 is an annotated version of figure 18 depicting where different room uses are situated. It is included as a reference point for table 5 which gives the breakdown of occupancy for each room. The occupancies for each room type are aggregated to produce the total according to the EPC survey.

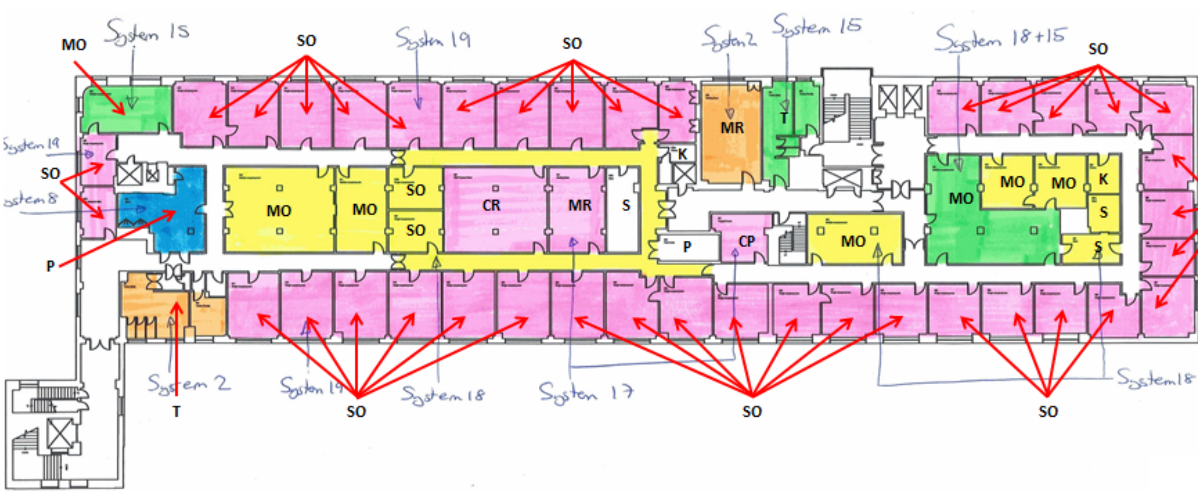


Figure 25: Annotated floor plan of the James Weir building, 6th floor

In a single zone approximation, the different room types are no longer relevant. The sum of all occupants in each room was then assumed to be evenly distributed over the whole floor. Equation 10 is used to find the total casual gains on account of people's occupancy, Q_{CO}, which is modelled as a constant source of thermal energy between the scheduled occupancy hours.

$$Q_{co} = O(Q_{SH} + Q_{LH}) \tag{10}$$

Room Type Key	Room Type	Aggregated Occupancy	Occupancy Pattern
SO	Single Occupancy Office	30	NCM
MO	Multiple Occupancy Office	38	NCM
T	Toilets	0	NCM
MR	Meeting Room	0	NCM
P	Plant Room	0	NCM
CR	Common Room	2	NCM
K	Kitchen	0	NCM
CP	Copier and Printer Room	0	NCM
S	Store	0	NCM

Table 5: Table of information on the occupancy of rooms in the James Weir building, 6th floor

Where O is the total number of people, Q_{SH} the sensible heat gain per person and Q_{LH} the latent heat gain per person. According to the ASHRAE (American Society for Heating, Refrigerating and Air-conditioning Engineers) Fundamentals Handbook 2001, the average sensible heat gain for an adult working in an office is 70W and the latent is 60W [163]. These numbers are statistical averages and are widely used in literature [48, 164, 165].

Using the values of 70W for Q_{SH} and 60W for Q_{LH} and the fact that there is an average of 70 people on the floor, the sensible and latent heat gains from people was easily calculated. Between the hours of 09:00-17:00 from Monday to Friday, the sensible heating was set at 4900W and the latent at 4200W. Outwith these hours the casual gains from people is set to zero.

Lighting can take up a significant portion of a building's overall energy use, rising as high as 40% of the total in some office buildings [166]. In the JWB, lighting makes up 17% of the total not including electrical appliances (see figure 12). Different lamp types have very different casual gain characteristics. For example, only around 8% of the energy output from incandescent bulbs is visible light. Fluorescent and LED (light emitting diode) lights are more efficient but still only around 21% of their energy output is visible light, the remaining being given off as heat [167].

Relatively comprehensive information was provided by the EPC survey and is detailed in table 6 for the whole JWB. The values for the power of each lamp is the product of the supply power and the lamp's efficiency. In terms of control, the use of a passive infrared controller (PIR) means lighting will be automatic based on the occupancy of its area of detection.

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	2239	Manual Switch
Fluorescent	28	141	Manual Switch
Fluorescent	65	116	Manual Switch
Fluorescent	58	849	PIR/Manual Switch
Fluorescent	125	66	Manual Switch
Fluorescent	70	354	Manual Switch
Fluorescent	14	182	PIR/Manual Switch
Fluorescent	35	201	Manual Switch
Fluorescent	36	394	Manual Switch
Compact Fluorescent	40	309	PIR/Manual Switch
Compact Fluorescent	26	373	PIR/Manual Switch
Compact Fluorescent	42	7	PIR/Manual Switch
Incandescent-Halogen	35	201	Manual Switch
Incandescent	100	2	Manual Switch
Metal-Halide	200	67	Manual Switch

Table 6: Table of information on electrical lighting in the James Weir building

The casual gains from lighting was defined in a very similar way to that of people. Table 6 displays the wattage and number of fittings for the whole JWB. There is no information on how the different lamp types are distributed throughout the building and so it was assumed that each floor shares the same proportion of the total wattage. Lighting only has sensible heating gains and so equation 11 can be used to calculate this value, Q_{cl} for any of the buildings in the EPC survey.

$$Q_{cl} = \frac{\sum_{i=1}^{n=l} P_i . f_i}{F} \tag{11}$$

Where P_i is the output power of lamp type i and f_i is the number of fittings for that lamp type, with there being l lamp types. F is the number of floors in the building which for the JWB is 8. Using the values from table 6, Q_{cl} was calculated to be 25102W which followed the exact same schedule as the occupancy of people.

The EPC does not take account of electrical appliance use therefore no information was provided in the survey. However, sensible heating from IT equipment will affect the heating load and so must be included in the ESP-r model. Studies have shown that heat gains from standard office equipment can be generalised [168] however there are a large amount of assumptions that must be carried out.

Firstly, there is the question of what office equipment is present. When no other information is present, there are basic assumptions that can be made as to the quantity and type of office equipment [169]. In this case, it is assumed that every person has their own desktop computer with monitor and also that there is a laser printer present for both the east and west sections of officespace. The 2001 ASHRAE Fundamentals Handbook [163] accumulates heating gain guidelines from studies such as [170] and it is from there that the estimated casual gains from IT equipment was taken. Table 7 displays the generalised values for computers, monitors and laser printers when in operation and in idle/energy saving mode.

Equipment	Continuous Use Heat Gain (W)	Continuous Use Heat Gain Density ($W.m^{-2}$)	Idle Use Heat Gain (W)	Idle Use Heat Gain Density ($W.m^{-2}$)
Computer	65 (55 – 75)	0.031 (0.026 – 0.036)	25 (20 – 30)	0.012 (0.001 – 0.014)
Monitor	70 (50 – 80)	0.033 (0.024 – 0.038)	0	0
Printer	550	0.262	125	0.06

Table 7: Table of casual heat gains from assumed office equipment in the James Weir building, 6th floor

Low and high values are shown in brackets whilst the value used in the model is given outside the parentheses. The used value is roughly the average of the low and high bounds in each case though is described as a ‘conservative’ value by [163]. Values of energy density are quoted using the floor area of $2100m^2$ which is used for estimating other building’s IT use. Equation 12 is used to calculate the total casual heat gains from equipment Q_{ce} in the single zone.

$$Q_{ce} = O(Q_{comp} + Q_{mon}) + 2Q_{pr} \tag{12}$$

Where O is the number of occupants, each of which are assigned one computer and one monitor. The sensible heating load from each computer and monitor is denoted Q_{comp} and Q_{mon} respectively and Q_{pr} corresponds to that from a single printer.

It is assumed that all equipment is left idle/in energy saving mode during weekends, holidays and out of normal working hours. Continuous usage will occur between the hours of 09:00 and 17:00 on weekdays, in keeping with the occupancy schedule. Figure 26 gives the total casual gains for when each respective source is non-zero (and thus at its maximum) ie. 09:00 - 17:00 during weekdays for people, lighting and IT equipment and idle IT equipment for all other times. It is clear that lighting dominates the casual heat gain load.

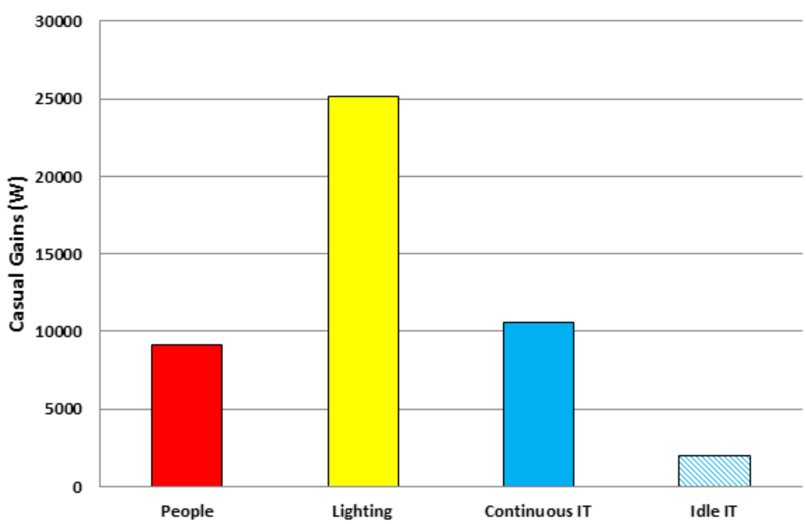


Figure 26: Maximum casual gains from people, lighting and IT equipment on a weekday for the James Weir building, 6th floor

Systems

Some information on the systems was also provided from the survey which is displayed in table 8. The timing set-points displayed are those assumed in the SBEM calculations and are only available for heating. No temperature set-point is given but this is assumed to be 19°C, as advised in the SBEM database [171]. For this investigation, only the heating times are required. System 19, supplying heating and ventilation to the offices is most prevalent. The local ventilation and core heating systems are less dispersed as would be expected. The heating systems provide for a far greater area than the ventilation systems and also provide the hot water. All the systems will affect the energy performance of the building however in terms of consumption, this project is only interested in that which is supplied by gas - systems 2 and 15.

System	Function	System Area (m^2)	Weekday Start	Weekday End	Weekend/Holiday Start	Weekend/Holiday End
2	Heating	3384	06:00	18:00	Off	Off
8	Split Air Conditioning	271	N/A	N/A	N/A	N/A
15	Heating	1563	06:00	18:00	Off	Off
17	Local Ventilation	117	N/A	N/A	N/A	N/A
18	Local Ventilation	861	N/A	N/A	N/A	N/A
19	Local Ventilation and Heating	875	06:00	18:00	Off	Off

Table 8: Table of information on mechanical systems present on James Weir, 6th floor

Section 3.4 already explained why only gas consumption was to be investigated in this project. It is therefore apparent that the heating system must be included in the ESP-r model. It is less obvious however as to whether the cooling systems ought to be included also. A synoptic analysis of the weather file, using a heating set-point of 19°C and a cooling set-point of 25°C, revealed that there were no typical weeks requiring both cooling and heating. Altering these set-points slightly showed that there was a small overlap during some summer weeks but overall the influence of cold air would be negligible on the yearly heating load. Figure 12 also reveals that cooling only comprises 2% of the total JWB energy consumption. Therefore, its usage would only be used on rare occasions and never within a short time frame of the heating system. The inclusion of mechanical cooling was disregarded for all subsequent building models for the same reasons.

Table 8 shows that there are three systems dedicated to space heating (systems 2, 15 and 19) but 19 is supplied by electricity. Systems 2 and 15 were combined into one aggregate heating system for the single zone approximation with the same control scheme. An ideal heating control was adopted as it is the most simple means of representing the central heating system and can easily incorporate the heating schedule. An ideal control system has no time lags in thermostat response, transport of fluid or machinery action. It requires a sensor and actuator to be defined which are simply placed at the zone's air node along with a heating schedule, capacity and set-points [146]. The heating schedule was specified in the EPC survey as being from 06:00 - 18:00 during weekdays all year round and so this was adopted for the model under discussion. The rest of the time, the heating control is off and the indoor temperatures are simply free floating. A temperature set-point of 19°C was used meaning that radiators would be switched on if the indoor temperature is below this value between the hours of 06:00 - 18:00 on weekdays.

Ventilation and Infiltration

ESP-r allows for ventilation and infiltration of air to either be modelled as a mechanical system with periodic operation, similar to the heating system previously described, or an air mass flow can be imposed upon the building and/or zone. The latter of these options was chosen as there was great uncertainty in ventilation system parameters to justify using in-depth and more sophisticated modelling techniques which are out of this project's scope. The act of imposing an approximate air infiltration rate is often acceptable practice, particularly for purposes of gleaning information on overall energy output [122]. In effect, the infiltration rate has been modelled as climate independent which is the opposite of reality [122, 172, 173].

The imposed infiltration rate will need to incorporate the mechanical ventilation, as highlighted by systems 17, 18 an 19 in table 8, as well as the natural. Standard air mass flow rates have been established based upon what is acceptable and appropriate for humans doing particular activities [172]. For an office environment, an air change rate of 2-6AC.hr^{-1} is regularly cited [121, 171, 174–177]. The average value of 4AC.hr^{-1} was chosen for the JWB 6th floor model which is equivalent to roughly 10L.s^{-1} per person and includes both mechanical and natural ventilation. Mechanical ventilation is only required when people are present and so the value of 4AC.hr^{-1} was only imposed for the hours between 09:00 - 17:00 on weekdays. The remaining times were all subject to natural infiltration which was set at 1AC.hr^{-1}, which is quoted as a typical air infiltration allowance by [177].

4.2.3. Modelling the 3rd Floor of the Architecture Building

Figure 27 shows the satellite image used to extract the Architecture building's (AB's) floor area. There are noticeable grooves and irregularities on the north and south façades however it was decided that these were to be ignored. The floor area could therefore be approximated as a simple rectangle.

Figure 27: Satellite image annotated with architecture building dimensions

The description of the AB's fabric from its EPC survey is near-identical to that of the JWB and so the construction could be easily applied using table 4. The only difference is that the glazing is stated as being single rather than double. One glass pane, the same that were used for the JWB, therefore sufficed for window construction. The area of single glazing could then be accounted for using aerial images. The images in figure 28 were used to estimate the glazed surface as being half the area of the southern and northern façades whilst only a quarter for the eastern and western. Figure 29 then shows the wireframe view of the AB as modelled in ESP-r.

(a) Northern façade

(b) Southern façade

(c) Eastern façade

(d) Western façade

Figure 28: Aerial images of the (a) northern, (b) southern, (c) eastern and (d) western façades of the architecture building

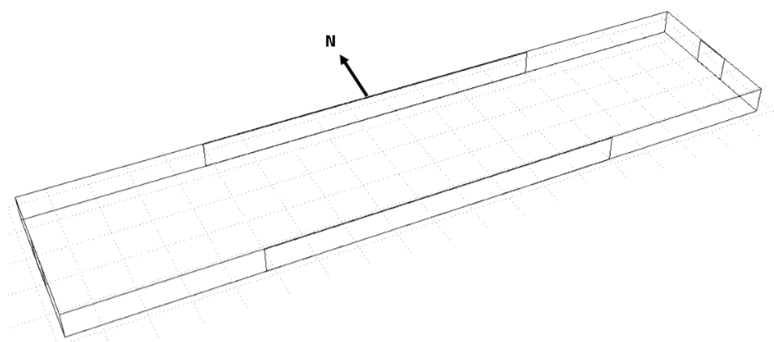


Figure 29: Wireframe view of Architecture Building, 3rd floor as modelled as a single zone in ESP-r

The number of occupants and amount of lighting was estimated in the same way as section 4.2.2. Occupancy and lighting tables, equivalent to tables 5 and 6 can be found in appendix M. The same casual gain schedules were assumed for the AB as the JWB and equations 10 and 11 were used to calculate the heat gains from people and lighting respectively. An amendment was made to 12 in calculating the sensible heat gain from IT. As with the JWB, it was assumed that each occupant was assigned one desktop computer and monitor but for the printers, it was decided that an area ratio between the JWB and all subsequent buildings would be used. The modified equation for calculating equipment heat gains, Q'_{ce} now becomes:

$$Q'_{ce} = O'(Q_{comp} + Q_{mon}) + 2Q_{pr}.\frac{A'}{A} \tag{13}$$

Where those symbols appearing in 12 previously, retain their meanings. O' is the occupancy of the new building under question and A' is its floor area. A is the floor area of the JWB 6th floor. In effect, a constant number of W.m^{-2} is assumed for all buildings.

The EPC survey offers no indication of heating schedules, simply marking them as unknown. However, figure 30 indicates that there are clearly mechanical systems in use. These systems relate to heating and ventilation and so operations of these must be inputted to the model. The floor area of the AB is similar to that of the JWB (1932m^2 and 2100m^2 respectively) as is their use. Therefore it was assumed that the heating and ventilation would exactly mirror that used in the JWB model. Heating was set to be in operation between 06:00-18:00 during weekdays with a set-point of 19°C and simply free floating out of these times. An infiltration rate of 4AC.hr^{-1} was imposed at times of occupancy, that being between 09:00-17:00 on weekdays. For hours outside this period, 1AC.hr^{-1} was imposed.

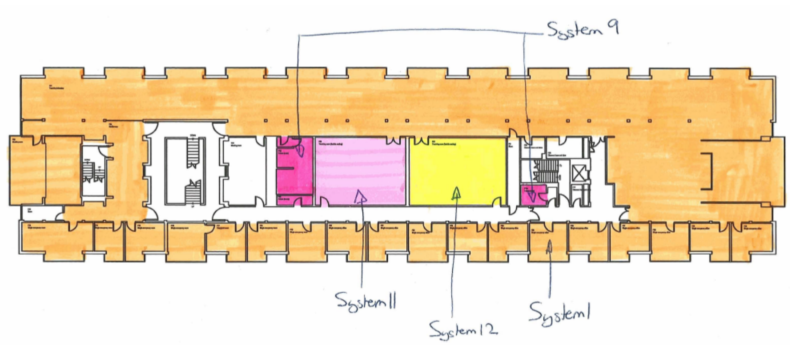


Figure 30: Floor plan of the Architecture Building, 3rd floor

4.2.4. Modelling the 6th Floor of the Graham Hills Building

The geometry of the Graham Hills building (GHB) is a lot more irregular than the JWB and AB previously, as the floor plan in figure 31 shows. Nonetheless, a satellite image as presented by figure 32 was used to measure the required lengths for defining the ESP-r model geometry. The construction, as defined by the EPC survey, was the same as that used for the AB ie. table 4 with single glazing. Aerial images shown by figure 33 then depict northern, southern, eastern and western aspects for glazed area and solar absorption value extraction. The northern, southern and eastern façades were estimated to have approximately half their area covered by glazing whilst the western was assigned a third. Due to the GHB having internal enclosed areas with walls facing each other, glazing was also estimated for these. Figure 34 then shows the GHB as modelled in ESP-r, taking account of the geometry and glazed areas.

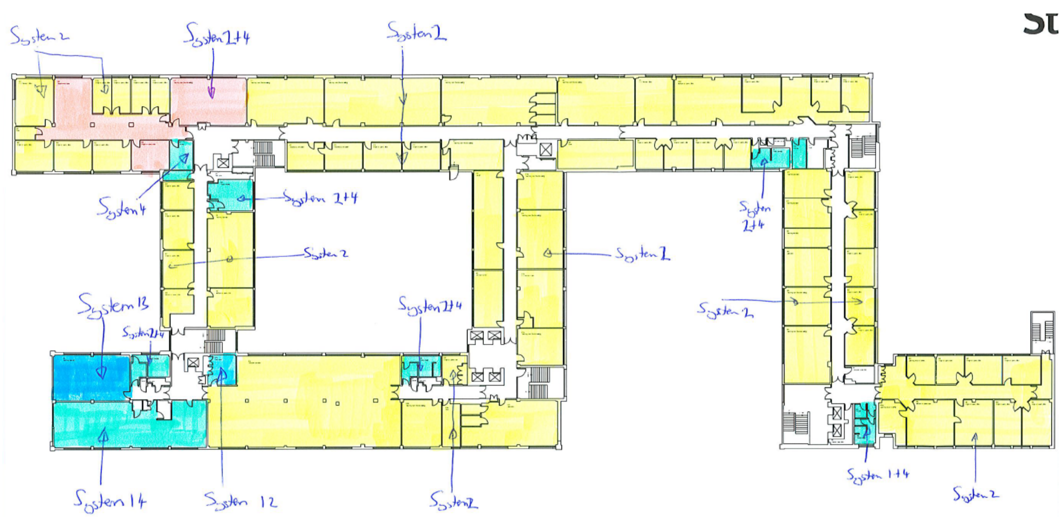


Figure 31: Floor plan of the Graham Hills Building, 6th floor

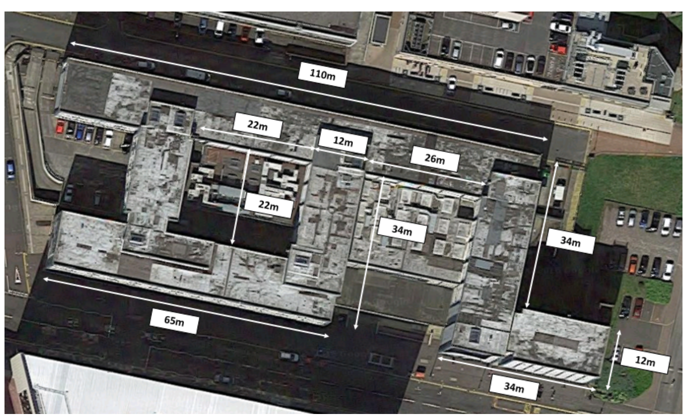
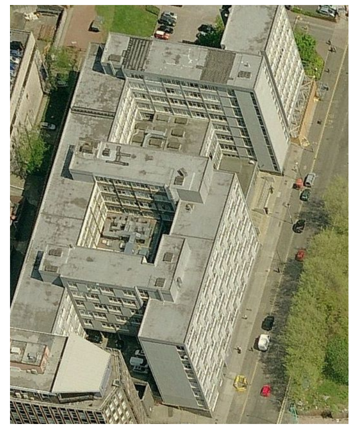


Figure 32: Satellite image annotated with Graham Hills Building dimensions

(a) Northern façade

(b) Southern façade

(c) Eastern faąde



(d) Western façade

Figure 33: Aerial images of the (a) northern, (b) southern, (c) eastern and (d) western façades of the Graham Hills Building

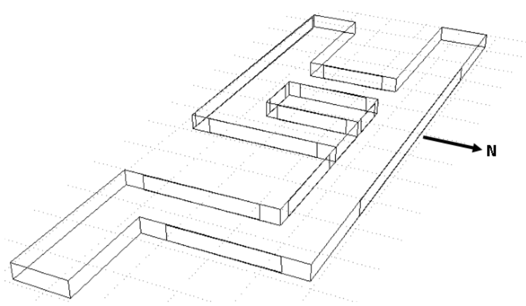


Figure 34: Wireframe view of Graham Hills Building, 6th floor as modelled as a single zone in ESP-r

The GHB has heating systems operational on weekends as well as weekdays according to its EPC survey. On weekdays, heating is said to be from 08:00-21:00 whereas on weekends this slightly reduces to 09:00-21:00. Without any information to suggest otherwise, a set-point of 19°C was again assumed. The need for heating on weekends implies that the building is occupied. As such, the standard occupancy, lighting and IT schedules and casual gains as calculated by equations 10, 11 and 13 also apply to weekends. The loads for each is likely reduced compared to weekdays but without any further data, it was assumed that people would occupy the building from 09:00 - 17:00 on all days of the week and use the same amount of electrical equipment and lighting. Occupancy and lighting tables for the GHB can be found in appendix N. The extra occupancy also has an effect on the required ventilation. Mechanical ventilation will be needed when people are present and so an infiltration rate of 4AC.hr^{-1} from 09:00 - 17:00 was enforced for weekends too, mimicking the weekday schedule.

4.2.5. Modelling the 2nd Floor of the Henry Dyer Building

The description of the construction for the Henry Dyer Building (HDB), supplied by its EPC survey was exactly the same as that of the JWB and thus table 4 could be used as inputs to the model. Satellite (figure 35) and aerial (figure 36) images were, as ever, used to define the geometry and fenestration respectively. Only northerly and southerly aspect aerial images are presented as these are better placed to estimate the total east and west facing glazed area. Aerial images from the east and west are obstructed by neighbouring buildings. As such, all façades other than the eastern were deemed as only having a quarter of their area covered by windows. The eastern façade was assigned half of its total area as glazing. This is due to the 26m long section (see figure 35) having near all of its eastern-facing wall covered by windows. The aerial images were additionally used to check that the solar absorption of the façades was similar to those quoted in table 4. The information on geometry, construction and fenestration was compiled to produce the ESP-r model given by figure 37.

Heating is timed to come on during weekends as well as weekdays according to the EPC survey. On weekdays, heating is from 08:00-21:00 and on weekends from 09:00-18:00. In a similar way to the GHB model, occupancy of people was assumed to be non-zero over weekends on account of timed heating being present. People were assumed to fully occupy the floor between the hours of 09:00-17:00 for all days of the week at which times they would also use lighting and equipment. Sensible heating from lighting use was set to zero for times outwith this range whereas IT equipment was set at the idle value. Equations 10, 11 and 13 were used to quantify these casual gains. The number of occupants can be taken from table 14 in appendix O which also contains information on the HDB's installed lighting.

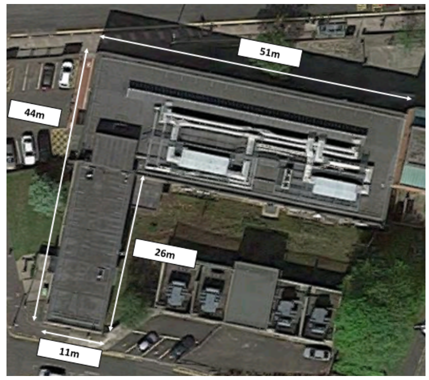


Figure 35: Satellite image annotated with Henry Dyer Building dimensions

(a) Northern façade

(b) Southern façade

Figure 36: Aerial images of the (a) northern and (b) southern façades of the Henry Dyer Building

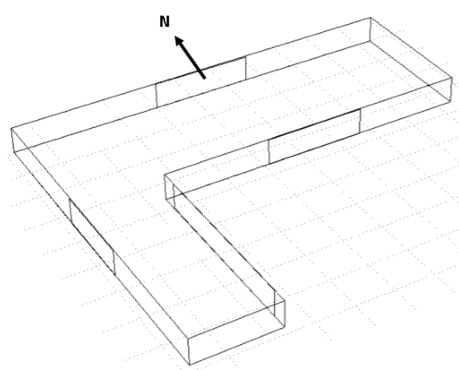


Figure 37: Wireframe view of the Henry Dyer Building, 2nd floor as modelled as a single zone in ESP-r

The weekend occupancy calls for additional ventilation. The mechanical ventilation was modelled as constant forced infiltration in the same way as described in section 4.2.2. This took the form of 4AC.hr^{-1} between the hours of 09:00-17:00 on all days of the week and 1AC.hr^{-1} at all other times.

4.2.6. Modelling the 7th Floor of the John Anderson Building

Only minor adjustments to the data input was required in modelling the 7th floor of the John Anderson building (JAB) compared to the 6th floor of the JWB. The geometry was sourced from a satellite image (figure 38) and simplified to a rectangular floor area for modelling. The EPC survey floor plans (figure 39) show this isn't quite true but the extrusions on the south-west and north-east sides of the building are approximated to be negligible for this study. The construction details in the EPC survey are identical to that shown in table 3 with the exception that the windows are single glazed instead of double. From figures 40a, 40b, 40c and 40d, it was approximated that the glazed area of each façade was a third of the surface area. A wireframe image of the JAB as modelled in ESP-r is shown in figure 41.

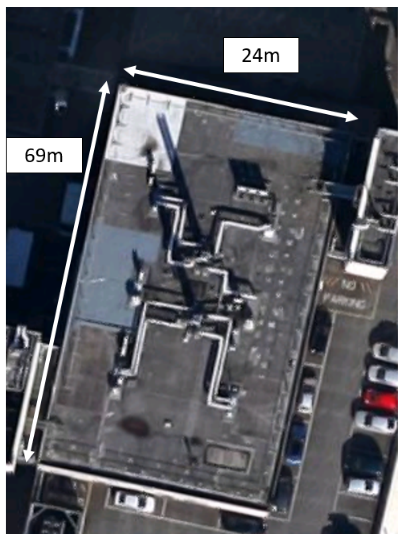


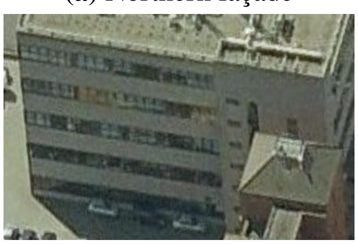
Figure 38: Satellite image annotated with John Anderson Building dimensions

Details on the occupancy of rooms on the 7th floor as well as lighting was available from the EPC survey. These can be viewed in appendix P. The usual equations, 10, 11 and 13, were used to quantify the casual gains from people, lighting and IT equipment respectively. Occupancy schedules were assumed to be the same as in the JWB building in section 4.2.2, that being maximum capacity between 09:00-17:00 on weekdays. Lighting and IT equipment use, along with ventilation, then followed this same schedule.

Figure 39: Floor plan of the John Anderson Building, 7th floor

(a) Northern façade

(b) Southern façade



(c) Eastern façade

(d) Western façade

Figure 40: The (a) northern, (b) southern, (c) eastern and (d) western façades of the John Anderson Building

Figure 39 shows the various HVAC systems installed on the floor. The heating time-settings is said to be from 06:00 - 21:00 as detailed in the EPC survey. A heating set-point of 19°C was again chosen, on account of no other information being available.

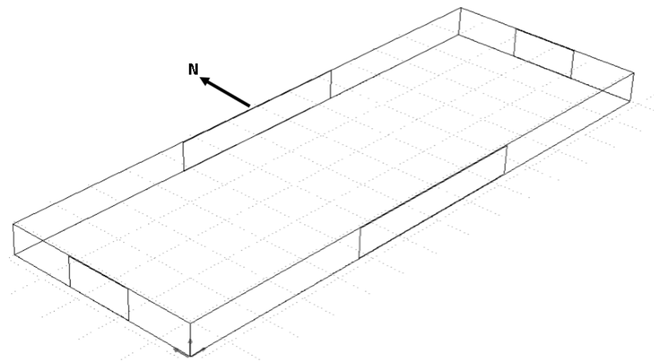


Figure 41: Wireframe view of the John Anderson Building, 7th floor as modelled as a single zone in ESP-r

4.2.7. Modelling the 5th Floor of the John Arbuthnott Building

The John Arbuthnott building (JArB) was constructed in 1998 and so is far younger than the other buildings in the stock (see table 1). As expected, its construction, as described in its EPC survey, is noticeably different from that displayed in table 4 which refers to the JWB (and others), built in 1958. Its construction is still described as a cavity wall but now to 1997 building regulations and with a reduced U-value of $0.55W.m^{-2}.K^{-1}$.

A combination of literature, EPC information and ESP-r common construction files was used to determine the exact materials that are likely to make up the JArB's external walls. As the construction year is later than for the JWB, the concrete used is likely to be more insulating [150, 151]. Hence, lightweight concrete was selected rather than the mediumweight used for previous building constructions. Equation 9 was then used to arrive at sensible layer thicknesses that would give the EPC U-value. The final thermophysical construction properties for the external walls of the JArB is given in table 9 where the values for thermal conductivity, density, specific heat, absorptivity (though compared with aerial images) and emissivity are taken from [40]. The ceiling/floor was described as in section 4.2.2 for the JWB, however it was decided to replace the concrete with that highlighted in table 9.

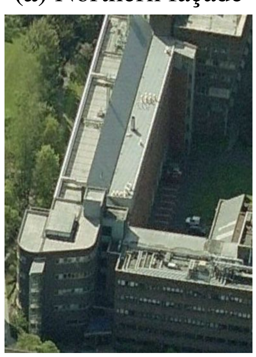
The windows are double glazed and aerial images, as shown by figure 42, were used to estimate the northern and eastern façades having half their surface area covered by glazing, the southern to have three quarters covered and the west only a quarter.

External Wall, U-value = 0.55W.m^{-2}.K^{-1}, Thickness = 48cm							
Layer	Material	Thickness (cm)	Thermal Conductivity (W.m^{-1}.K^{-1})	Density (kg.m^{-3})	Specific Heat Capacity (J.kg^{-1}.K^{-1})	Absorptivity	Emissivity
1	Render (cement/sand aggregate)	2	0.57	1860	840	0.73	0.93
2	Brick	20	0.77	1700	1000	N/A	N/A
2	Air	5	0	0	0	N/A	N/A
3	Mineral fibre	5	0.04	290	800	N/A	N/A
4	Lightweight concrete block	15	0.64	1660	840	N/A	N/A
5	Light plaster	1	0.16	600	1000	0.5	0.91

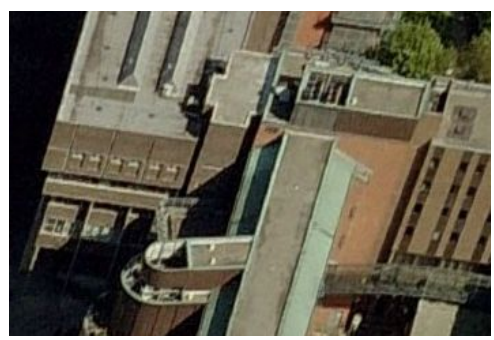
Table 9: Table of thermophysical properties for the external walls of the single zone John Arbuthnott Building

(a) Northern façade

(b) Southern façade



(c) Eastern façade



(d) Western façade

Figure 42: Aerial images of the (a) northern, (b) southern, (c) eastern and (d) western façades of the John Arbuthnott Building

The floor plan in figure 43, as well as highlighting the use of HVAC systems, shows a relatively complex geometry with a curved easterly wall and obscure variations. It was decided that the curved feature would be simplified as straight edged and the exposed irregularities amalgamated into a simple rectangular shape. Dimensions of the building's simplified rectangular geometry was extracted from the satellite image in figure 44. Together with the aerial images, it was used to create the ESP-r model as shown in figure 45.

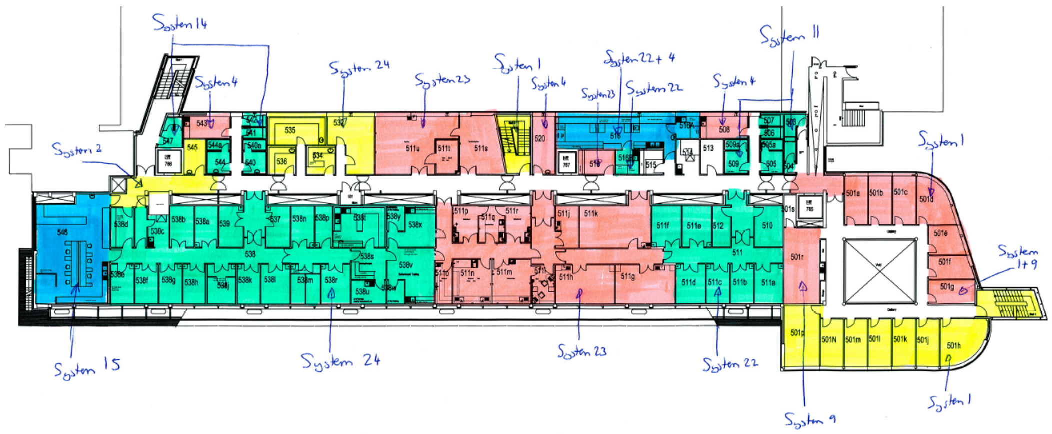


Figure 43: Floor plan of the John Arbuthnott Building, 5th floor

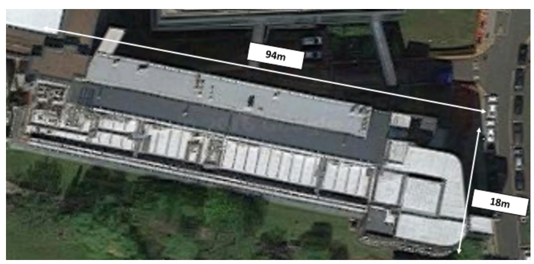


Figure 44: Satellite image annotated with John Arbuthnott Building dimensions

The heating is stated as being operational at all times in the JArB from 00:00-24:00 on all days of the week. This schedule was applied in the ESP-r model with the usual set-point of 19°C. Rather than this heating schedule from the EPC survey suggesting greater occupancy, it was assumed that occupancy would be limited to weekdays only from 09:00-17:00. At these times, casual gains from lighting and IT equipment would be at their maximum. IT equipment would be at a reduced idle level out of this time range. A breakdown of occupancy in different room types on the 5th floor was not available from the EPC survey and thus, no table is presented in the appendices. However, a total occupancy number was still available as input to equation 10 for calculating the sensible and latent heat gains from people. Casual gains from IT equipment and lighting were calculated using equations 13 and 11 respectively with a table for the latter presented in appendix Q. Ventilation was made to follow the same schedule and with the same magnitudes as detailed in section 4.2.2.

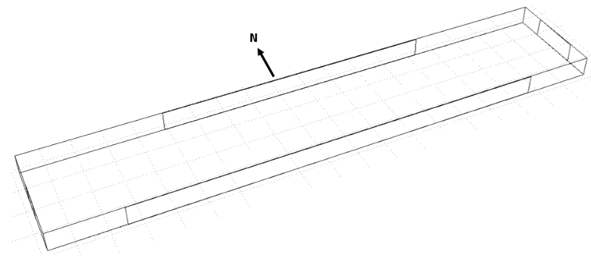


Figure 45: Wireframe view of John Arbuthnott Building, 5th floor as modelled as a single zone in ESP-r

4.2.8. Modelling the 4th Floor of the McCance Building

Following the same procedure as previous, the geometry for the McCance building (MB) was extracted from a satellite image, shown by figure 46. The shape of the MB is slightly more complicated than most other buildings but simple to model. The first two floors are rectangular but then the remaining three are in a rigid horseshoe-like shape. As the majority of floors are this latter shape and these three higher floors are mainly used as office space, it was decided that this geometry would be modelled. Figure 47 shows this horseshoe floor plan as taken from the EPC survey.

The construction materials from the EPC survey are the exact same as for the JWB but with single glazed windows. The most involved difference in modelling the MB comes in the form of glazing. The more unusual shape means that there are now 8 façades rather than 4. Not all of these require glazing to be modelled on them though. As section 2.3.3 explains, the total area covered by glass facing one orientation can be amalgamated into one larger area. However, there are two walls facing east and west respectively which face each other and so a further two glazed areas will need estimated. The north and south facing walls were estimated to be half covered in glass whereas the east and west have approximately only a quarter. The internally facing east and west walls also have approximately a quarter of their area covered by glazing. Figure 48 shows the aerial images of the different façades. Figure 48b is the best aerial image of the eastern façade available as there is a tall tower blocking the eastern view. Figure 49 shows a wireframe view of the modelled MB geometry in ESP-r.

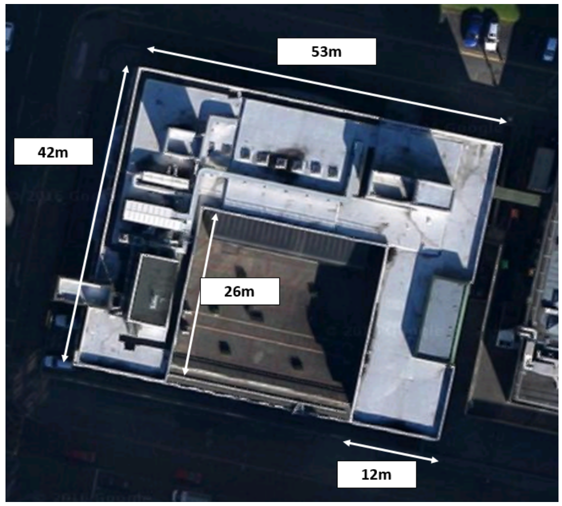
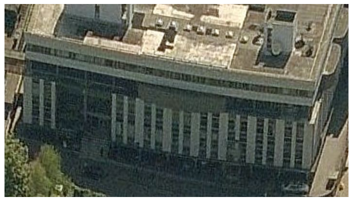


Figure 46: Satellite image annotated with McCance Building dimensions

Figure 47: Floor plan of the McCance Building, 4th floor

Occupancy and lighting tables can be viewed in appendix R and their casual gains are calculated as described in section 4.2.2. Sensible heat gains from IT equipment was calculated using equation 13. The casual gains are confined by the same schedules as described for the JWB as are the ventilation and infiltration rates. Heating is set from 06:00-17:00 with a temperature set-point of 19°C.



(a) Northern façade

(b) Southern façade

(c) Western façade

Figure 48: The (a) northern, (b) southern, and (c) western façades of the McCance Building

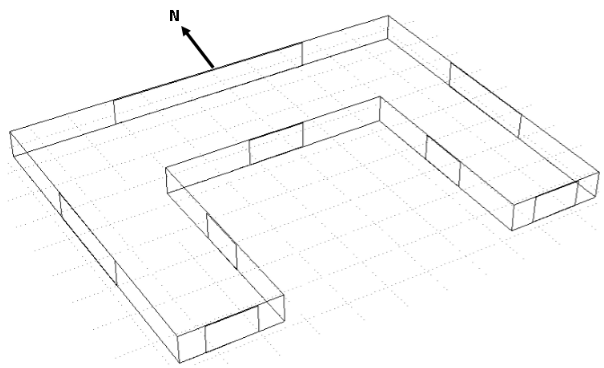


Figure 49: Wireframe view of the McCance Building, 4th floor as modelled as a single zone in ESP-r

4.2.9. Modelling the 3rd Floor of the Royal College Building

The Royal College Building (RCB) differs the most in terms of geometry and construction from the JWB. Its unusual layout is shown by its floorplan in figure 50, as taken from the EPC survey. This layout is consistent for all floors other than the ground floor which does not contain the open spaces. Inside knowledge was also used to estimate the ceiling height as 4.5m for each floor. The RCB is the only modelled building to have the height of each level differ from 3.5m. The usage on each floor varies quite considerably however the 3rd was chosen for modelling because it mostly consists of office space and so can use the example methodology as outlined in section 4.2.2 for the JWB. Tables for room type occupancy on the 3rd floor and the installed lighting for the whole RCB can be found in appendix S. As the 3rd floor is primarily an office environment, occupancy and casual gain schedules were set the same as for the JWB. These were quantified using equations 10, 11 and 13 as ever. Ventilation rates followed the occupancy schedule with no change to values from the JWB example and the heating system was set to be operation from 06:00-18:00 on weekdays with a set-point of 19°C.

Figure 50: Floor plan of the Royal College Building, 3rd floor

The satellite image in figure 51 was used to provide measurements for the floor dimensions which are marked. Aerial images in figure 52 were then used to estimate the glazed area which is comprised of single glazing. The total glazing for walls facing in a given direction were aggregated into one glazed area. All façades were estimated to have half their area covered with glazing. A wireframe view of the RCB as modelled in ESP-r is shown in figure 53 which is made from a combination of information on geometry and fenestration.

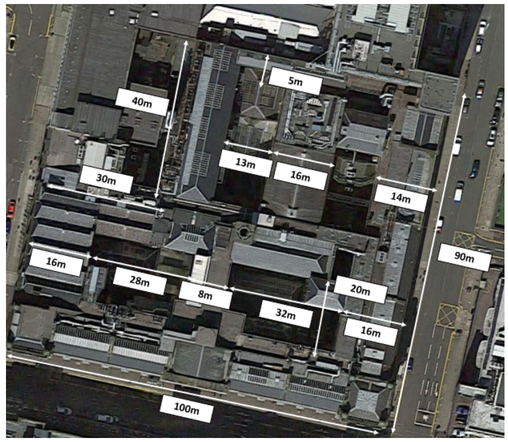
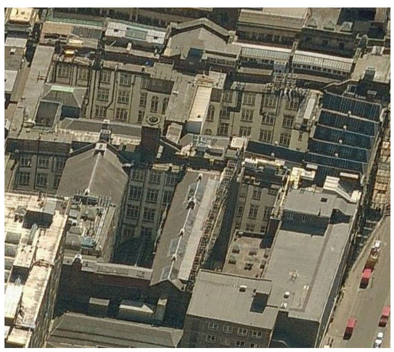
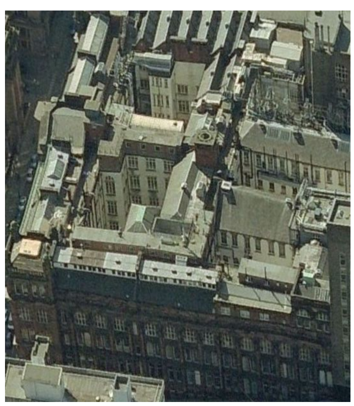


Figure 51: Satellite image annotated with Royal College Building dimensions

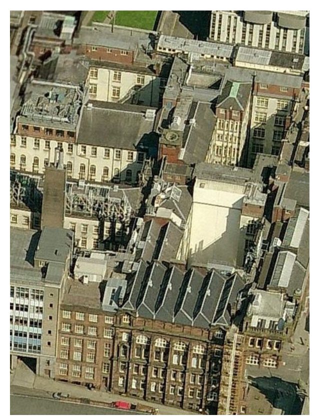


(a) Northern façade

(b) Southern façade



(c) Eastern façade



(d) Western façade

Figure 52: Aerial images of the (a) northern, (b) southern, (c) eastern and (d) western façades of the Royal College Building

The RCB is the oldest of the 10 buildings that were identified for modelling, having been constructed in 1903 (see table 1). It was therefore expected that the buildings materials would differ from that of the JWB, built in 1958. Indeed, the EPC survey describes the external walls as being sandstone blocks but still with an overall assumed U-value of $1W.m^{-2}.K^{-1}$. The thermal conductivity of sandstone (and all other materials) differs with porosity, water and air content, temperature and presence of impurities [178]. As [40] was used for previous thermal conductivities in table 4, this was again used for estimating that of sandstone which was found to be $1.3W.m^{-1}.K^{-1}$. Using equation 9, the thickness of external walls was estimated to be approximately 1.1m which is reasonable. Although the RCB is composed of stone, as figure 52 confirms, the ceiling/floor partitions are still described identically to those of the JWB. As this study looks to use EPC data for building fabric input, the same ceiling and floor constructions were then assigned to the RCB.

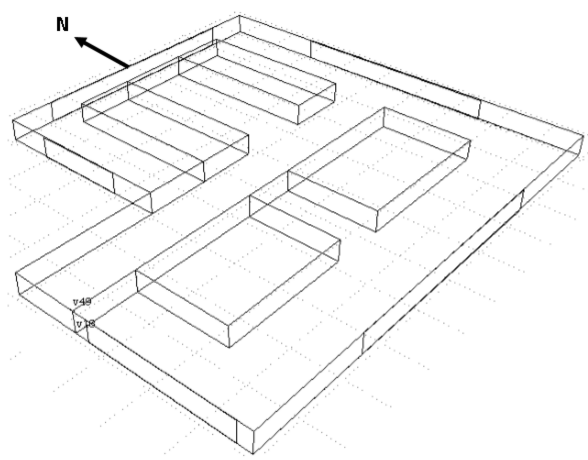


Figure 53: Wireframe view of the Royal College Building, 3rd floor as modelled as a single zone in ESP-r

4.2.10. Modelling the 4th Floor of the Sir William Duncan Building

The Sir William Duncan Building (SWDB) exhibits a more irregular geometry than the JWB or JAB but far more simple one than the JArB or RCB. This is shown by the satellite image of figure 54 which was used to extract the floor dimensions. Its construction was modelled exactly as the JWB on the basis of information from the EPC survey.

The glazed areas were deciphered from aerial images as ever. Every façade was estimated to have approximately a third of its surface area covered in windows. Figure 55 displays these aerial images and a depiction of the 4th floor as modelled in ESP-r is given by figure 56.

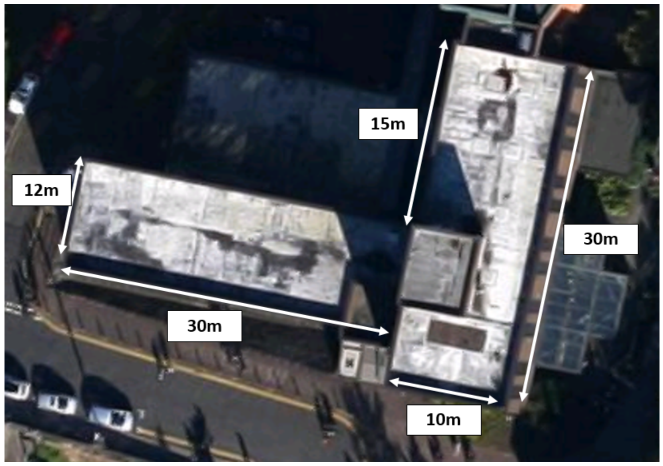
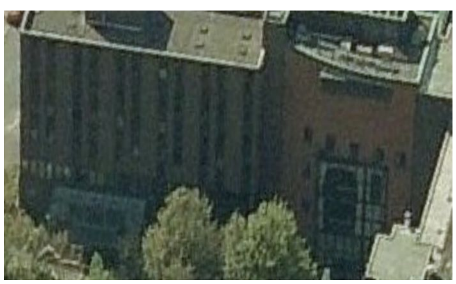


Figure 54: Satellite image annotated with Sir William Duncan Building dimensions

(a) Northern façade

(b) Southern façade



(c) Eastern façade

(d) Western façade

Figure 55: The (a) northern, (b) southern, (c) eastern and (d) western façades of the Sir William Duncan Building

The SWDB has a heating schedule applied at weekends as well as weekdays. On weekdays it is from 08:00-21:00 and from 09:00-18:00 on weekends. The need for heating on weekends implies that the building is occupied. As such, the standard occupancy, lighting and IT schedules and casual gains as calculated by equations 10, 11 and 13 respectively also apply to weekends. The loads for each is likely reduced compared to weekdays but without any further data, it was assumed that people would occupy the building from 09:00-17:00 on all days of the week and use the same amount of electrical equipment and lighting. The extra occupancy also has an effect on the required ventilation. Mechanical ventilation will be needed when people are present and an infiltration rate of 4AC.hr^{-1} from 09:00-17:00 was enforced, mimicking the weekday schedule. Tables for the SWDB, 4th floor occupancy and whole building lighting can be viewed in appendix T.

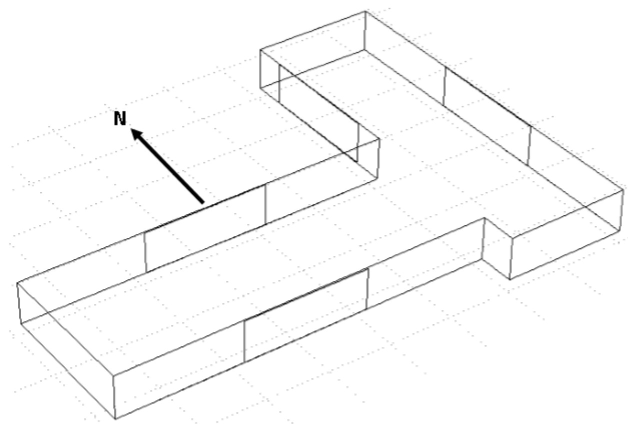
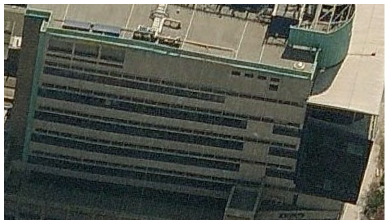


Figure 56: Wireframe view of the Sir William Duncan Building, 4th floor as modelled as a single zone in ESP-r

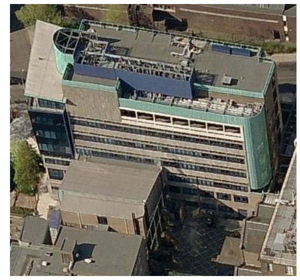
4.2.11. Modelling the 6th Floor of the Thomas Graham Building

Figure 57 was used to approximate the glazed area of the south and north as half the surface area, the west as three quarters and the east as a quarter. The aerial image of figure 57c was taken from the south on account of obstruction from adjacent buildings. Additionally, the aerial image of figure 57b gives insight into the geometry of the TGB. The majority of the building could be approximated as rectangular with its length running east-west which would be simple to model. However, there is a sizeable extension to the south which ought not to be ignored. It was decided that the rectangular section would be modelled in ESP-r and then the southerly obtrusion would be compensated for, the details of which are in section 4.2.12. For the calculation in section 4.2.12 to be performed, the areas of both building segments need quantified. This was done using a satellite image as with the previous building models which is given by figure 58.

The floorplan shown by figure 59 shows a number of unusual features such as a curved south-eastern edge which is asymmetric with respect to the western façade. As with the JArB, these features were simplified as straight edges and so the floor was modelled as rectangular. The final ESP-r model is shown by figure 60.

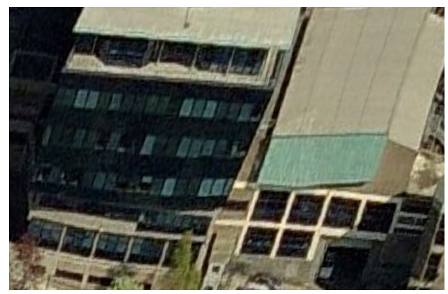


(a) Northern façade



(b) Southern façade

(c) Eastern façade



(d) Western façade

Figure 57: The (a) northern, (b) southern, (c) eastern and (d) western façades of the Thomas Graham Building

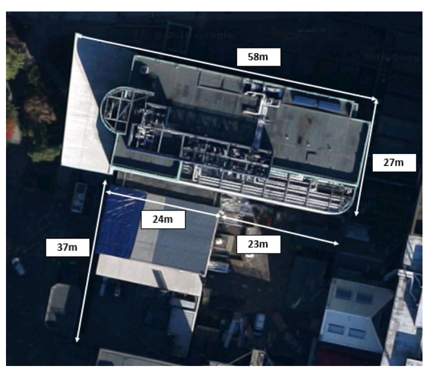


Figure 58: Satellite image with Thomas Graham Building dimensions

The construction information from the EPC survey had the usual layers and U-value for the walls and floor/ceiling and has double glazing as detailed in table 4. The casual gain values were calculated in the same way as with previous building models and the occupancy schedule was assumed to be 100% occupancy between 09:00-17:00 on weekdays and zero otherwise. Occupancy and lighting tables can be viewed in appendix U.

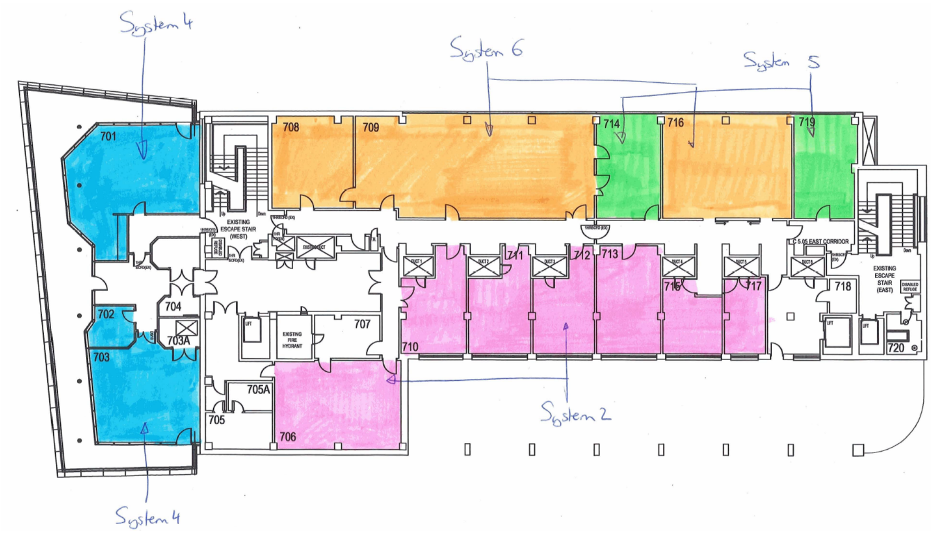


Figure 59: Floor plan of the Thomas Graham Building, 7th floor

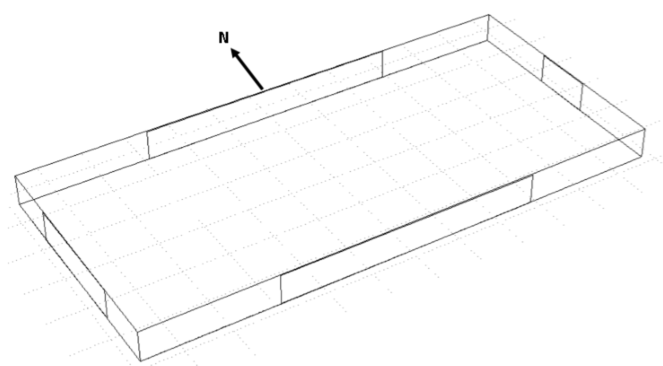


Figure 60: Wireframe view of the Thomas Graham Building, 7th floor as modelled as a single zone in ESP-r

Interestingly, as with the AB, the heating time set-points are noted as 'unknown' in the EPC survey. Hence, an assumption had to be made. The floor area of the TGB is only marginally greater than that of the MB and the floor usage is not dissimilar. Therefore, it was assumed that the heating control for the TGB operates from 06:00-17:00 with a set-point of 19°C.

4.2.12. Calculation of Modelled Buildings' Energy Consumption for Comparison with EPC and Utility Data

Once the geometry, construction, internal gains, heating system and infiltration rates are set, simulation of the building's heat flows can then take place. The simulation output result of interest is that of space heating energy consumption which is given in kWh.year^{-1} (though the time period can be altered as desired). For comparison with EPC ratings and measured data, this value must be modified to kWh.m^{-2}.year^{-1} incorporating both space heating and hot water gas consumption.

Firstly, the ESP-r output value must be converted into an energy density. This is easily done by dividing the output value by the area of the floor. The EPC and measured data are for total gas consumption whereas the model output is only for space heating. Therefore, an approximate factor for hot water must be incorporated into the final calculation. Such a separation of space heating and hot water use can be found in [52]. Figure 12 shows space heating accounting for 68% of total energy consumption in the JWB whilst hot water is only 3%, according to the EPC survey. Pie charts for other buildings can be found in appendices A-K. This means that for every kWh of space heating demand in the JWB, there is a further 3/68kWh of hot water demand. Given an ESP-r output of H' for the space heating, the final gas energy consumption (E) for a given building can be calculated using equation 14:

$$E = \left(1 + \frac{HW}{H}\right)\frac{H'}{A} \tag{14}$$

Where HW and H are the percentages of total energy consumption from the EPC survey corresponding to hot water and space heating respectively. A is the floor area that was extracted from the relevant satellite image. Taking the JWB as an example, equation 14 becomes:

$$E = \left(1 + \frac{3}{68}\right)\frac{H'}{2100m^2} \tag{15}$$

$$E = (4.97x10^{-4})H \tag{16}$$

Solving for equation 16 then gives the final answer for comparison with measured data and EPC ratings. Equation 14 was used for all the modelled buildings but, as mentioned in section 4.2.11, the TGB requires some additional tweaking. This is on account of the southerly obtrusion that was not included in the ESP-r model. A simple multiplying factor defined by the ratio of the two building segment volumes was used to generate a final value, E', using equation 17.

$$E' = \left(1 + \frac{V_2}{V_1}\right) E \tag{17}$$

Where E is the energy consumption as calculated by equation 14, V_1 is the volume of the rectangular segment and V_2 is the volume of the southerly extension. The volumes are calculated by equation 18 where F is the number of floors in each segment. It is assumed that all floors are of the same height (3.5m) and so there was no need to include the height. This means that the 'volume' is in fact an amended area.

$$V = A.F \tag{18}$$

4.3. Results for the Dynamic Simulation of Individual Building Energy Consumption

The metered utility data that was made available for this project is monthly whilst the EPC survey supplies an annual prediction. ESP-r produces results in hourly time-steps however analysis is limited by the time resolution of the utility and EPC data. Results must therefore be presented in either monthly or yearly values. Equation 8 from section 3.4 is used to calculate the SPD between ESP-r and measured values.

Figure 61 is the dynamic simulation equivalent of figure 13 in section 3.4. There is reasonably good agreement between the predicted and measured annual energy consumption for all buildings except the TGB. Taking the 10 buildings as the stock, the SPD between simulated and measured energy consumption over the whole stock is **42%**. The average SPD between individual buildings is lower, calculated at **35%**. For all buildings the dynamic simulation underestimates the true energy consumption, on average by **86kWh.m^{-2}** over a year. Using the context examples from section 3.4, taken from [142], this value is over half a solar photovoltaic farm more accurate than EPCs. Using another measure, the difference in energy consumption prediction between the project method and NCMs is the equivalent of a whole offshore wind farm in terms of energy density (not to be confused with actual energy production). The range of measured energy consumption values for the JWB and JAB is intersected by the dotted line of equality indicating a strong match between dynamically simulated prediction and measured energy consumption. Overall, the range of predicted annual energy consumption over the stock is 83-173kWh.m^{-2}. This range is far narrower and has lower bounds, particularly the upper, than the actual range which is 118-381kWh.m^{-2} for the 10 modelled buildings.

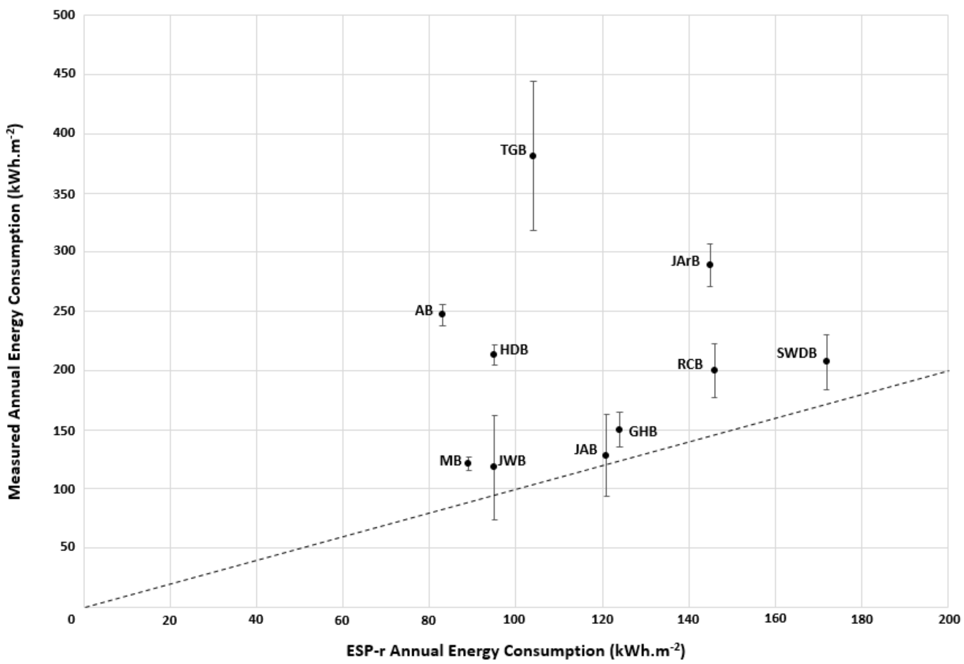


Figure 61: Consumption of natural gas for different buildings: dynamic simulation vs utility data

It has been commented on that the ESP-r simulation underestimates the measured energy consumption for all modelled buildings. However, as figure 61 shows, this underestimation is, as expected, different for each building. Figure 62 shows the mismatch between energy consumption calculated as an EPC, using ESP-r and measured for each building graphically.

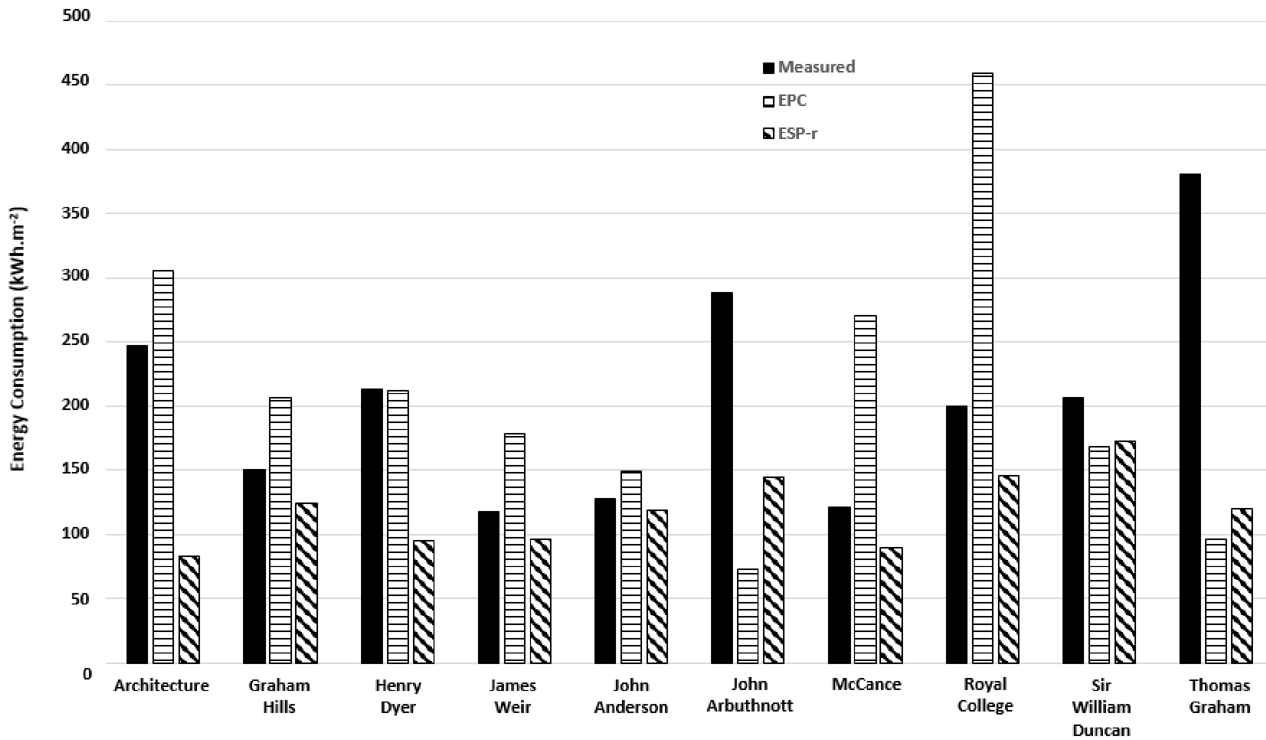


Figure 62: Consumption of natural gas for different buildings: dynamic simulation vs mean utility data vs EPC

ESP-r models are shown to more accurately predict energy consumption than EPC methods for all the modelled buildings other than the AB and HDB. Some building models such as those for the JAB, JWB, GHB and MB exhibit very close matches to the measured energy consumption. Interestingly, for these four buildings, the EPC overestimates energy consumption, in contrast to the dynamic simulation. The ESP-r prediction for TGB is widely inaccurate but is still a marginal improvement on that from its EPC. A very large improvement in prediction is observed for the RCB and the JArB as a result of using the project method rather than those for EPCs. A general trend in dynamic simulation prediction accuracy is detected from figure 62 whereby those buildings with greater heating loads have their consumption more poorly predicted. This is to be expected from the disparity in energy consumption ranges across the stock.

In order to analyse the relationship between high heating loads and accuracy of prediction further it is useful to investigate energy consumption at different times of year when heating is either high or low. Analysis of the weather file showed that January was the coldest month and July the hottest and so these were used as the two extremes of high and low heating demands. Figure 63 is very similar to figure 61 but applies only to January. Similarly, figure 64 corresponds only to July.

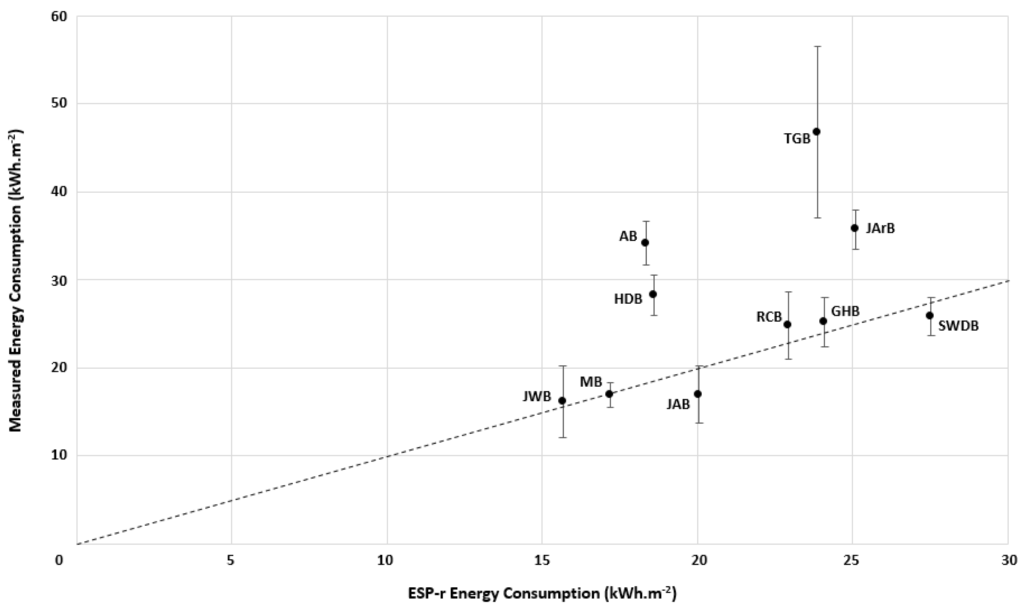


Figure 63: Consumption of natural gas for different buildings in January: dynamic simulation vs utility data

Annually, the JAB and SWD had their energy consumptions underestimated but for the highest heating month of January, consumption is now overestimated. Predictions for the JWB, MB, RCB and GHB are extremely accurate with the MB in particular having had its energy consumption almost exactly estimated. That for the TGB however, is still grossly underestimated closely followed by the AB. The SPD over the stock is lower than the yearly value at 22% and 32% between individual buildings. The average absolute difference for a given building is only 6.6kWh.m^{-2} indicating a very good match between calculated and measured energy consumption.

The data points in figure 64 pertaining to energy consumption in July show a very clear deviation between dynamically simulated and measured results. The SPD over the building stock is an extremely large 90% whilst the average for individual buildings is an enormous 3446%. Despite these extremely high numbers, the mean absolute difference between predicted and measured energy consumption is still only 4.6kWh.m^{-2}.

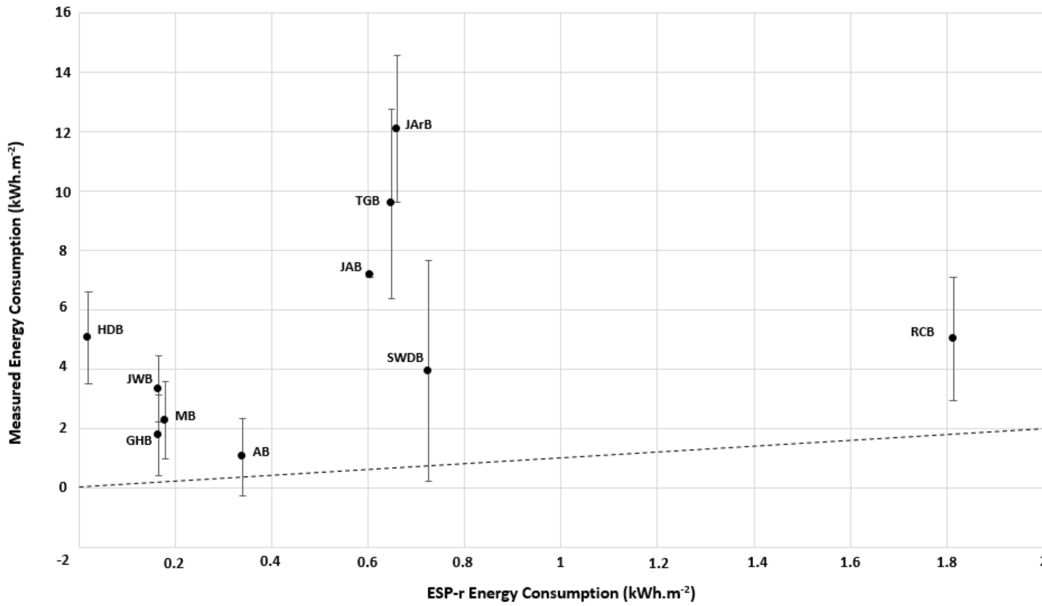


Figure 64: Consumption of natural gas for different buildings in July: dynamic simulation vs utility data

The mean bias error (MBE) between dynamic simulation prediction and measured energy consumption is slightly greater for times of high heating demand as shown by figures 63 and 64. This point is emphasised by figure 65 which shows the ESP-r and measured energy consumption for the JWB in all months of the year. Equivalent graphs for the remaining 9 buildings can be seen in appendix V. For winter months, particularly January and December, heating loads are generally overestimated. The opposite is then observed for summer months. An obvious exception to this trend is observed for the TGB in figure 90 where the dynamic simulation continually underestimates the very large measured heating load. Though the MBE is greater for cold months, the SPD is less. Extending these findings to buildings over a whole year, it is found that the proportional accuracy of prediction increases with greater heating demands.

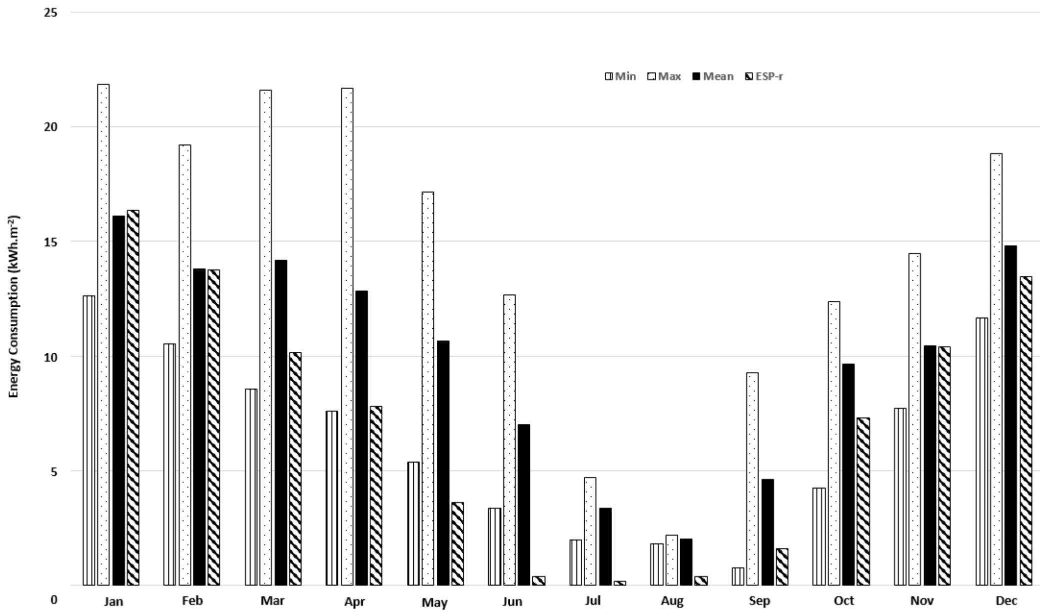


Figure 65: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the James Weir Building

In section 3.4, it was investigated whether the floor area of buildings or their age had any relation to the inaccuracy of their EPC prediction. It is therefore appropriate to carry out the same investigation for predictions made from the project method. Figure 66 shows how the absolute difference between dynamic simulation prediction and measured data relates to the age of individual buildings in the stock. Figure 67 displays the prediction-measured mismatch as the SPD and again compares this difference to the building ages. The majority of buildings are between 40 and 60 years old and within this age group the largest range of results occur. Both the smallest and greatest absolute differences exist within this range and likewise can be said for figure 67 showing the SPD. From the available data, no relationship can be discerned between the age of buildings and how accurately their energy consumption can be predicted using the project method.

Figures 68 and 69 show the relationship between the floor area of buildings and the absolute difference and SPD between predicted and measured energy consumption respectively. Both graphs are very similar but neither exhibit a clear link between the floor area and inaccuracy of prediction. The three buildings with the greatest floor area have relatively small absolute differences and SPDs compared to the average of the whole stock. However, those buildings with smaller floor areas display inaccuracies both higher and lower than those three buildings with the highest differences. Overall, no apparent relationship exists between the floor area of buildings and how accurately the project method is capable of predicting their energy consumption.

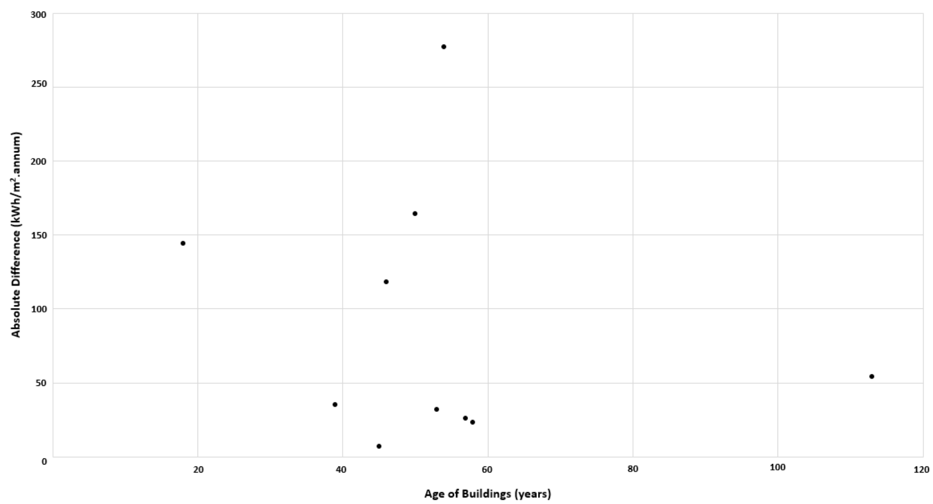


Figure 66: Relationship between the age of buildings and the absolute difference between their measured energy consumption and that predicted by dynamic simulation

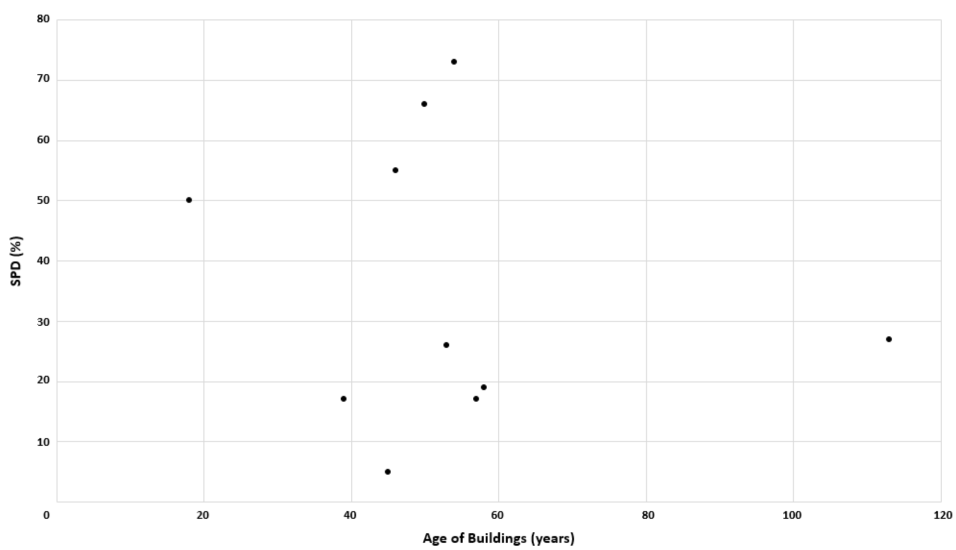


Figure 67: Relationship between the age of buildings and the SPD between their measured energy consumption and that predicted by dynamic simulation

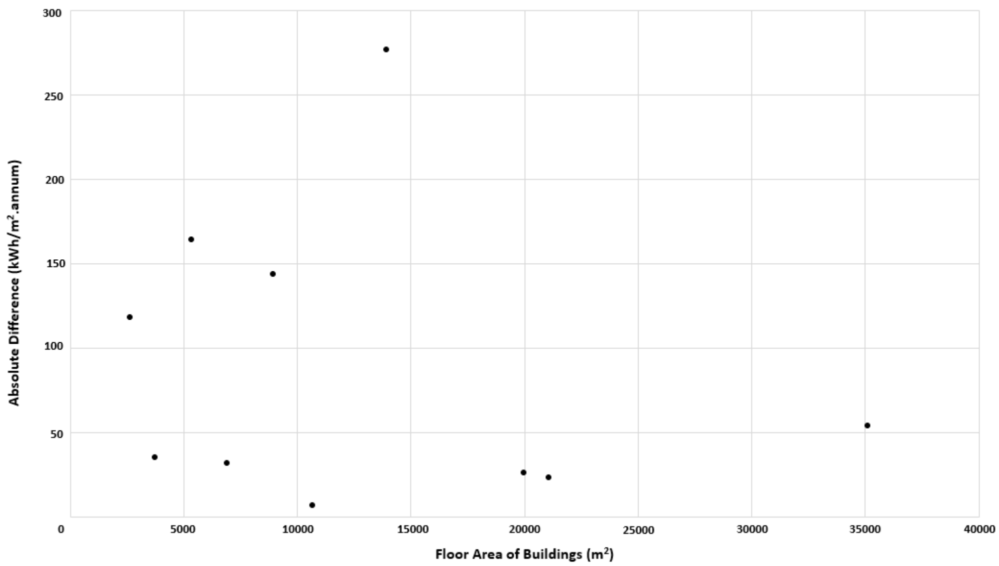


Figure 68: Relationship between the floor area of buildings and the absolute difference between their measured energy consumption and that predicted by dynamic simulation

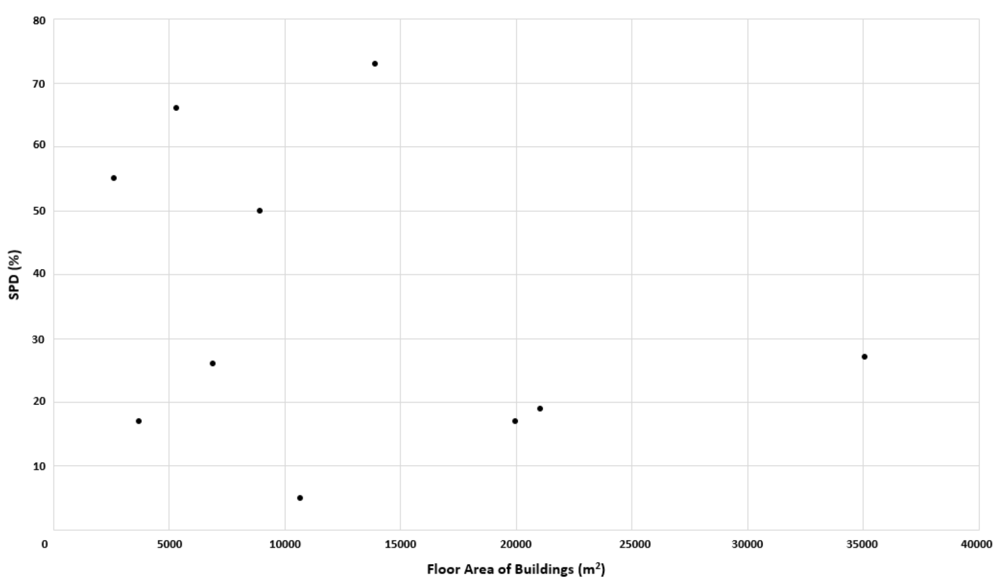


Figure 69: Relationship between the floor area of buildings and the SPD between their measured energy consumption and that predicted by dynamic simulation

5. Discussion of Results for the Dynamic Simulation of Individual Building Energy Consumption

5.1. Introduction

The results in section 4.3 revealed that dynamic simulation using individual building geometry was a better predictor of true energy consumption for space heating and hot water than EPC ratings. This section strives to explain why this is the case but also why a difference between predicted and real persists. Finally, an analysis of why certain buildings have their energy consumption predicted more accurately than others is discussed.

5.2. Discussion on the Energy Consumption Estimation Using Individual Building Geometry and Dynamic Simulation

In section 4.3 it was divulged that the project method for predicting energy consumption for space and hot water heating was more accurate than current EPC methods for five chosen buildings. In this section, the question must be asked as to why this is the case and also why there is still a significant mismatch between the predicted and measured energy consumptions? Also, if there is an explanation for why some buildings have their energy use better estimated than others?

It was found that the average absolute difference (MBE) across the modelled building stock was an 86kWh.m^{-2} underestimation. This translated to an SPD of 42% over the building stock and an average of 35% between individual buildings. Having a higher SPD over the whole stock compared to individual buildings is the opposite to what was found in section 3.4 where the SPD over the stock was a very small 3% and between buildings was a far greater 66.5%. These figures from 3.4 relate to the stock of 14 buildings. For those 10 buildings modelled, the average SPD over the building stock remains at 3% however between individual buildings the value rises considerably to 82%. The reason for such a small SPD using EPC survey data is because there is an equal number of buildings in the stock that were over and underestimated which acted to almost entirely cancel one another out. The SPD between individual buildings provides a far clearer indicator of the EPC's poor predictive performance. Studies such as [119], [44] and [56] all used EPC-style calculation methods to create models to estimate urban scale energy consumption. In all instances, the results are similar to what is observed in section 3.4. There is an excellent match in energy consumption over the whole building stock but the models fail at the individual building level.

The methodology developed in this project focuses in on the individual building scale and achieves greater success in predicting their energy consumption than NCM-based studies. Figure 61 shows that all the modelled buildings' energy consumption is underestimated. Therefore, no such cancelling out of over and underestimation occurred and the final SPD value over the building stock is larger than for the EPC method. Another study comparing dynamic simulation and NCMs found that dynamic simulation always produced lower values [120]. The JArB, SWDB and TGB in figure 62 are the only modelled buildings that refutes these findings.

For individual buildings, the average SPD between simulated and measured energy consumption is 35% which is a very significant improvement from current best practice methods such as EPC. The absolute difference in the form of a MBE also sees a great improvement from an average of 110kWh.m^{-2} (115kWh.m^{-2} for the stock of 10 buildings) for individual buildings to 86kWh.m^{-2}, an improvement which is equivalent to an entire offshore wind farm [142]. A study by [148] developed a new physical model using a single zone and achieved a remarkably accurate energy profile for an individual building over a whole year. This model, however, very specifically targetted a single building and refined the model until such results were achieved. This model lacks the transferability characteristic which the project method presented in this dissertations aims to improve upon.

Studies by [131, 144, 145] all found a relationship between building archetypes (comprising of age and floor area) and gas consumption. They suggest that predicting gas consumption should correlate to the age and floor area of buildings. However figures 66, 67, 68 and 69 distinguish no such relationship for this study. Those studies mentioned are site-specific like the UoS case study however comprise of a far greater number of buildings in their stock. Such a difference perhaps explains why this investigation does not yield similar results. What figures 66-69 do reveal however is further evidence of the failing of archetypes for energy prediction at the individual building scale.

The project method aimed to improve upon current practice adopted by governments by replacing NCMs with dynamic simulation and improved data sources. The reason that better predictions are made using the project method than EPCs is a combination of both an improved data source and calculation tool. Dynamic simulation is more suitable for coping with the functional and thermophysical complexities of buildings, allow for including more complicated HVAC systems and have a greater time resolution than NCMs [40, 49, 120, 179–181]. Replacing steady-state calculation with dynamic simulation undoubtedly improves the accuracy of the model in predicting energy consumption. As [49] highlights though, the increasing complexity of software for dynamic thermal modelling leads to the impact of model improvements diminishing. In other words, changing the model from using a simplified calculation method as with EPCs to a dynamic simulation engine such as ESP-r will improve the accuracy of results a great deal. However, to further improve the process as a whole, the accuracy of input data becomes more and more important. As an example, [179] found that dynamic simulation lead to far more accurate results than EPC methods for a single family home in Italy. The investigation concluded that the marked improvement in results was not down to the difference in dynamic and simplified calculations but rather the greater defined data input compared to EPC assumptions.

Using satellite and aerial images to provide information on geometry, glazed area and solar absorption goes some way to improving the data input to models. The satellite and aerial images are not as accurate as EPC surveys but are publicly available and so this method could theoretically be applied anywhere in the world without the trouble of countries or regions having to spend limited resources in obtaining the information.

5.3. Discussion on the Discrepancy Between Energy Consumption Predicted by Dynamic Simulation and Utility Data

Though the data acquisition method undertaken in this project is an improvement upon NCMs, there are still noticeable assumptions that must be addressed. Assumptions involving glazing area along with construction materials, casual gain values and schedules, heating set-points and ventilation go some way to explaining why there is still a MBE of $86kWh.m^{-2}$ between calculated and measured space and hot water energy consumption.

The construction was based off the available information from the EPC survey in table 3 and some literature on materials as discussed in section 4.2.2. Assumptions had to be made about exactly what material each layer comprised of and its thickness estimated. The chosen construction for each building, as displayed in table 4 for the JWB, will not be exact and thus the true thermophysical properties of the building fabric are not reflected in the model. Simulation output values for energy consumption of the building will therefore not be wholly accurate. Even if the information from the EPC survey had been transferred perfectly to the dynamic simulation model, uncertainties would still arise due to the assumption in producing the EPC. A wealth of information exists in assessing the thermal conductivity and thicknesses of materials and in calculating the U-value of a construction. A wide range of values are quoted in the literature and so the values assumed true in the EPC survey are very likely not to mirror reality [155, 182, 183]. The glazed surfaces were estimated from aerial images. This is an improvement in terms of data availability on present EPC practice but leads to a decrease in model precision. The area was manually extracted via simple approximation which carries with it a degree of uncertainty.

A large amount of assumptions and simplifications were made during the definition and quantification of casual gain loads in the building models. Firstly, the amount of occupants was taken from the EPC survey, the numbers for which are extremely arbitrary. Secondly, there is no indication of temporal deviancy with regards to the quoted values. Therefore, a very simple occupancy schedule had to be assumed for all models. That being full occupancy between 09:00-17:00 on weekdays and zero outwith this time boundary unless heating was also specified on weekends. Such rigid conformity removes any randomness in the model which, of course, has no bearings on the workings of real life. A lot of research has been conducted into improving occupancy schedules for modelling purposes such as the prototype occupancy schedules developed by the US DoE (United States Department of Energy) for commercial office buildings shown in appendix W [162]. This profile is commonly used in literature but more novel techniques have been studied including using sensors, lighting switch data, Monte-carlo, Markov chain and other statistical methods [38, 159–161, 184, 185]. As well as the occupancy schedule, the values assigned to each person for sensible and latent heat gains is very generalised and, thus, adds another layer of uncertainty.

The schedules for IT equipment and lighting followed on from that of people and hence carry the same uncertainty based on assumption. Any random occupant use has been removed from the model which is a very important omission. In studies involving predicting electricity consumption the ramifications would be more severe but studies involving modelling heating estimation still cite occupancy use as one of the greatest uncertainties [186, 187]. The type of IT equipment was also very crudely estimated and is likely to be higher. The calculation of other equipment use for all buildings after the JWB example using equation 13 is also very approximated. The sensible heat gains were taken from the literature as standard, generalised values [168, 170] but this does not guarantee their accuracy or validity [40].

Lighting was assumed to only be operating when people are present. This is a reasonable enough assumption for when PIR control is present but with manual controls, it is likely that occupants will leave lights on rather regularly. Figure 26 shows that lighting has the biggest casual gain so occupant behaviour could be significant in skewing results. The data on lighting available from the EPC survey was relatively detailed and the calculation method described by equation 11 is reasonable as the floor is assigned to be representative of the whole building.

In general, the scheduled occupancies and corresponding casual gains for each building are likely to be slightly underestimated. People come and go during and outwith the prescribed times but this is likely to more or less level out over the course of a year. The greater uncertainty lies in IT and lighting use which are both likely to be higher than the values used in the building models. Higher casual gains will act to reduce the heating load and therefore the yearly consumption for the buildings is likely to be diminished. As the estimated energy consumption underestimated the measured for each building, the difference between predicted and actual energy consumption will actually increase as a result. Thus, reducing the accuracy of the dynamic simulation model.

Any assumptions regarding casual gains will be dwarfed by those pertaining to the HVAC systems which are the most important with regards to this project. In order for a fair comparison to be made between dynamic and NCM calculations, the heating set-points from the EPC were used. For the JWB, this was set at 06:00-18:00 all year round. However, upon consultation with the UoS Estate Management, it was found that the heating time was actually set from 06:30-18:00 in the summer months and until 20:30 in winter. A greater amount of overall heating would be expected accordingly. A short sensitivity analysis revealed that the total heating over the year would increase by over 10kWh.m^{-2} which amounts to 6% of the building's total heating load. This would act to override any increase in casual gains and thus the difference in energy consumption between estimated and measured will decrease and improve the accuracy of the model. The newly supplied information on heating times does not, however, account for the difference between predicted and measured energy consumption.

The final model input yet to be discussed is that of ventilation. The values assumed for when mechanical ventilation and natural infiltration are present are very arbitrary. They are based off standard values and are very simplified in that they remain constant throughout the year. Natural ventilation depends on wind characteristics and air temperature differences between the inside and outside of the building. Both of these factors are so variable that a constant infiltration rate is near impossible [177]. Infiltration affects the overall thermal performance of a building immensely and so such a simplification greatly trivialises the complicated physical process. The determination of infiltration values and of desired ventilation rates is very hard to predict and have changed a lot over years of research [172]. Altering the air change rate by ±1AC.hr^{-1} but keeping the same ventilation schedule in the JWB leads to a 20% difference in energy consumption according to the ESP-r model. Such a large variation in energy consumption on account of ventilation rate indicates a strong dependency, more so than for the heating set-point or schedule.

Changes in air mass will affect heating and so the true energy consumption will be altered on account of differing wind and air temperature of the outdoor environment. The weather file used for dynamic simulation is from 1986 whereas the measured data is from 2012-2015 and thus temperature and wind differences may be significant. On account of assumed air change rates, schedule and weather, the predicted values from the dynamic simulation will not be accurate. However, EPCs also presume a constant infiltration and ventilation profile and use a standard weather file so the findings of greater accuracy from the dynamic model can still be taken as valid.

The calculation method for finding the final energy consumption is given by equation 16 which is based on the assumption that the floor being modelled is representative of every other floor and hence the whole building. The floor plans of the EPC survey and geometry from satellite images indicate that this assumption is not true. The geometry and use on going from floor to floor is varied for all buildings. For example, the JWB has office floors similar to that modelled but the ground and first floor are far wider and are used as workshops and laboratories. Similar scenarios occur for the other modelled buildings. The accuracy of each model is reliant upon the reproducibility of each floor, none of which are ideal. This inaccuracy will be reflected in the final value for the energy consumption of the building.

Equation 14 also involves the assumption that the EPC's energy breakdown involving space heating and hot water is correct. Any inaccuracy with respect to these values will not affect the improvement in dynamic simulation compared to NCMs as this uncertainty runs through both.

5.4. Discussion on the Observed Differences in Predicted and Measured Energy Consumption for Individual Buildings

The simulations for all buildings do not factor in exact shading. This poses a problem for the MB and SWD in particular as their eastern façades are almost entirely cast in shadow by neighbouring buildings. This will result in reduced levels of solar insolation and thus slightly higher heating loads. As this shading is not accounted for in the ESP-r models, a marginal underestimation of energy consumption would be expected. This is indeed the case for all buildings however it is unlikely that the shading effect could be accountable for the full difference between calculated and measured energy consumption for any of the buildings, even the MB.

The ESP-r models assume a completely detached building for all examples with the external walls all entirely exposed to the outdoor environment. In reality, thermal bridging exists for all buildings other than the MB and GHB. Thermal bridging has the affect of reducing the overall heating requirements for an individual building. This is the opposite effect of neglecting shading but is similarly unlikely to cause any great difference in final results. The MB has its energy consumption predicted almost exactly for January (see figure 63) which may be partially because of the model truly describing the building's environment unlike with the others.

Figures 65 and 82-90 show that the diversity in energy consumption from month to month is not as great as the dynamic simulation predicts. A possible reason for this relates back to occupancy uncertainty. People will have gotten accustomed to habit and so heating systems will not be adjusted as much as temperature differences might dictate.

Section 5.3 mentioned the fact that the heating times in the JWB's EPC survey was incorrect. The integrity of the EPC timing set-points for heating in the rest of the buildings must then be called into question. A gross uncertainty for heating timings exists for the AB and TGB as none were supplied by the EPC survey. A supposition that these would be similar to that of JWB and MB respectively was applied but there is no evidence other than similar floor areas to support this assumption. The absence of any information on heating times for the AB and TGB is likely to contribute to why energy consumption was so poorly estimated. In addition to the great uncertainty in heating timings, the temperature set-point of 19°C could also be incorrectly assumed and differ from building to building.

The heating timings and set-point were investigated for the AB to see their relative effect on why the ESP-r model performs worse than the EPC in predicting the measured gas consumption. It was found that a change in heating set-point from 19°C to 20°C alone improved the accuracy of the model so it gave a better prediction than EPC. Independently adding heating and occupancy at weekends also results in the model being closer to the measured consumption than the EPC. Such factors highlight how important data input is and the great uncertainty that exists in assumptions relating to heating schedules. The poor result for the AB skews the overall result for project method accuracy. Removing the AB from the study, the MBE reduces to a 78kWh.m^{-2} underestimation of the building stock. The average SPD for individual buildings also reduces to 32%.

The TGB has its EPC and ESP-r model drastically underestimate its gas consumption. Upon consultation with the UoS Estate Management team it was revealed that fume cupboards are present in the TGM which have an abnormally high air exchange rate and are not present in other buildings. When the fume cupboards are operational then the heating is also. For safety reasons the fume cupboards extract air frequently and thus the heating consumption for the buildings is unusually high. Both the EPC and dynamic simulation methods fail to account for these fume cupboards which explains why such a disparity between calculation and measurement is observed. It is worth noting that the project method still offers a better result than the EPC calculation method.

The project method is less accurate than the EPC in predicting the energy consumption of the HDB. Rather than this indicating a particular issue with the project method, an unusual circumstance is highlighted where the EPC is especially accurate. It is not clear why this is the case but emphasises that the project method is in need of improvement.

Overall, there is an enormity of possible reasons for why there is an observed difference between the calculated and measured energy consumption using the project method. The likelihood is that the difference is due to a combination of all these factors to varying degrees for each building. It is extremely hard to isolate the degree of influence of specific factors in affecting the outcome without an extensive sensitivity analysis. The short sensitivity analyses for the JWB showed that changing the ventilation had a greater affect on hot water and space heating energy consumption than changing either the heating set-point or schedule.

6. Conclusion

The project method of using dynamic simulation for calculation, satellite images for building geometry and aerial images for glazed surface area and solar absorption of the building façades for building stock modelling has been shown to improve the accuracy of energy consumption estimation compared to NCMs. EPC data had an MBE of 110kWh.m^{-2} across the building stock with 14 buildings and 115kWh.m^{-2} with the 10 when compared to measured utility data. The 14 buildings were split evenly between under and overestimation of space and hot water heating energy consumption. In addition, the average specific percentage difference across the building stock came to 66.5% between the predicted and measured energy consumption for space heating and hot water. Only 10 out of the 14 previously studied buildings were chosen to model using dynamic simulation and alternative data extraction methods. The MBE in this case came to 86kWh.m^{-2} with all simulation outputs underestimating the measured value. This translated to an average difference of 35% difference across the smaller building stock.

The mismatch between the project method approach and measured utility data can be attributed to the various assumptions that were required in defining the buildings' construction, casual gain schedules and assigned values, heating timings and temperature set-points and infiltration rates. A simple sensitivity analysis on the JWB for heating schedule and set-point and enforced ventilation rate revealed that ventilation has the greatest influence on gas consumption. The values for these assumptions were taken or adapted from the EPC survey and combined with information from the literature. Therefore, although they are highly responsible for the difference between calculated and measured results, they commonly influence the outcome of the EPC ratings and make for a fair comparison.

Some simplifications in the final calculation after dynamic simulation must also share responsibility for why a significant mismatch still persists. Each modelled floor was deemed representative of its respective building which is seen to not be wholly true from floor plans and other EPC survey information. A further factor relating to the new calculation method is that the dynamic simulation models did not factor in shading or thermal bridging. Both of these appear potently in reality and thus the final results will be somewhat skewed. Finally, the adjustment to the model output value to account for hot water usage uses further information from the EPC survey which may be unreliable.

The measured diversity in heating load between periods of low heating demands and high is not as great as predicted. It is postulated that occupancy use is responsible for this observation. People get accustomed to their habits including when to turn the heating on and so there is not as great a deviation between winter and summer as the simulation expects.

Although there are limitatons and many assumptions in the dynamic simulation project model, many of these are shared with the EPC prediction. The exceptions being the geometry and fenestration are taken from satellite and aerial images respectively. For satisfying the aim of this project, identifying the most influential assumptions is not so important as producing a predictive method for energy consumption that is more accurate than NCMs. Improvement is observed from the EPC calculation by changing to dynamic calculation and altering the data input. This new data input is less accurate than the information provided by the EPC but is, importantly, more widely accessible. The results from this investigation show that some data accuracy in geometry and fenestration definition can be sacrificed for an improved calculation method.

This investigation has shown that improvements to current building stock models for energy mapping is very possible. A switch from a simplified calculation methodology to dynamic simulation and replacing EPC survey data with publicly available building images already shows a significant improvement in true energy consumption prediction. The satellite and aerial images were accessed via public websites, free of cost. They can in principle be applied anywhere in the world and so offer excellent transferability opportunities in building stock modelling. It is hoped that the conclusions drawn from this thesis can open up a new era in building stock modelling whereby publicly available images can be processed to extract accurate individual building information that will effect its energy performance. In doing so, policy makers can be better informed about the energy consumption and efficiency of the building stock and take appropriate action to enhance and protect the health and well-being of people and the natural environment.

7. Limitations to the Project

Though the findings from this investigation are encouraging for developing building stock modelling practice, there are notable limitations which must be brought to attention.

The assumptions in data input for models in terms of construction, occupancy, heating schedules and set-points and ventilation and infiltration will affect the true outcome. In particular, ventilation has a significant impact on final gas use and so any quantification will carry a large uncertainty. Additionally, the weather file used for dynamic simulation does not correspond to the same year as the measured data which results were compared to. The calculations in dynamic simulation also assumed a completely detached and openly exposed building thus neglecting thermal bridging and shading.

The scope of the project focused only on gas for hot water and space heating. If the project method were to be modified to include electrical consumption, the superiority (or otherwise) of the project method to NCMs could be further assessed. The investigation is further restricted by the small building stock that was available for study. A greater number of buildings and scaling up the project to include electrical consumption would give further validity to the findings.

8. Future Work in Investigating Building Stock Models Using Individual Building Geometry and Dynamic Simulation

This investigation used single zone models for dynamic simulation. These were of the necessary complexity to establish the benefits of using the project method instead of NCMs. However, the use of single zone models in dynamic simulation has been criticised [56] for failing to adequately reflect true building systems. The accuracy of results could be improved if a multiple zone approach was adopted instead, as in [30] which would increase confidence in the model's predictions.

Section 7 mentions the omission of electricity consumption which presents an opportunity for further work. In particular, estimating electricity consumption for cooling loads would affect both the thermal and electrical energy usage. This would be especially useful if this investigation were to be extended to regions of different climate and types of buildings. Testing the project method for different climactic zones and different building types would test the transferability of the method and promote its use.

An expansion in what data can be extracted from satellite and aerial images would also greatly improve the exchangeable nature of the project method. A study by [188] for instance investigates using airborne LiDAR for extracting the thermal energy performance of a residential housing stock. Using such techniques for supplying input data to dynamic simulation models would eliminate the need for inaccurate, low-employable and resource thirsty EPC methods.

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Appendices

A. Architecture Building EPC and Energy Profile

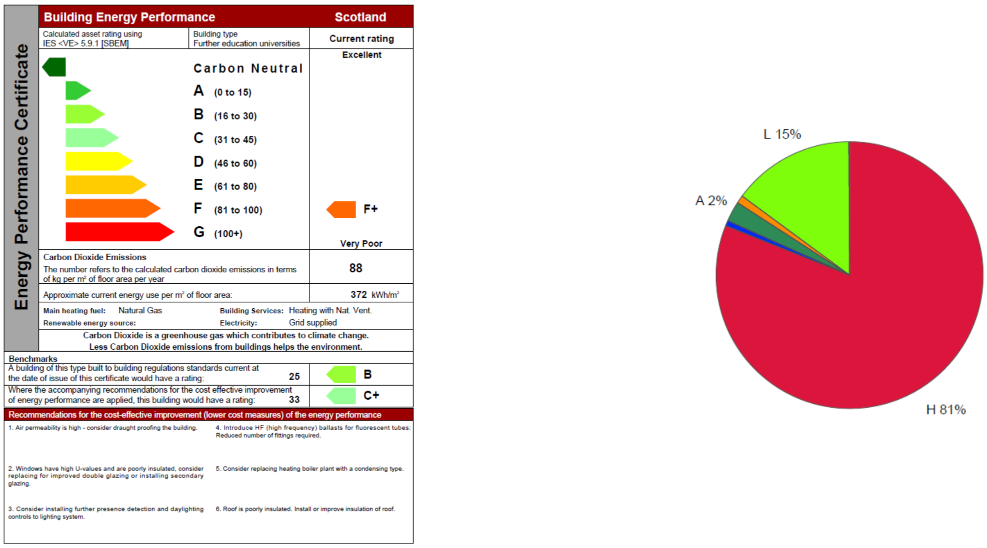


Figure 70: Architecture Building EPC and energy profile

B. Barony Hall EPC and Energy Profile

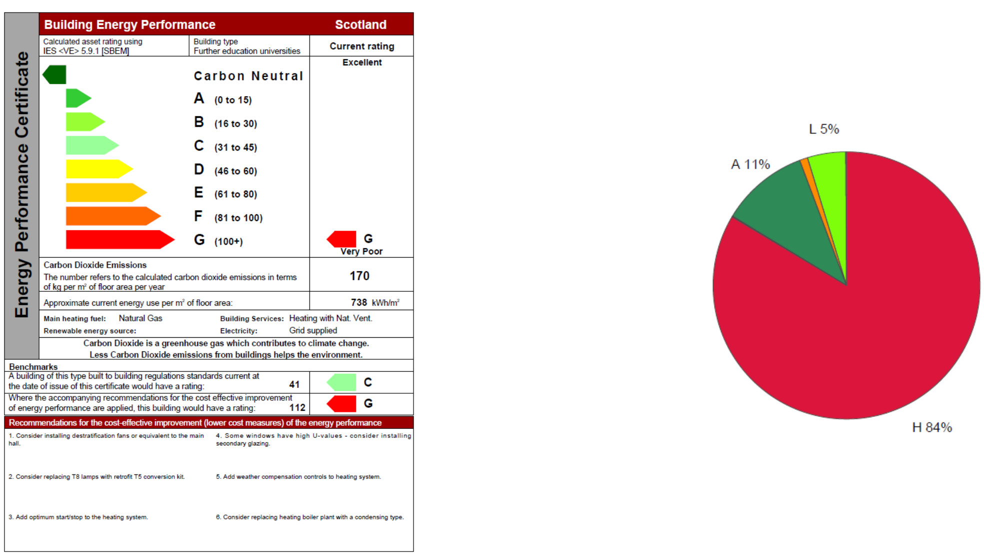


Figure 71: Barony Hall EPC and energy profile

C. Graham Hills EPC and Energy Profile

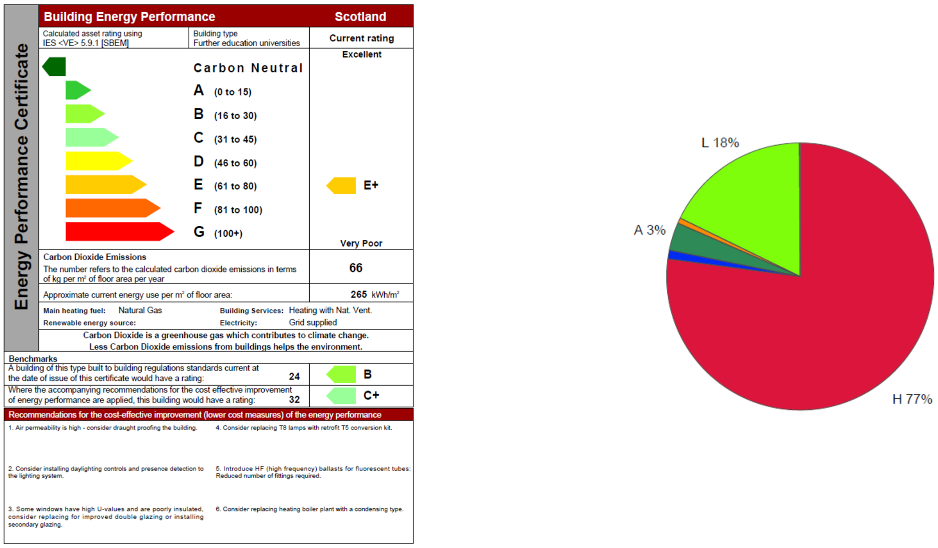


Figure 72: Graham Hills EPC and energy profile

D. Henry Dyer EPC and Energy Profile

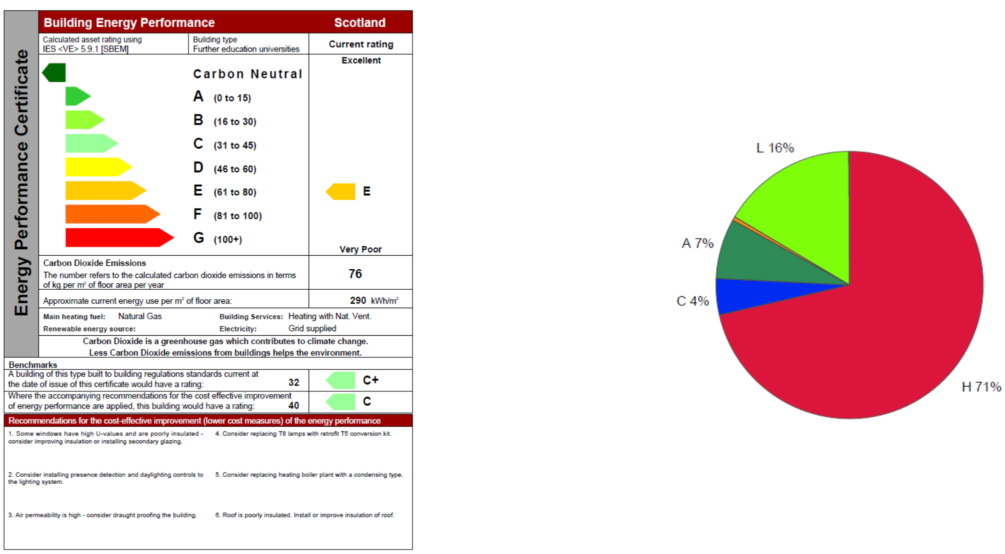


Figure 73: Henry Dyer EPC and energy profile

E. John Anderson Building EPC and Energy Profile

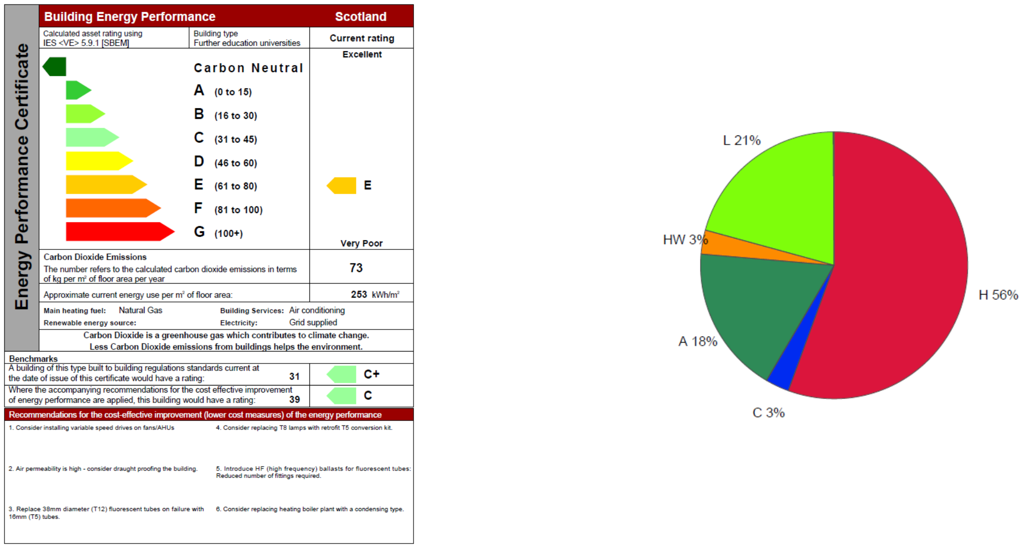


Figure 74: John Anderson EPC and energy profile

F. John Arbuthnott (Robertson Wing) Building EPC and Energy Profile

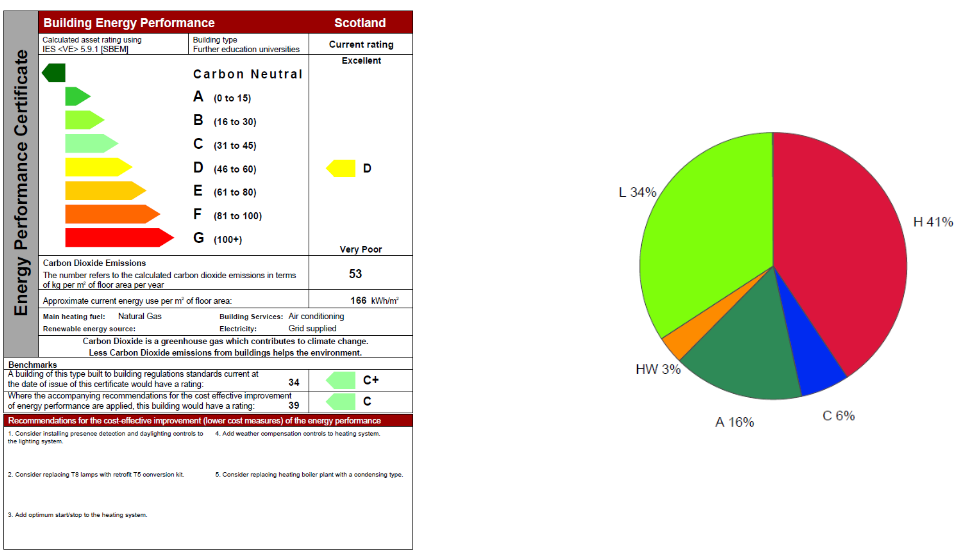
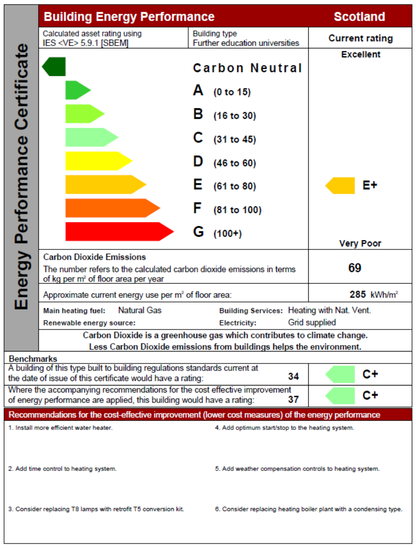


Figure 75: John Arbuthnott EPC and energy profile

G. Lord Todd Building EPC and Energy Profile



Energy Performance Certificate

Building Energy Performance — **Scotland**

Calculated asset rating using IES <VE> 5.9.1 [SBEM] | Building type: Further education universities | Current rating

Excellent

Carbon Neutral
A (0 to 15)
B (16 to 30)
C (31 to 45)
D (46 to 60)
E (61 to 80) — E+
F (81 to 100)
G (100+)

Very Poor

Carbon Dioxide Emissions
The number refers to the calculated carbon dioxide emissions in terms of kg per m² of floor area per year: 69

Approximate current energy use per m² of floor area: 285 kWh/m²

Main heating fuel: Natural Gas
Renewable energy source:
Building Services: Heating with Nat. Vent.
Electricity: Grid supplied

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

Benchmarks
A building of this type built to building regulations standards current at the date of issue of this certificate would have a rating: 34 — C+
Where the accompanying recommendations for the cost effective improvement of energy performance are applied, this building would have a rating: 37 — C+

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

1. Install more efficient water heater.
2. Add time control to heating system.
3. Consider replacing T8 lamps with retrofit T5 conversion kit.
4. Add optimum start/stop to the heating system.
5. Add weather compensation controls to heating system.
6. Consider replacing heating boiler plant with a condensing type.

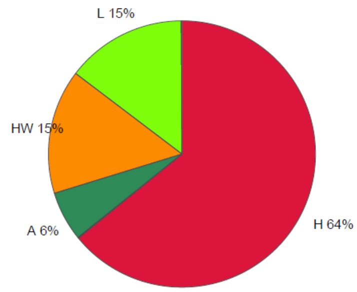
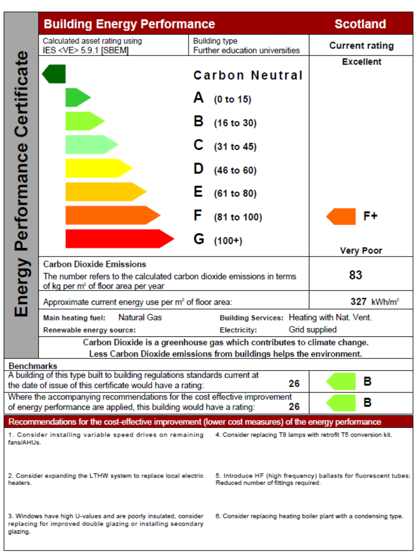


Figure 76: Lord Todd EPC and energy profile

H. McCance Building EPC and Energy Profile



Energy Performance Certificate

Building Energy Performance — **Scotland**

Calculated asset rating using IES <VE> 5.9.1 [SBEM] | Building type: Further education universities | Current rating

Excellent

Carbon Neutral
A (0 to 15)
B (16 to 30)
C (31 to 45)
D (46 to 60)
E (61 to 80)
F (81 to 100) — F+
G (100+)

Very Poor

Carbon Dioxide Emissions
The number refers to the calculated carbon dioxide emissions in terms of kg per m² of floor area per year: 83

Approximate current energy use per m² of floor area: 327 kWh/m²

Main heating fuel: Natural Gas
Renewable energy source:
Building Services: Heating with Nat. Vent.
Electricity: Grid supplied

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

Benchmarks
A building of this type built to building regulations standards current at the date of issue of this certificate would have a rating: 26 — B
Where the accompanying recommendations for the cost effective improvement of energy performance are applied, this building would have a rating: 26 — B

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

1. Consider installing variable speed drives on remaining fans/AHUs.
2. Consider expanding the LTHW system to replace local electric heaters.
3. Windows have high U-values and are poorly insulated, consider replacing for improved double glazing or installing secondary glazing.
4. Consider replacing T8 lamps with retrofit T5 conversion kit.
5. Introduce HF (high frequency) ballasts for fluorescent tubes: Reduced number of fittings required.
6. Consider replacing heating boiler plant with a condensing type.

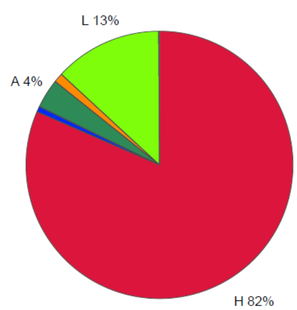


Figure 77: McCance Building EPC and energy profile

I. Ramshorn Theatre EPC and Energy Profile

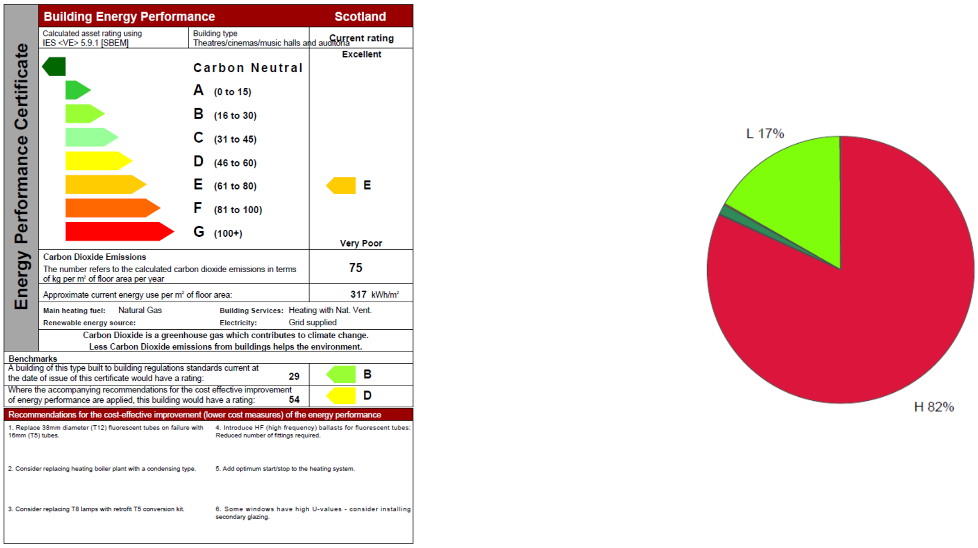


Figure 78: Ramshorn Theatre EPC and energy profile

J. Sir William Duncan Building EPC and Energy Profile

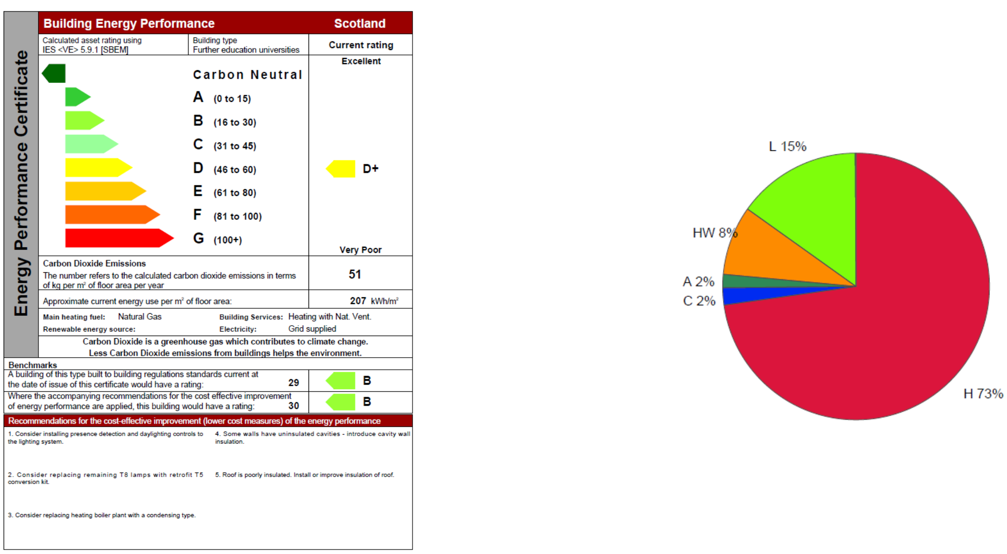


Figure 79: Sir William Duncan EPC and energy profile

K. Thomas Graham Building EPC and Energy Profile

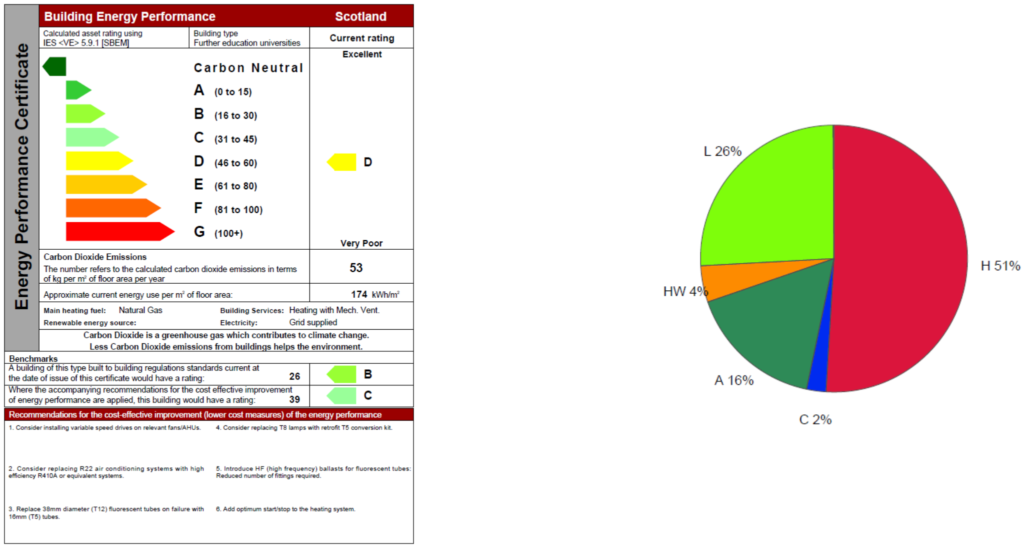


Figure 80: Thomas Graham EPC and energy profile

L. University Centre EPC and Energy Profile

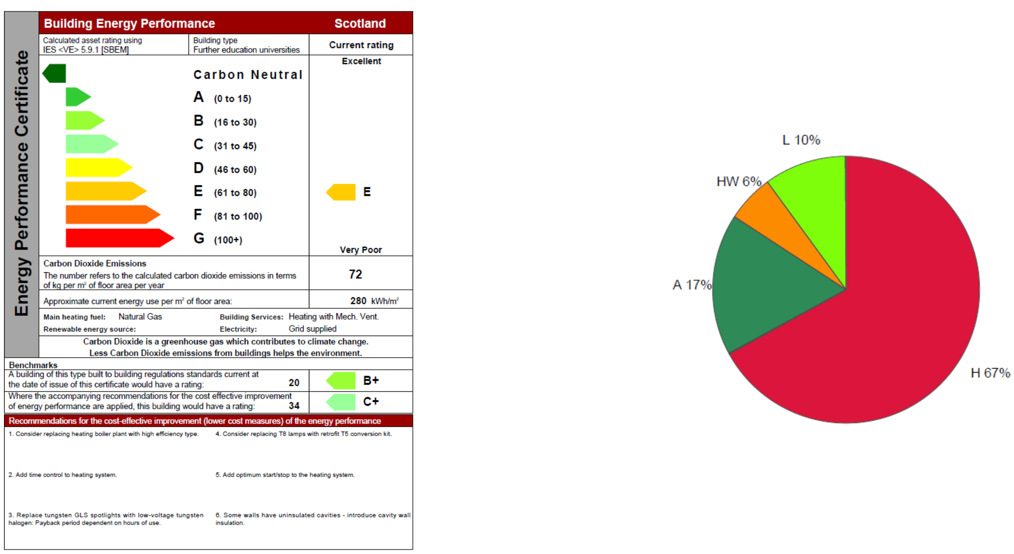


Figure 81: University Centre EPC and energy profile

M. Architecture Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	18
Meeting Room	15
Teaching Laboratories	100
Teaching Room	96
Copier and Printer Room	0
Store	0
Toilets	0

Table 10: Table of information on the occupancy of rooms in the Architecture Building, 3rd floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	16	41	Manual Switch
Fluorescent	36	137	Manual Switch
Fluorescent	28	42	Manual Switch
Fluorescent	58	883	Manual Switch
Fluorescent	70	99	Manual Switch
Fluorescent	65	53	Manual Switch
Fluorescent	125	30	Manual Switch
Compact Fluorescent	26	4	Manual Switch
Compact Fluorescent	40	32	Manual Switch
Incandescent-Halogen	35	46	Manual Switch
Incandescent	100	2	Manual Switch

Table 11: Table of information on electrical lighting in the Architecture Building

N. Graham Hills Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	30
Multiple Occupancy Office	10
Research Office	6
Computer Lab	106
Computer Server Room	0
Meeting Room	9
Teaching Room	198
Store	0
Copier and Printer Room	0
Toilets	0
Plant Room	0
Kitchen	0
Library	4
Common Room	10
Teaching Lab	45
Laboratories	4

Table 12: Table of information on the occupancy of rooms in the Graham Hills Building, 6th floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	3423	Manual Switch
Fluorescent	36	1354	Manual Switch
Fluorescent	28	60	Manual Switch
Fluorescent	58	1182	Manual Switch
Fluorescent	70	26	Manual Switch
Fluorescent	14	550	Manual Switch
Fluorescent	35	40	Manual Switch
Fluorescent	40	9	Manual Switch
Fluorescent	40	2	Manual Switch
Fluorescent	65	40	Manual Switch
Fluorescent	75	1	Manual Switch
Compact Fluorescent	28	10	Manual Switch
Compact Fluorescent	18	38	Manual Switch
Compact Fluorescent	40	6	Manual Switch
Compact Fluorescent	55	6	Manual Switch
Compact Fluorescent	26	80	Manual Switch
Incandescent-Halogen	35	40	Manual Switch
Incandescent-Halogen	50	50	Manual Switch
Incandescent	60	6	Manual Switch

Table 13: Table of information on electrical lighting in the Graham Hills Building

O. Henry Dyer Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	22
Multiple Occupancy Office	67
Meeting Room	0
Library	0
Computer Server Room	0
Toilets	0
Teaching Room	40
Store	0
Copier and Printer Room	0
Kitchen	0

Table 14: Table of information on the occupancy of rooms in the Henry Dyer Building, 2nd floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	280	Manual Switch
Fluorescent	36	51	Manual Switch
Fluorescent	28	47	Manual Switch
Fluorescent	24	200	Manual Switch
Fluorescent	58	170	Manual Switch
Compact Fluorescent	40	240	Manual Switch

Table 15: Table of information on electrical lighting in the Henry Dyer Building

P. John Anderson Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	17
Multiple Occupancy Office	14
Computer Lab	28
Computer Server Room	0
Meeting Room	0
Research Office	3
Store	0
Copier and Printer Room	0

Table 16: Table of information on the occupancy of rooms in the John Anderson Building, 2nd floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	601	Manual Switch
Fluorescent	28	99	PIR/Manual Switch
Fluorescent	65	469	Manual Switch
Fluorescent	58	582	Manual Switch
Fluorescent	125	11	Manual Switch
Fluorescent	70	159	Manual Switch
Fluorescent	85	226	Manual Switch
Fluorescent	35	24	Manual Switch
Fluorescent	14	123	Manual Switch
Fluorescent	36	55	Manual Switch
Compact Fluorescent	40	122	Manual Switch
Compact Fluorescent	26	164	PIR/Manual Switch
Incandescent-Halogen	35	24	Manual Switch
Incandescent	100	7	Manual Switch
Metal-Halide	200	6	Manual Switch

Table 17: Table of information on electrical lighting in the John Anderson Building

Q. John Arbuthnott Building Lighting Data

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	815	Manual Switch
Fluorescent	36	294	Manual Switch
Fluorescent	28	10	Manual Switch
Fluorescent	58	908	Manual Switch
Fluorescent	70	8	Manual Switch
Compact Fluorescent	26	26	Manual Switch
Compact Fluorescent	40	40	Manual Switch
Incandescent-Halogen	50	5	Manual Switch
Metal-Halide	150	7	Manual Switch

Table 18: Table of information on electrical lighting in the John Arbuthnott Building

R. McCance Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	43
Research Office	18
Computer Lab	25
Computer Server Room	0
Meeting Room	0
Teaching Room	45
Store	1
Copier and Printer Room	0
Toilets	0
Medical Rooms	0
Kitchen	0

Table 19: Table of information on the occupancy of rooms in the McCance Building, 2nd floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	1146	PIR/Manual Switch
Fluorescent	36	78	PIR/Manual Switch
Fluorescent	28	71	PIR/Manual Switch
Fluorescent	28	2	PIR/Manual Switch
Fluorescent	58	468	PIR/Manual Switch
Fluorescent	70	306	PIR/Manual Switch
Fluorescent	14	20	PIR/Manual Switch
Fluorescent	8	28	PIR/Manual Switch
Compact Fluorescent	18	11	PIR/Manual Switch
Compact Fluorescent	40	125	PIR/Manual Switch
Compact Fluorescent	26	209	PIR/Manual Switch
Incandescent-Halogen	35	54	PIR/Manual Switch
Metal-Halide	150	26	PIR/Manual Switch

Table 20: Table of information on electrical lighting in the McCance Building

S. Royal College Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	74
Multiple Occupancy Office	64
Research Office	41
Computer Lab	66
Laboratories	9
Meeting Room	6
Teaching Room	158
Store	0
Foyer	17
Toilets	0
Common Room	0
Kitchen	0
Workshops	6
Learning Resource Centre	12
Plant Rooms	0

Table 21: Table of information on the occupancy of rooms in the Royal College Building, 2nd floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	1983	Manual Switch
Fluorescent	36	888	Manual Switch
Fluorescent	28	203	Manual Switch
Fluorescent	35	258	Manual Switch
Fluorescent	58	916	Manual Switch
Fluorescent	70	120	Manual Switch
Fluorescent	28	3	Manual Switch
Fluorescent	54	236	Manual Switch
Fluorescent	14	174	Manual Switch
Fluorescent	125	618	Manual Switch
Fluorescent	65	217	Manual Switch
Fluorescent	75	60	Manual Switch
Compact Fluorescent	26	604	Manual Switch
Compact Fluorescent	40	245	Manual Switch
Compact Fluorescent	55	19	Manual Switch
Metal-Halide	150	56	Manual Switch
Metal-Halide	200	10	Manual Switch
Incandescent-Halogen	35	151	Manual Switch
Incandescent	60	14	Manual Switch

Table 22: Table of information on electrical lighting in the Royal College Building

T. Sir William Duncan Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	16
Multiple Occupancy Office	16
Research Office	10
Plant Room	0
Common Room	0
Meeting Room	8
Foyer	0
Store	0
Copier and Printer Room	0
Toilets	0

Table 23: Table of information on the occupancy of rooms in the Sir William Duncan Building, 2nd floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	60	Manual Switch
Fluorescent	36	35	Manual Switch
Fluorescent	28	41	Manual Switch
Fluorescent	35	378	Manual Switch
Fluorescent	58	56	Manual Switch
Fluorescent	70	2	Manual Switch
Fluorescent	65	14	Manual Switch
Fluorescent	85	2	Manual Switch
Compact Fluorescent	26	297	Manual Switch
Compact Fluorescent	40	127	Manual Switch
Incandescent	26	1	Manual Switch
Metal-Halide	35	23	Manual Switch

Table 24: Table of information on electrical lighting in the Sir William Duncan Building

U. Thomas Graham Building Occupancy and Lighting Data

Room Type	Aggregated Occupancy
Single Occupancy Office	7
Multiple Occupancy Office	4
Research Office	24
Laboratories	50
Waiting Room	0
Store	8
Toilets	0

Table 25: Table of information on the occupancy of rooms in the Thomas Graham Building, 2nd Floor

Lamp Type	Power (W)	Number of Fittings	Control Method
Fluorescent	18	322	PIR/Manual Switch
Fluorescent	36	298	PIR/Manual Switch
Fluorescent	28	127	PIR/Manual Switch
Fluorescent	70	263	PIR/Manual Switch
Fluorescent	58	586	PIR/Manual Switch
Fluorescent	100	16	PIR/Manual Switch
Fluorescent	49	132	PIR/Manual Switch
Fluorescent	14	8	PIR/Manual Switch
Fluorescent	65	7	PIR/Manual Switch
Fluorescent	75	6	PIR/Manual Switch
Fluorescent	125	62	PIR/Manual Switch
Compact Fluorescent	18	1	PIR/Manual Switch
Compact Fluorescent	40	1251	PIR/Manual Switch
Compact Fluorescent	26	823	PIR/Manual Switch
Incandescent-Halogen	35	16	PIR/Manual Switch
Incandescent-Halogen	50	1	PIR/Manual Switch
Metal-Halide	150	7	PIR/Manual Switch

Table 26: Table of information on electrical lighting in the Thomas Graham Building

V. Graphs Comparing Monthly Dynamic Simulation and Measured Data for Individual Buildings

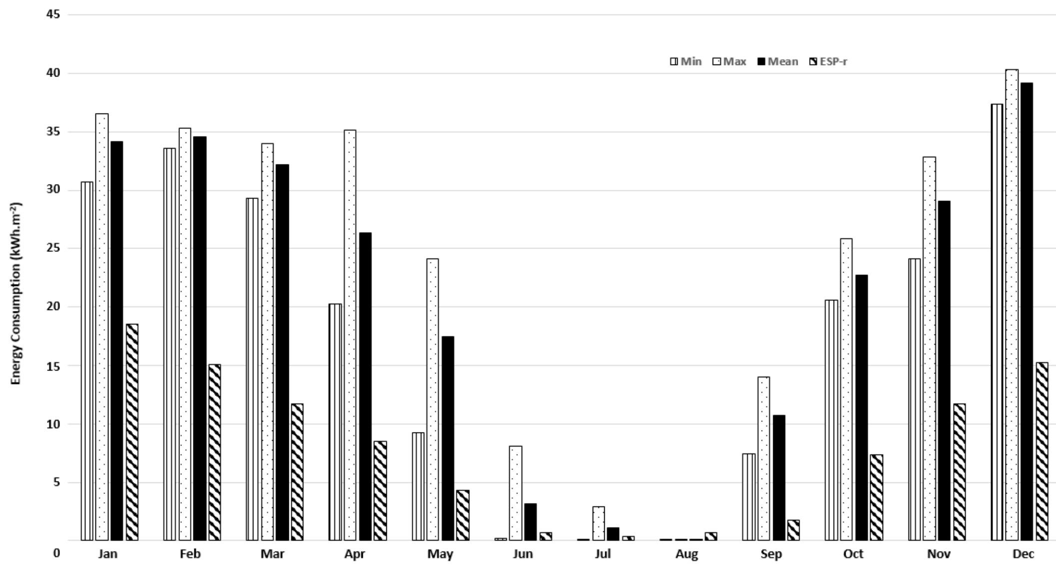


Figure 82: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the Architecture Building

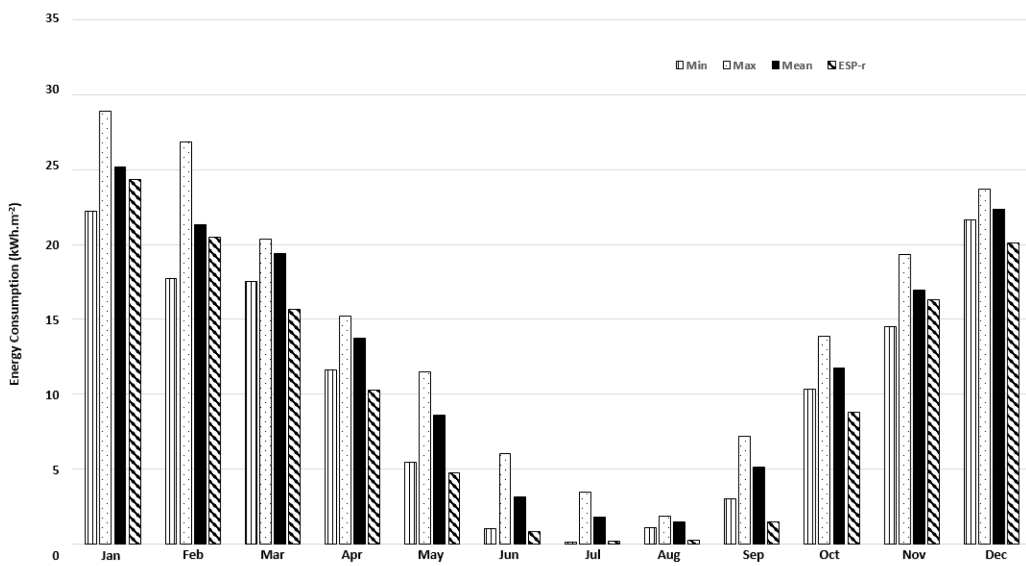


Figure 83: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the Graham Hills Building

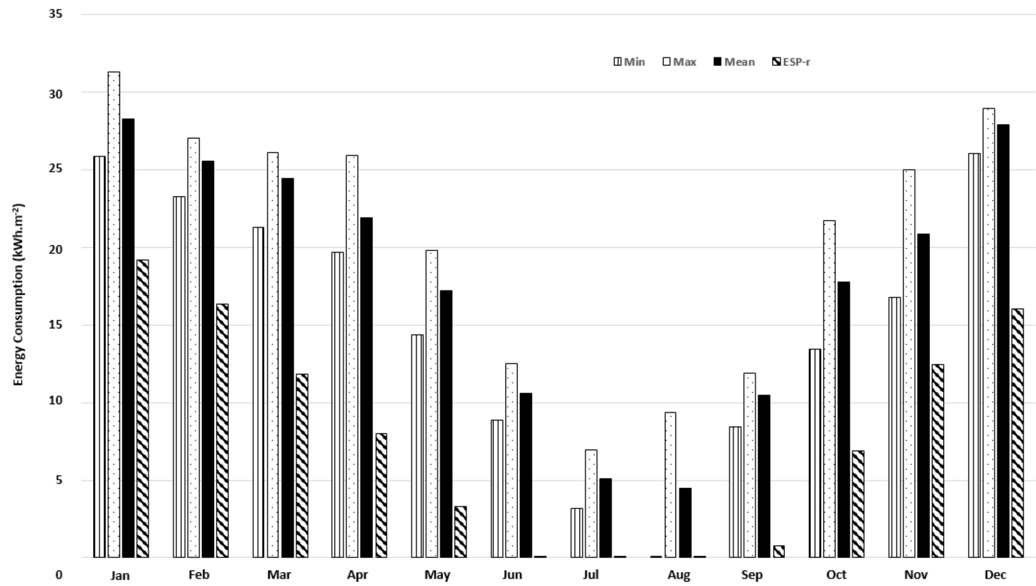


Figure 84: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the Henry Dyer Building

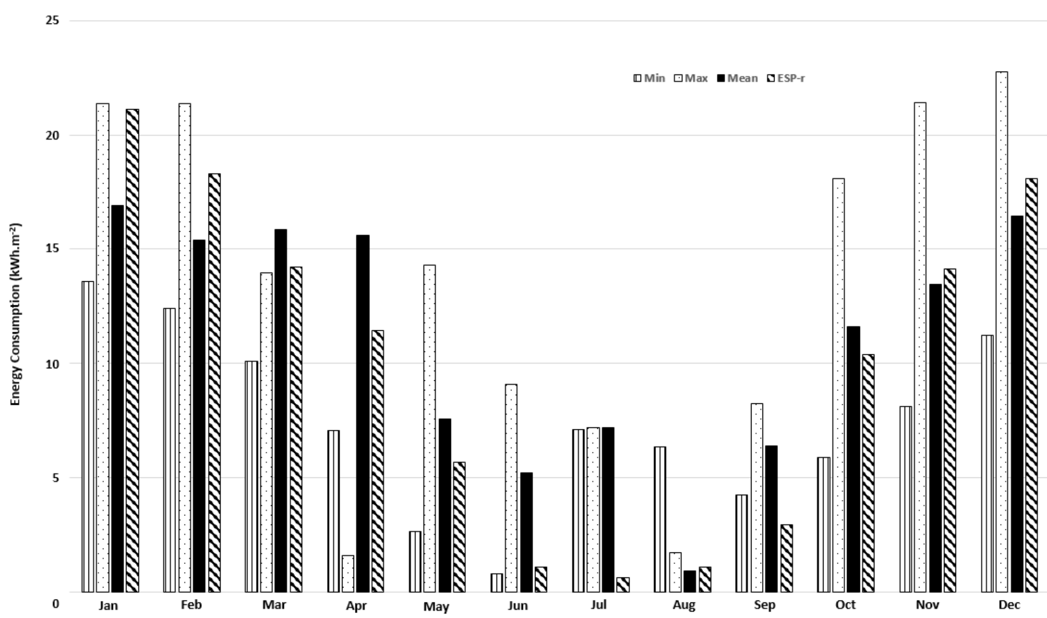


Figure 85: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the John Anderson Building

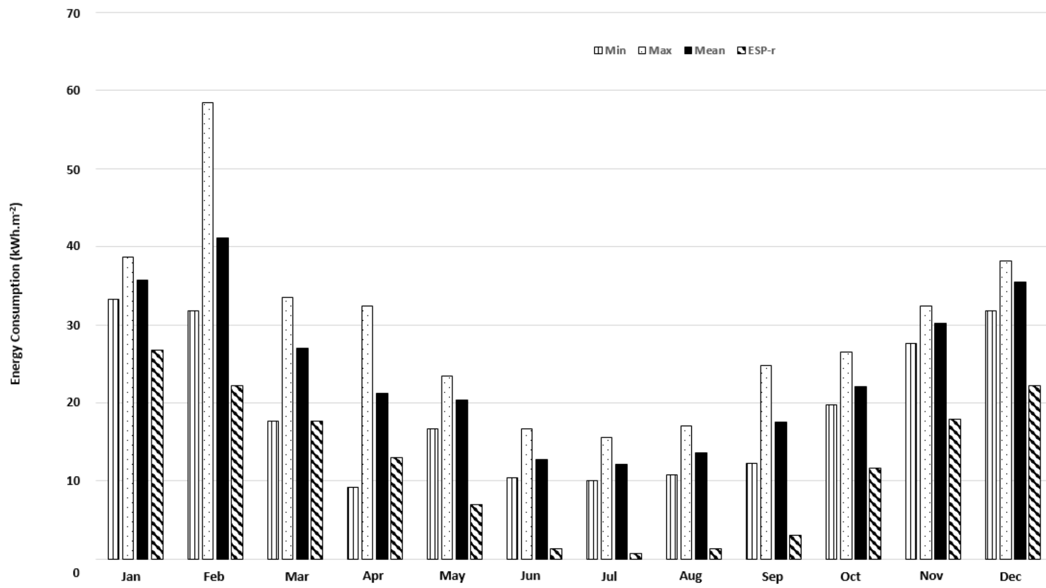


Figure 86: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the John Arbuthnott Building

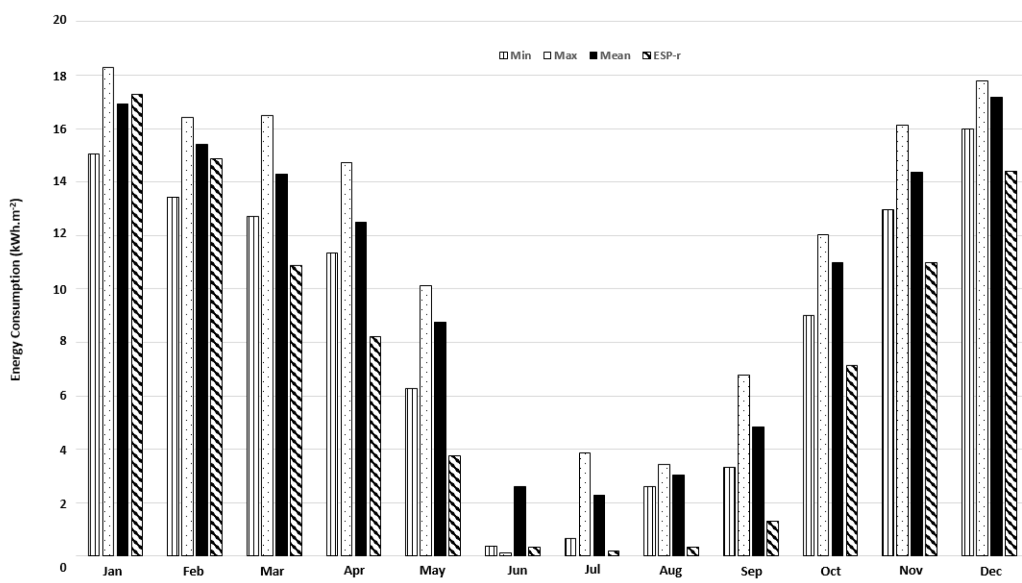


Figure 87: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the McCance Building

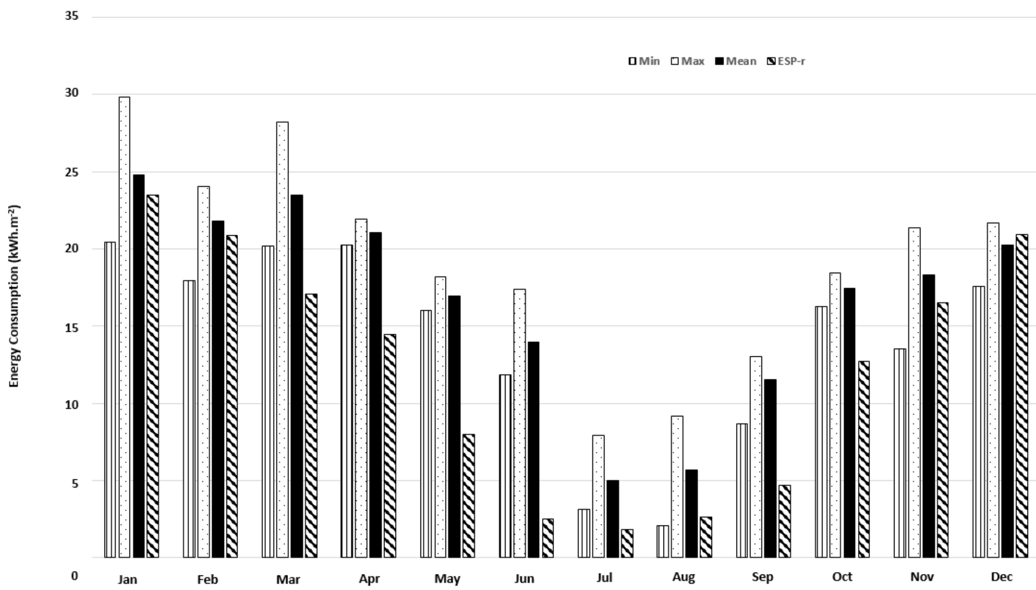


Figure 88: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the Royal College Building

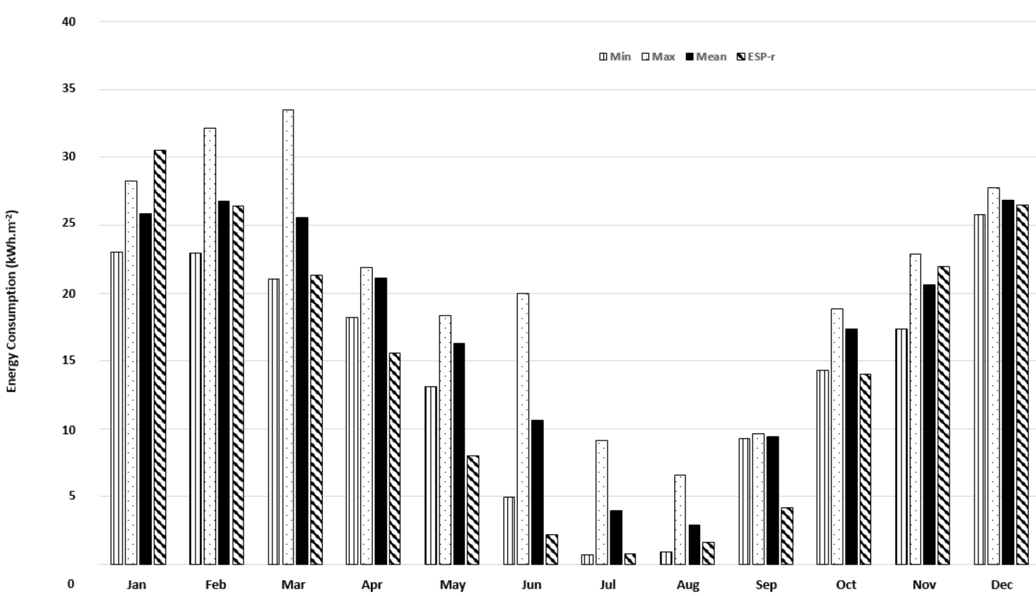


Figure 89: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the Sir William Duncan Building

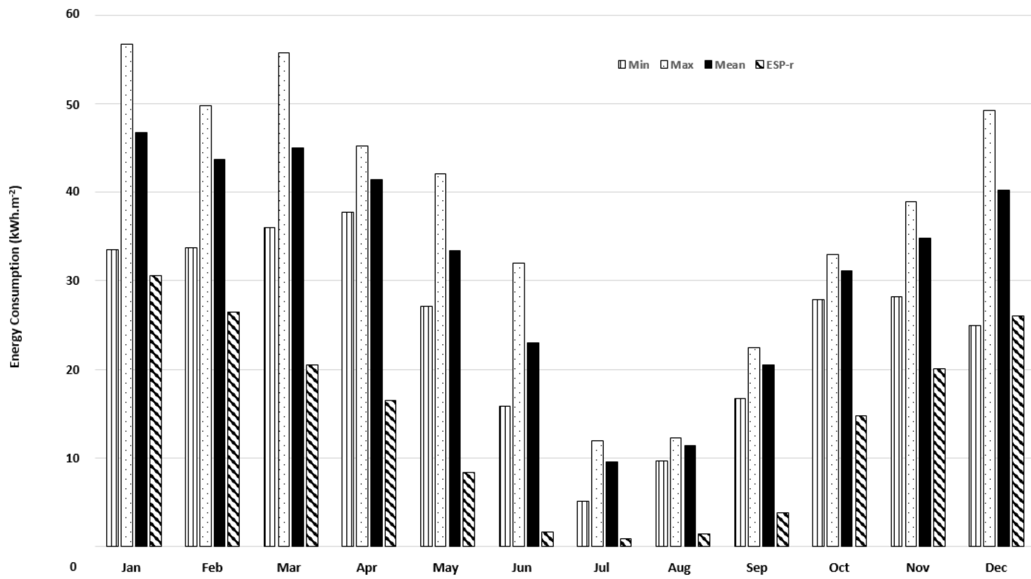


Figure 90: The mean, minimum and maximum monthly measured energy consumption vs dynamic simulation for the Thomas Graham Building

W. United States Department of Energy Standardised Occupancy Schedules for Office Buildings

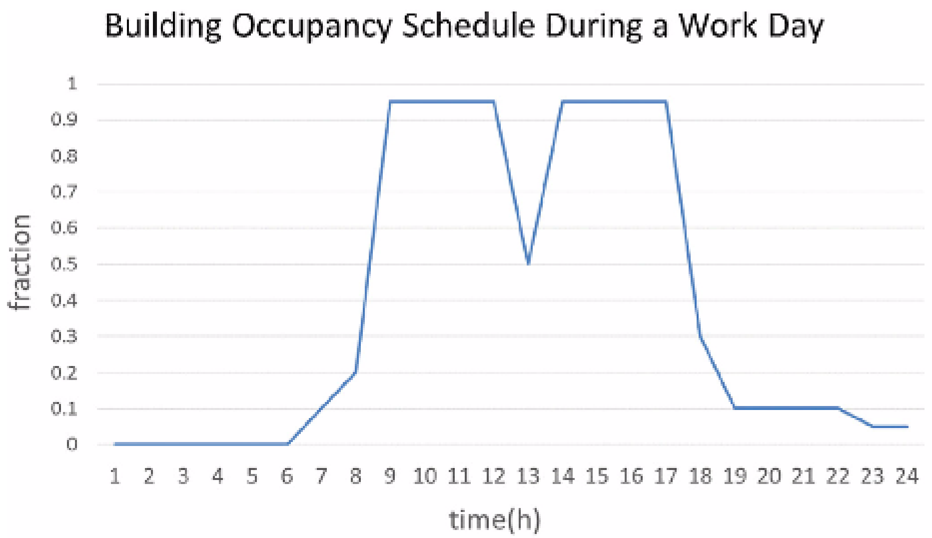


Figure 91: Standardised office building occupancy schedule for working days [162]

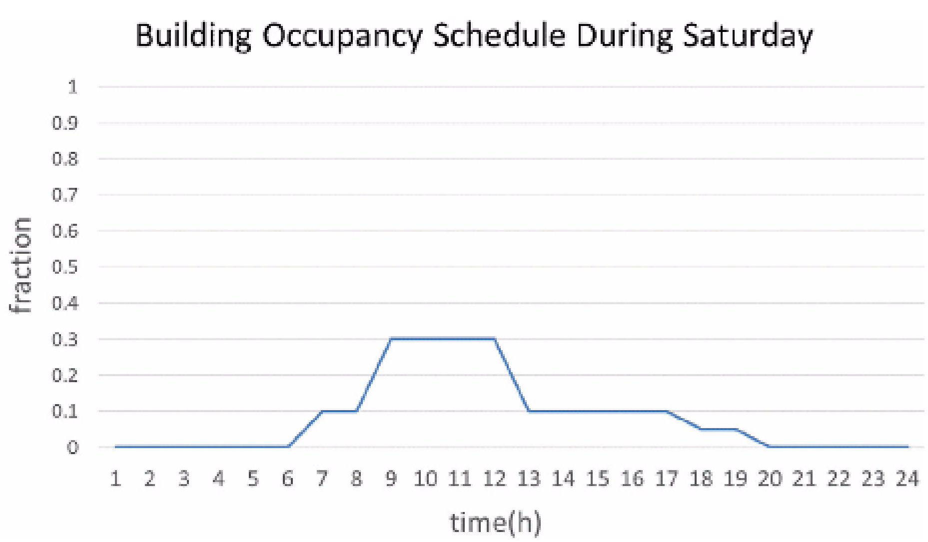


Figure 92: Standardised office building occupancy schedule for Saturdays [162]

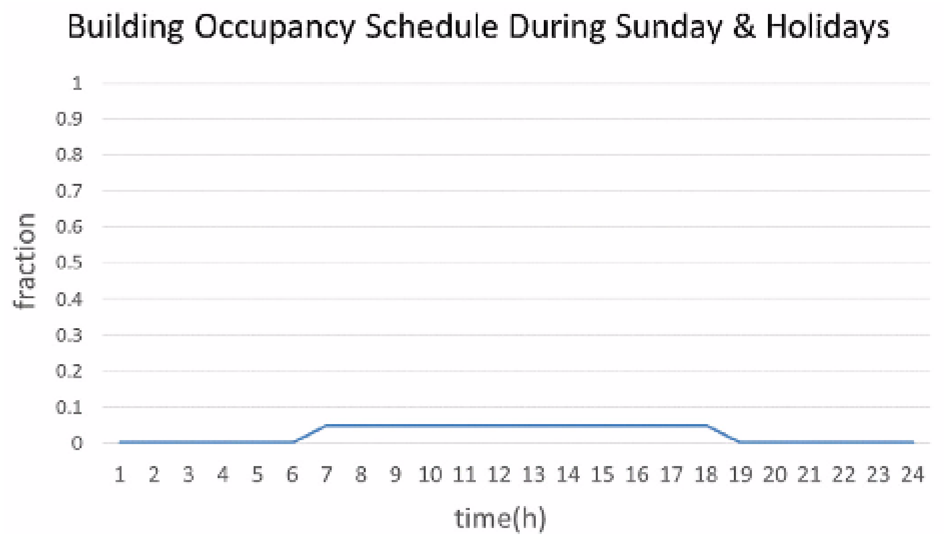


Figure 93: Standardised office building occupancy schedule for Sundays [162]