Modelling thermal loads for a non-domestic building stock. Associating *a priori probability* with building form and construction - using building control laws and regulations.

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Thesis submitted to the University of Nottingham
for the Degree of Doctor of Philosophy

June 2009

Acknowledgements

I would like to thank Dr. Shenyi Wu for his guidance and support in carrying out the research work presented within this thesis. He has given me great insight into how best to approach research and has helped develop a solid base from which I look forward to growing my research skills and career.

Professor Saffa Riffat has acted as my second supervisor and has shown a great deal of trust in my ability, to which I am truly grateful.

This thesis was sponsored by EPSRC and E.ON. E.ON offered the opportunity to utilise a building for a case study, which helped to develop my knowledge of energy modelling and building physics. John Bateman, Alistair Howie and Andy Swaine have (among others) provided support from E.ON. Their time and efforts are greatly appreciated.

Carrying out this PhD has resulted in many stressful times that were always put into perspective by my fantastic wife, Esmé, and most recently by the arrival of our daughter - Solveig Lilja. Their love and support has made all the difference.

I would also like to acknowledge the unofficial support and advice that has come from fellow PhD candidates and other research staff within the School of the Built Environment.

Abstract

Building Energy Assessment at stock level is an important task in identifying the best strategies for achieving a more energy efficient and low carbon society. Non-domestic buildings are identified to make up 17% of total energy consumption in England and Wales and 19% of CO_2 emissions. To understand the energy requirement of the non-domestic stock, large scale energy surveying has been carried out namely in the Non-Domestic Building Stock project, Carbon Reductions in Buildings project and Technology Assessment for Radically Improving the Built Asset Base project. The energy assessment process has relied mainly on empirical data collection with some complimentary modelling work.

It is recognised that building energy surveys are difficult to carry out and expensive on time and technical resources. Metered energy use is (on a large scale) necessarily crude and does not capture a detailed breakdown as to where the measured energy is being used.

With improving computer ability, dynamic energy modelling tools allow for detailed assessment of building energy use and comfort performance. Using Monte Carlo simulation a method of assessing the probable variability in non-domestic building thermal energy loads was developed. The method was developed to capture the high variability in non-domestic buildings at national stock level and determine how stock level physical form variations impact thermal loading.

The high level variability in non-domestic building form and surrounding topography (influencing energy demands) are considered to be influenced by building control laws and building regulations. It is recognised that such control documentation often stipulates guidelines and best practice - not precise values. As such historical regulations were used to develop basic probability distributions of potential physical characteristics associated with non-domestic buildings.

Stating that the building form and site characteristics are randomly determined from the defined probability distributions, a stochastic modelling process to represent thermal variation in a building stock was developed. The process utilised historical building control documentation to describe the existing non-domestic building stock. This provided a potential means for categorising buildings by period of construction. The model utilised a dynamic simulation model as a 'black-box' for predicting base thermal loads.

Keeping internal casual gains as constant per unit floor area in all model runs, the model inputs of construction, window-wall ratio, roof pitch/type, adventitious leakage, radiative view factors and urban solar obstruction were varied according to period of construction control. Other factors, such as floor area, number of storeys, length width ratio and internal layout were also considered.

Running the model separately for each identified period of construction showed a general trend in reduced heating loads for buildings built under latter building regulations, but with a reversed trend in cooling loads. This reflects the nature of building energy regulations that stipulate maximum U-values of building components, without consideration of the dynamic thermal behaviour of a building. This raised an important question of whether simple U-value regulation will result in a less thermally efficient building stock for a warming climate.

By separating open plan and cellular building forms the Monte Carlo simulations showed a significant impact of increased thermal mass on thermal behaviour. The increased thermal mass of the cellular

models positively impacted cooling loads, most notably for latter construction periods. The cellular model resulted (in some instances) in over a four-fold increase in the mean heating load as compared to the equivalent load distribution for open plan layout.

Adventitious leakage was recognised as an important influence on thermal loads. Investigating the literature highlighted little available data on air leakage rates in existing buildings. A building component leakage model was developed to calculate the adventitious leakage rate to be applied in the probability modelling. This model demonstrated a large variability in uncontrolled leakage rates of a building.

Radiative thermal loading by long wave (Infrared) exchange and short wave (solar) loading were considered in relation to surrounding topography. In an urban environment, buildings (and other physical structures) provide solar shading to other buildings and obscure the most influential radiative heat exchange of a building surface (i.e. that of the surface to the sky). Town planning laws and daylight design control methods were used to calculate modal angles of elevation between the base of one building and the top of an opposing building.

Simplifications of expected urban topography were made in order to calculate modal sky view factors and associated solar obstructions. In the light of building models only applying a single sky view factor to all external walls of a building the simplifications required by this method were considered reasonable.

Two methods of validating the stock level assessment method were presented. The first method, applies a statistical downscaling to the model that can be used in comparison to the results of detailed energy models of existing buildings. A second process aimed to validate the distributions applied to the model inputs. Expert knowledge had to be used in a qualitative assessment as empirical data on stock level parameter distribution was not available.

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Nomenclature

α	Thermal Diffusivity - accounts for thermal conductivity and flux (m^2/s)
$\mathbf{\Delta P}$	Pressure Differential (Pa)
γ	Distribution Skew
∞	Infinity
κ	Thermal Conductivity (W/m.K)
μ	Mean
ϕ_d	Decrement time lag (h)
ϕ_s	Surface factor time lag (h)
ϕ_Y	Admittance time lead (h)
ρ	Density (kg/m^3)
σ	Standard Deviation
σ_{SB}	Stefan-Boltzmann constant of black body radiation($W/m^2/K^4$)
θ	Temperature (K) - also used to represent angles in geometric descriptions
θ_{sub}	Temperature (K) of substance or object denoted by subscript 'sub'.
ξ	Surface Emissivity
ACH	Air Changes per Hour - total volume air change of modelled air zone
A	Surface Area (m^2)
BEM	Building Energy Modelling
$\mathbf{c}_p$	Specific Heat Capacity (J/kg.K)
CDF	Cummulative Density Function
DSM	Dynamic Simulation Model - with respect to building energy modelling
FFA	Floor Footprint Area (m^2)
f	Decrement factor - ratio of external heat wave amplitude to the internal heat wave amplitude

h_c Forced convection coefficient relating to surface roughness and wind speed (W/m^2/K)

HVAC Heating, Ventilation and Air Conditioning

iqr Inter-Quartile Range - a measure of dispersion incorporating all values from the 25th to the 75th percentile

KS Kolmogorov-Smirnov test - a goodness-of-fit test of two one-dimensional distributions.

LWR Length Width Ratio

MCA Monte-Carlo Analysis

m Modal value (statistical definition)

NDBS Non-Domestic Building Stock (specifically considered for England and Wales)

ND Non-Domestic

PDF Probability Density Function

q_{conv} Unit convective heat exchange (W/m^2)

Q_{sub} Air flow rate (m^3/s) - where a subscript is indicative of the building component to which the flow is related

q Net radiant heat exchange (W)

R Thermal Resistance (K.m^2/W)

Sν Sky view factor

s Surface Response factor - re-admitted heat flux (to the internal environment node) to the total absorbed heat flux at constant temperature

U U-value, total thermal transmittance (W/m^2.K)

V Wind speed (m/s)

WWR Window Wall Ratio

Y Y-value (admittance), thermal storage (W/m^2.K)

Chapter 1

Introduction

In an era of high concern over energy use, energy security and associated greenhouse gas emissions, research efforts to improve building energy efficiency are of increasing importance. For countries within the Organisation for Economic Co-operation and Development (OECD), building stocks are usually well established. In Britain approximately 75% of non-domestic building floor space was built before the introduction of Building Energy Regulations Part-L (1985) [3, 19]. Bruhns et al. [20] identify a low replacement rate in the UK's established building stock; placing greater emphasis on low carbon retrofit strategies for impacting short-to-mid term (~50 year) CO_2 emissions. This drive was highlighted by a CIBSE event as part of their 100 day carbon clean up campaign [21, 22] and is recognised in research and by government as an important consideration in improving national energy efficiency and sustainability [23] .

The European Energy Performance in Buildings Directive (EPBD - 2002) requires buildings within the EU Member States to be given an energy rating - with the intention to encourage improved energy efficiency and reduced CO_2 emissions. This requires all new buildings to provide an energy certificate based on calculation methods (Asset Rating) and metered energy use (Operational Rating). Existing buildings, however, are only required to carry out such certification when undergoing significant refurbishment or at change of tenancy.

The asset rating for existing buildings, however, is problematic in the likely event of limited design data required for energy calculation (whether by detailed dynamic simulation or by use of the Simplified Building Energy Model (SBEM)) [24]. This is raised as a concern within the Carbon Reduction in Buildings (CaRB) Project [25, 26].

At a stock level, the collection of asset and operational ratings on existing buildings is a lengthy task that could hinder the effectiveness of energy saving initiatives for the short-to-mid term. There is, therefore, a requirement for a (relatively) quick stock level modelling approach that can offer insight into non-domestic building energy usage and efficiency potential.

This thesis investigates a modelling method that can account for the complexity and variability in the non-domestic building stock. Utilising a dynamic energy simulation tool to calculate probable building thermal energy performance, period of construction was used as the main identifying criteria for setting expected value ranges and distributions associated with input parameters to the model.

1.1 Project Aims and Objectives

The high level of variability in the non-domestic building stock makes stock level assessment and understanding of non-domestic building energy performance a complex subject. Large scale empirical assessment of the UK non-domestic stock, combined with sample building modelling, has been carried out to improve stock level understanding of building energy performance and the potential for improved performance [27, 28, 29, 1, 26, 30, 31]. These studies aim(ed) to provide simple models to aid building authorities, government and other relevant organisations to predict energy use and potential energy savings within the building stock.

To contribute to the field of non-domestic stock level assessment the aims of this thesis were:

(i) to assess a methodology for understanding the impact of uncertainty in non-domestic building energy consumption and

(ii) to assess the impact of building period on thermal energy performance - as a potentially useful method for categorising a building stock.

The objectives were:

(i) to utilise building laws and regulations (in combination with published data on building characteristics) as tools for developing an understanding of probable variation in building structure and form characteristics for the non-domestic building stock of England and Wales

(ii) to design a method of assessing the influence of variable building structure and form on probable thermal energy loads - incorporating dynamic building simulation tools

(iii) to compare the sensitivity of building component form on annual thermal loading according to different building periods.

The objectives required a review of the historical building regulations, by-law and town planning laws documentation. From this, instability in the building control laws pre-1894 was identified as problematic in understanding the building stock so a period of 1894 to Present day was chosen for modelling.

For some building energy concerns (such as adventitious air leakage and radiative view factors - see chapters 5 and 6, respectively) building laws did not offer direct control on physical values. In these instances interpretation of laws/regulations deemed to indirectly affect these concerns was necessary. Published data from relevant research were used in combination with the building controls in these instances.

To identify the building characteristics of concern to energy performance - specifically in the context of dynamic energy modelling - a review of literature pertaining to building energy assessment methods was carried out. As uncertainty in building characteristics at stock level was to be captured within the modelling procedure, methods of uncertainty modelling and analysis for building energy simulation were also reviewed (chapter 2).

The methods of building energy simulation utilised in the investigation are discussed in chapter 3 to better understand how the building data should be presented for modelling purposes. Basic distribution types were identified for parameters that could not be associated with detailed probability distributions at stock level (see chapter 3).

The probability model was designed using the Monte-Carlo principle, by which input parameters were randomly chosen, using pseudo-random algorithms representative of the associated probability distribution for the considered parameter. Conditional relationships between building parameters were identified in certain building regulations. These conditions formed part of the program logic when 'randomly' setting the building parameters.

The influence of parameter variability on a set of base-case buildings for each identified building period was carried out by one-at-a-time sensitivity analysis. This provided an understanding of the varying thermal influence of building component properties according to different periods of construction.

1.2 Probability Modelling

The intention of the thesis is not to capture the exact variability in stock level thermal performance but to offer a relatively quick modelling method that offers insight into the impact of probable stock variability on thermal loading. The energy influencing characteristics of a building are, therefore, randomly determined from theoretically derived probability distributions: resulting in a building model that is representative of a probable (i.e. non-specific) building in the considered stock. As the building characteristics are randomly determined from the applied probability distributions the method offers a stochastic modelling process for assessment of thermal loads in the building stock.

Associating the parameter distributions with period of construction[1] the model can assess the statistical significance of construction period on non-domestic thermal energy loads.

This approach was taken to consider the heterogeneity of the non-domestic building stock: a key factor in the currently limited understanding of the stock *'composition and energy use'* [32].

1.3 Building Construction Period

The development of a building stock is influenced by socio-economic factors [33, 6] with guidance from building controls and town planning laws. For a developed building stock, such as that in England and Wales, building controls have improved and broadened focus on different factors to influence structural, comfort and, more recently, energy performance of buildings [34, 35, 36, 37, 38]. On an individual basis a building's design and location is influenced by design preferences, expected use and money constraints that result in a random mix of buildings within a building stock.

A building's energy performance is dependent on the structural and design methods and building components used in construction [32]. Building Regulations (introduced 1965/1966) provide guidance to design and construction and increasingly have placed greater emphasis on energy performance. Prior to the introduction of regulations, building by-laws were issued by government and used as guides to safe (and healthy) building development [39, 14].

[1] By use of building regulations as a tool for identifying modal (in the statistical sense) parameter values and/or ranges in parameter values.

In combination with town planning laws, building regulations and by-laws are considered to offer insight into the parameters of existing non-domestic buildings. Using these historical instruments for the purpose of modelling results in a categorisation of building types. The period of construction - by which the model categorises probable building parameter values - is a result of the control laws/regulations in force at the time of the stated period.

1.4 Base Thermal Load

Base thermal load is defined here as the heating and cooling loads not met by the basic structure of a building (i.e. with no heating, cooling or ventilation systems in place) to maintain set levels of thermal comfort. The base thermal load therefore, provides a measure of the thermal performance of a building's basic structure. In the case of this study thermal comfort was considered by internal air temperature alone.

1.5 Motivation

A focus has been given to building thermal loads as empirical data shows heating and cooling loads dominate non-domestic building energy demands: accounting for an average of 60% of total energy use [1, 40, 41, 42, 43]. Introducing strategies that enable effective reduction in heating and cooling loads to existing non-domestic buildings is, therefore, understood to offer a potentially significant route to reducing CO_2 emissions.

Two methods of CO_2 reduction can be applied to buildings: 1) energy supply from sustainable sources and 2) reduction in building energy demand. A combination of both methods can be adopted to provide the biggest carbon reduction. Current technology for harnessing sustainable sources is complicated by demand-supply temporal and spatial differences, low energy yields and siting issues[2]; it is important to pursue demand reduction strategies before considering low carbon energy supply.

Effective strategies for thermal energy reduction in buildings (at stock level) requires an understanding of the building stock to which policies are to be applied. An example for the domestic building stock for the UK is presented in [44]. The non-domestic building stock, however, is more complex than the domestic building stock due to greater variability in form and use.

Existing data from stock level non-domestic building energy assessment is currently limited. The Non-Domestic Building Stock (NDBS) Project [28], CaRB and TARBASE projects [26, 30] offer (to date) the largest studies of building stock form, use and energy performance. Though the NDBS Project offers the largest data set on non-domestic buildings (via examination of the Valuation Office Agency, VOA, database) energy performance surveys cover less than 1% of the building stock[3]. The building data offered by the VOA database is also complicated by the fact it presents data by premises. Premises are associated with occupant and, therefore, multiple premises can be associated with one building as can multiple buildings be associated with one premises.

A recent scoping study has summarised the work of the past 15+ years for investigating the non-domestic building stock of the UK in relation to energy use and CO_2 emissions [32]. The issue of premises and

[2] From environmental concerns to performance issues.
[3] $\sim$ 7000 premises of a total of 1.7 million held in VOA database.

building is raised; considering the generation of *'building entities'* a key task for future work as *'characteristics and thermal properties of buildings'* are paramount to determining their energy consumption and efficiency.

Associating surveyed energy data with premises is complicated by the inconsistent definition of premises, the basic capture of energy use in buildings[4] and influence of variable occupancy patterns and behaviour. A method that can investigate the impact of varying characteristics on energy demands should be favoured in order to help design an effective reductions strategy.

Computer based simulation allows for investigation of the influence of physical and operational building characteristics on energy loads. Utilising currently available building energy simulation tools requires knowledge of the construction and form characteristics to calculate thermal (and other energy) loads. The variation in construction parameters alone is not truly understood within the UK building stock and empirical assessment of such variability is not feasible (for temporal, financial and disruptive reasoning).

A theoretical approach is required that accounts for stock variability in a relatively cost and time efficient manner. It is recognised (as presented in [44]) that building regulations and other controls have and do influence building form characteristics. This thesis, therefore, examines a method for modelling the variation in thermal loading of the non-domestic building stock of England and Wales. The method chosen combines computational building simulation modelling with a statistical analysis of building control documentation.

Categorising the building stock helps to form smaller building groups that can be more effectively targeted by policy for energy reduction. As building control is to be used in developing a probabilistic representation of thermal loading associated with non-domestic buildings, the period of control laws under which a building was designed/constructed is presented as a building stock classifier. The ability of the different construction periods to provide clear categories in building thermal behaviour are, therefore, to be analysed.

1.6 Model Application

The modelling approach presented in this thesis provides a tool for strategic energy assessment of the existing building stock. Categorised by period of construction the statistical data can be used to provide guidance on best energy saving potential within a building stock. Though not developed in this thesis, the method also provides opportunity to statistically evaluate energy saving retrofit measures.

The high level data offered by the model would be best placed in government or other large organisation decision making. More specifically it could be used in decision processes for understanding (with statistical confidence) where investment in an existing stock - grouped by period of construction - is going to provide greatest energy saving for a given retrofit strategy/technology.

As the existing building stock undergoes replacement, the model can be used to demonstrate probable impact of a changing building stock on thermal loading (according to its makeup by different construction periods).

[4]From metered fuel consumption that does not account for system efficiencies or clear breakdown of energy use in all cases [40].

1.7 Thesis Structure

Chapter 2

A review of current building energy assessment methods and projects. A review of computational building energy simulation is given. Uncertainty modelling within dynamic simulation models is reviewed to help develop a method for modelling the impact of building variability on stock level thermal loading.

Chapter 3

An outline of the methodology used in developing a probabilistic assessment of building energy performance (in relation to period of construction) is given. Where period of construction is defined by periods of building control laws and regulations. This is developed within the context of dynamic thermal simulation.

Chapter 4

The investigation of different potential structural forms as presented by building regulations and control laws. The different building components are considered by dynamic thermal behaviour and sensitivity of the simulation tool to different form features.

Chapter 5

Air leakage is recognised as a significant contributor to heating loads - especially in otherwise more thermally efficient buildings. Investigating the literature showed inadequate empirical data on building air leakage rates for applying probable leakage rates to existing buildings. Utilising published experimental data on building component leakage rates, a model was developed to calculate a probabilistic adventitious leakage rate for any conceived building form.

Chapter 6

External environment influences building thermal performance by climate, solar loading, daylighting and long wave radiative view factors. Stock level distributions by climatic region were determined from data published under the NDBS Project. Building regulations, town planning laws and design guides on daylight and solar loading were used to investigate potential variation of wall sky view factors in urban regions. A relation of sky view to solar loading was investigated.

Chapter 7

A probabilistic stock level assessment of base thermal loading, as related to period of building construction, is presented in this chapter. A Monte Carlo method was applied in developing distributions in thermal loading according to period of building construction. A one-at-a-time sensitivity analysis of the identified uncertain parameters was carried out to investigate model behaviour in relation to period of construction.

A Kolmogorov-Smirnov test was applied to the modelled heating and cooling load distributions - identifying theoretical distributions that could best describe those resulting from the Monte Carlo simulations.

Chapter 8

Validation of the results and methodology prove to be beyond current ability due to lack of statistically significant stock level building data and the large task required to capture relevant data. Two methods of potential validation are presented.

Chapter 9

Conclusions and proposals for further work are presented here.

Chapter 2

Building Energy Assessment Methods - Reviewed in Context of Non-Domestic Building Stocks

In developed countries such as the majority member states of the Organisation for Economic Co-operation and Development (OECD), energy concerns associated with the building stock make up a significant proportion of total national energy use and CO_2 emissions. By definition the building stock of developed countries largely consist of older buildings, built before modern concerns of energy efficiency.

Pout et al. report ND buildings to account for 17% of total national delivered energy consumption and 19% of total CO_2 emissions in [3]. A further split shows 4% energy and CO_2 emissions can be attributed to industrial buildings, the remaining 13% and 15% associated with commercial and public sector buildings [19].

The later BRE report, [19], suggests greater accuracy in energy assessment is achieved from an improved state of knowledge in the field of building energy. A 'bottom-up' modelling approach is taken, applying a more detailed understanding of energy use associated with building characteristics. This resulted in the development of a loosely defined modelling process known as N-DEEM (Non-Domestic building Energy and Emissions Model).

Understanding the distribution of energy use and energy demands in a building stock is necessary to provide focus on effective energy saving strategies. Energy assessment is, therefore, essential to creating a 'low carbon' building stock.

Both reports [3, 19] utilise data collected on the ND building stock from an extensive survey carried out as part of the Non-Domestic Building Stock (NDBS) Project [27].

2.1 Non-Domestic Building Stock Project - England and Wales

The NDBS Project aimed to provide a detailed description of the non-domestic building stock and associated energy use. The project was supported by the UK Department of the Environment, Transport and the Regions as part of a response to reducing CO_2 emissions under the Kyoto Agreement [28].

The result of the project was a database designed to provide the most up-to-date statistical representation of the NDBS, with regards to energy use and building characteristics [29].

For England and Wales extensive databases on building type, use and energy demand have been developed as part of the NDBS Project [27]. Capturing the diversity in activity and building form of the NDBS is an important step in understanding energy saving potential [1].

To understand distributions in energy use, initial methods used national statistics divided into sectors by building type. Commercial buildings were given little attention in energy use as were considered to represent a small proportion of total building stock energy demands in the 1970's and 1980's [45]. Energy demand for the commercial building sector was calculated as the residual national energy use once the energy consumption of more considered sectors (i.e. domestic, industrial and transport) were calculated.

This initial breakdown proved of limited value as greater detail was needed to fully understand energy use in the diverse commercial/non-domestic building stock. Mortimer et al. highlight in [1] a statistically representative surveying approach to obtaining greater detail on energy consumption and related characteristics of buildings. This approach was first carried out (1979) by the American Department of Energy (DOE), known as the Commercial Buildings Energy Consumption Survey (CBECS) [46].

2.1.1 NDBS Project Data Sources and Project Aims

The Valuation Office (Inland Revenue) provided a comprehensive source on building size, construction, services and activity via property taxation data. Though this source provided extensive data on building stock, the omission/exclusion of certain buildings or communal areas within multiple occupancy buildings presented limitations in statistical analysis. Another problematic factor raised by Bruhns, were the grey areas in building classification, brought about by mixed use buildings for example [47].

To inform energy conservation a comprehensive review of the building stock in terms of size and physical composition was deemed necessary. The NDBS Project aimed to provide the required data for directing energy saving measures by addressing four issues [20]. These are summarised in table 2.1.

Table 2.1: Issues of the NDBS Project aimed at informing energy saving measures.

Issue	Required Information
Statistical Representation	Floor Space Construction and Geometry Characteristics Building Infrastructure Energy Use Energy Source CO_2 Emissions
Trends in Stock Composition	Transient pattern of floor space by building type Energy Use Trends
Assessing Energy Saving Strategies	Potential Use of energy saving measures Potential saving of different measures Cost
Assessing Current Measures	Success of implemented energy saving measures

2.1.2 NDBS Energy Use

Mortimer et al. carried out energy surveys that were designed to provide information on building use, age, construction, occupancy patterns and building services. Energy monitoring was not conducted in the survey, rather inspection of equipment and collection of metered energy consumption records were used to infer energy use [40].

This approach, combined with national statistics, has been used to develop a more detailed description of the NDBS's energy performance for England and Wales. The survey involved approximately 800 buildings. The intention being to provide enough detail to assess energy saving potential within the building stock.

Mortimer et al. [1] classifies buildings by activity as a framework for identifying an appropriate selection of buildings for survey. The survey was split into external and internal inspection, occupant interview and collection of energy consumption records.

From the gathered data, statistical summation of energy consumption was made. Figure 2.1, on page 11, shows the variation in energy consumption for ND buildings by activity. The figure clearly shows a diverse energy consumption associated with non-domestic activity. It is also evident that building energy performance is sensitive to more than just activity, where specific energy consumption within individual groups span over an order of magnitude in difference [1].

In Mortimer's study, each building activity group has a small sample size, relative to the total building stock. Mortimer et al. used sampling errors in the 95% confidence interval (i.e. 2 standard deviation) of the energy data for each surveyed group to determine whether the sample sizes were statistically representative of the building stock. This statistical analysis is applied from the CBECS survey method [46].

From this statistical analysis the sample sizes for office and retail buildings were considered significant, whilst further sampling of other types were required. Manufacturing processes are diverse in themselves and Mortimer et al. [1] suggested further categorisation within this building group was necessary.

The study shows diverse energy consumption within building use types and between different use types.

The energy study carried out by Mortimer et al. also provided an aggregate view of energy use within the main building use types identified in the study. Focus was given to Retail, Office, Manufacturing, Storage facilities and Business Services use types. From [1] it is clear that the greatest energy consumption is associated with thermal comfort control. For all of the main building use types identified by Mortimer et al., between 50% and 60% of energy consumption is associated with heating and cooling.

Figure 2.2, on page 12, shows the aggregate consumption for the 58 surveyed office premises.

Detailed information resulting from the studies carried out within the NDBS Project are presented in [3, 48, 49]. In [3] the data is structured into three parts that address the first two NDBS energy issues summarised in table 2.1 on page 9. All the data is presented by premises, rather than building, due to the available data sources.

2.2 Comparative Building Energy Surveys

Member states of the European Union (EU) are committed to reducing the energy demand and CO_2 emissions of their building stocks. The available data on the non-domestic/non-residential building stock of many EU countries has proved to be limited [50, 51]. A report by the European Commission [52] suggests a similar breakdown of energy consumption in non-residential buildings in the EU (52% Space

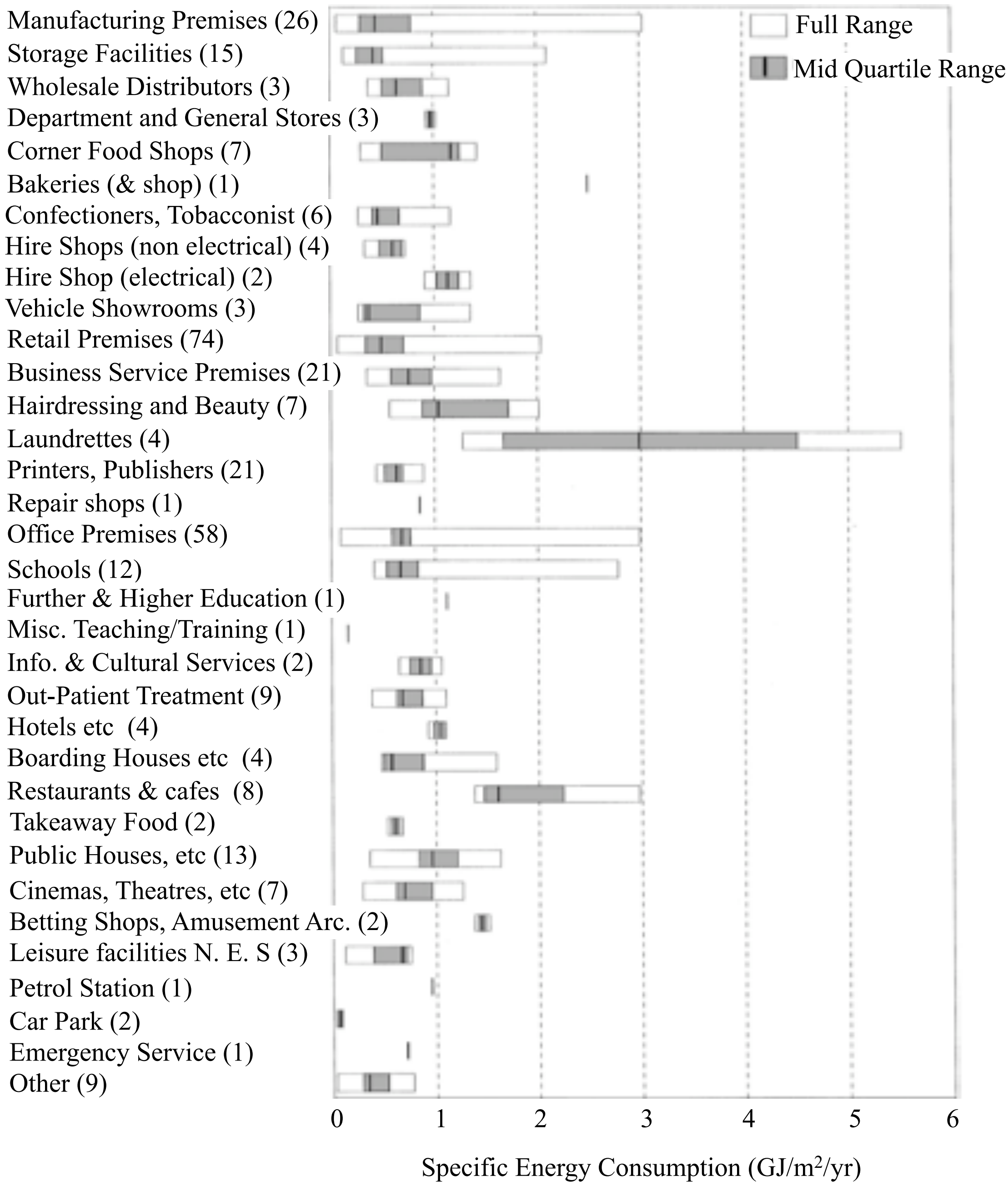


Figure 2.1: Specific Energy Consumption frequency distribution for different building activity [1].

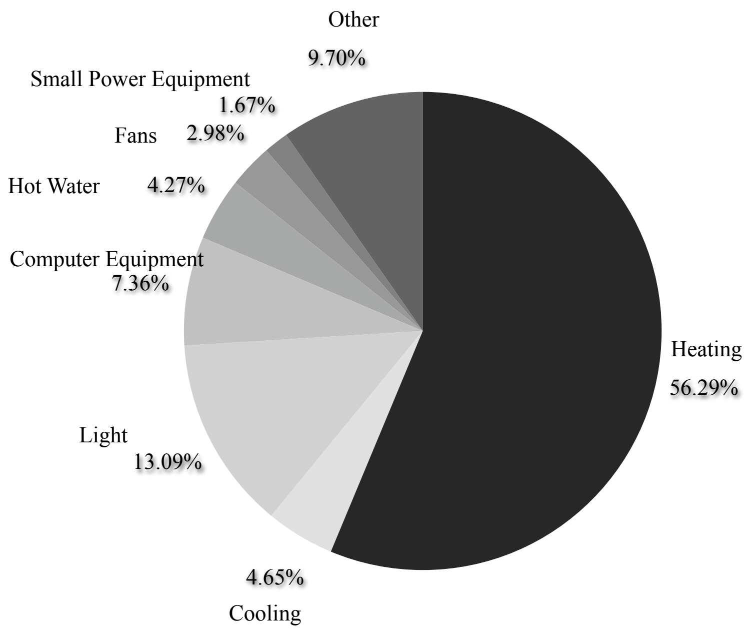


Figure 2.2: Aggregated Energy Consumption of office premises [1].

Heating, 4% Cooling, 9% DHW, 14% Lighting, 21% Other) as given by the NDBS project for England and Wales [1].

A global survey into available data sources for energy assessment of building stocks was carried out by the Tyndall Centre for Climate Change Research [53]. A general trend in more complete data for the residential building stock is reported globally. The CBECS project in the USA and the NDBS Project of England and Wales were identified as two leading sources for energy assessment for national ND buildings.

Two comparable studies to the NDBS Project of England and Wales have been identified in the literature. The CBECS project for the USA as reported in [53] and a more recent survey carried out on the Hellenic Building Stock.

2.2.1 Hellenic Building Stock Energy Assessment

A detailed empirical assessment of the Hellenic building stock has been undertaken by the Institute for Environmental Research and Sustainable Development, National Observatory of Athens [54]. This study draws many parallels with the NDBS Project for England and Wales, giving a breakdown of the building stock by period of construction, use and contribution to total energy consumption.

To provide further subcategories the buildings were assessed with respect to energy use issues, such as level of insulation, age and type of heating systems, climatic regions and use of sustainable microgeneration technology (i.e. solar collectors). By taking this approach to categorisation the study provides an assessment of energy conservation measures and the expected impact on the stock's CO_2 emission. By doing so a ranking of conservation measures was then applied to each usage class of non-domestic building.

Average values of energy saving for the assessed conservation measures were taken from published data, resulting from representative and specific building simulation studies. Estimates of savings also involved averaging values of building form identified by surveys, known building practices and by selected building codes/regulations.

Potential energy savings for the building stock were provided as percentage ranges rather than single values to account for variation in some parameters.

Each conservation measure was ranked according to the estimated potential energy saving to the stock. Recommendations of the considered energy conservation measures for each ND building type (by activity) resulted from this study.

The average energy values presented in [54] were calculated from survey data and representative studies that offer no insight into variation and distribution of energy influencing building characteristics within the stock. The effectiveness of energy saving measures in this assessment does not account for sensitivity to varying characteristics. This could lead to over/under prediction of energy saving potential of a building stock and considered energy saving measures.

2.2.2 American Commercial Building Energy Assessment

The importance of building energy efficiency became apparent in the USA during the 1970's oil crisis. As a result large efforts were made to better understand the energy consumption of buildings and the potential for reducing their energy demands. At the time it was recognised that improving energy efficiency in existing buildings held the greatest short-to-mid term energy saving potential [55, 56].

Monts and Blissett [55] report on the intention of government legislation (Omnibus Budget Reconciliation Act, 1981) to change the role of the U.S Department of Energy's Building Energy Performance Standards (BEPS) program from regulatory to informational. Research could, therefore, be carried out to provide a simple method of energy efficiency assessment and guides for improved efficiency.

Monts and Blissett identified a multivariate Energy Utilisation Index (EUI) as the most appropriate method for providing the expected energy performance of a ND building. A multivariate EUI was deemed necessary to account for the diversity factors influencing a building's energy performance. By comparing against actual energy use a ranking of potential improvement could ultimately be given.

It was recognised that in order for the EUI to prove reliable a statistical (regression) approach was needed. The resulting regression approach identified via [57], provided five influencing factors for regression based EUIs.

The five factors are: (i) climate and building location (ii) required thermal conditions (iii) occupancy patterns (iv) structural thermal performance (v) building use. Use of these factors in linear regression analysis showed limitations in this simple assessment approach due to assumptions made on a collinearity of the variables considered in the regression equation.

Potentially insufficient data in samples of given building classes will also effect the accuracy of a regression based relationship of energy performance to building characteristics. With careful consideration of the sources of uncertainty Monts and Blissett concluded that the approach offered a simple and quick tool for building energy assessment. At the time (1982) computing power limited the ability of simulation tools for large scale building energy assessment.

In 1979 the first CBEC Survey [46] was carried out in America to capture the characteristics of the commercial building stock that influence energy consumption. It is this survey process on which the NDBS Project of England and Wales was based (see above). The survey has been conducted 8 times from 1979 and provides an overview of the U.S commercial building stock's changing energy use intensities.

2.3 Energy Assessment

The energy surveys discussed above are intended to inform on the energy performance of ND building stocks. The resulting information can then be used as a guide for building energy assessment and energy saving measures.

The European Energy Performance of Buildings Directive (EPBD) stipulated EU member countries must employ a National Calculation Methodology for assessing and rating the energy performance of all buildings, by 2006. The main objective being promotion of improved energy performance [58, 59].

The EPBD identifies two main energy rating methods as:

- Asset Rating - based on the building structure, fabric and design values.
- Operational Rating - a weighted sum of the measured total energy use of a building.

Two methods of energy assessment exist to achieve these energy ratings:

1. Analysis of metered data and
2. Computational Simulation.

The first approach provides data for energy benchmarking of building stocks, providing statistical models that link building types to expected energy performance. This is described as a 'black-box' approach by Friere et al. [60] that with an adequate data source provides a more rapid assessment method than using simulation tools for building specific assessment.

From the section above, this method depends on large scale surveying to provide a statistically significant model. The large scale stock assessment provides a means for benchmarking energy performance of buildings within the considered stock.

In any statistical assessment procedure normalisation of the buildings is commonly applied to give a fair representation of the building's energy efficiency compared to other buildings. Typical normalisation factors are building size, operational patterns and weather [55, 57, 61, 62]. Energy benchmarking studies are discussed in section 2.3.1.

The second approach (of computational simulation) applies energy and mass conservation equations to provide a more explicit energy assessment of a building. This allows greater analysis of the influence of building characteristics on the predicted energy performance, leading to a more detailed understanding of how to maximise energy efficiency improvements. The development of simulation methods is reviewed in section 2.3.2.

2.3.1 Energy Benchmarking by Statistical Analysis of Survey Data Sets

Benchmarking of energy performance in the UK is well established, resulting in guides on general energy saving measures [63, 64]. The process of benchmarking requires a standard to which a building's performance is evaluated. Two methods of benchmarking are identified in [28], the first being based on a reference building and the second based on statistical representation of energy performance.

A reference building, based on construction and occupant activity, can be derived from survey data or a theoretical performance expected from building regulations, for example. As to which method is used, depends on what the benchmarking procedure is intended to show.

A benchmarking study of commercial buildings in Hong Kong by Chung et al. [65] used multiple regression analysis to develop a relationship between a building's Energy Use Intensity (or Energy Utilisation Index as in section 2.2.2 - EUI) and the influencing factors. By regression analysis of surveyed data, buildings of the same use class can be compared to indicate the relative energy efficiency of the building.

Different statistical interpretations of the regression based EUI can be used to determine whether a surveyed building can be deemed efficient. Lee [66] utilises data envelopment analysis to benchmark building energy performance. The process was then applied to assess the impact of energy saving management methods. This shows that benchmarking can be used to highlight energy inefficiency in buildings as well as qualify the success of energy saving measures.

Other simplified correlation methods have been investigated to characterise building energy consumption such as the Princeton Scorekeeping Method (PRISM) [67]. It is noted in [67] that such simple methods do not give any insight into building reaction to certain conditions (i.e. free thermal gains such as solar load and internal casual gains). As a result more sophisticated methods that take into account influential factors have been developed that have the potential to assess energy saving measures.

Utilising regression analysis implies a representative sample of the building stock has been taken and that error within the measured EUI (the dependent variable) is subject to normal distribution. Santamouris et al. argue that the diversity in a building stock (as seen in the NDBS project [27]) means this required condition is not always applicable [61].

In [61] a clustering technique is employed to better understand the energy performance of buildings belonging to groups of building with "very similar characteristics". Assessing the energy performance of buildings within groups identifies clusters of building energy performance, resulting in a robust classification of expected energy performance.

The methods discussed and the the data available from building stock surveys allow for assessment of relative building energy performance and general improvement potential within a building stock. However, associating greater confidence with the potential energy efficiency improvements for specific retrofit measures requires more detailed assessment techniques.

2.3.2 Building Energy Assessment - Computer Simulation

With the increased drive towards a better understanding of building energy performance and increasing computer power since the 1970's, building energy simulation tools have been developed into a major resource for energy assessment.

Shaviv et al provide an early example of applying a finite difference method to coupled partial differential equations to solve transient thermal behaviour of a building. A case study is used to demonstrate incremental improvement to the thermal efficiency of the building design [68].

Other tools have been developed since the 1970's that are now widely used in research and within commercial building design practices. Whilst some tools have been developed to investigate specific thermal/hygrothermal/lighting behaviour at component level [69, 70, 71, 72], sophisticated whole building energy simulation exist.

Tools such as TRNSYS [73], EnergyPlus and DOE-2 [74] and ESP-r [75] have been developed over 30 years to provide energy assessment of a building's thermal energy performance. A good source, though not exhaustive, for summarising current modelling tools is provided by [76].

The capabilities of 20 major building energy performance tools have been compared in [77]. This provides a good source for quickly deciding on an appropriate modelling tool for a given project. Another review [78] was carried out to provide an understanding of industry based user requirements, capabilities of existing tools and provide guidelines for future development of these tools.

The use of energy simulation tools has historically been limited by the ability of computers and as a result Clarke [4] identifies 4 generations of building energy models. Third and fourth generation tools (see table 2.2) were intended to provide greater potential to simulation methods and encourage a greater user base [4].

The review undertaken in [78] highlights the benefit of combining Computer Aided Design (CAD) capability within all energy simulation tools, as recognised by Clarke (table 2.2).

Table 2.2: Generations of Building Energy Models [4, 5].

Generation	Description	Issues
1st	Handbook orientated Simplified	Indicative Limited Application
2nd	Considers dynamics Simplified	Improved description of physical relationships
3rd	Use of numerical modelling methods. Integration of energy sub-systems. Heat and mass transfer	Further improved description of the physical world.
4th	Computer Aided Building Design. Advanced numerical methods. Improved software engineering.	Predictive Generalised Easy Use

It is evident from surveying the literature that use of building performance simulation tools is wide spread. In some instances, however, the complexity associated with use of these simulation tools is argued as a reason for pseudo-first and second generation tools. An example is that developed by Baker et al. - the LT Method [79].

This is also supported by conclusions made about future use of energy simulation tools in [78]. Where an easy to use tool that can inform early stage design decisions is seen as important.

The LT method was designed to reduce complexity associated with energy modelling to improve the concept-to-design process. The model is based on a set of curves relating lighting and thermal performance to building characteristics. To achieve these curves mathematical modelling of 'cells' (single rooms within a building) are pre-run to provide an understanding of the theoretical relationship between energy performance and building characteristics [80].

The process of defining the curves makes many assumptions about the building components (glazing type, room height, wall u-values) and location (North UK or South UK) and as such is limited in use. The LT method considers building design, building services and occupant behaviour as the main categories equally impacting building energy performance.

Methods of simulating thermal performance in buildings are still a topic of research. Complexity of code design, high data processing and issues of validity, sensitivity and model uncertainty are some of the most current topics of concern.

Freire et al. show that regression techniques can be applied to show a correlation between input data and output in simulation models such as ESP-r and EnergyPlus [60]. This (as well as the LT Method [80]) suggest building energy simulation tools can provide a comparative 'black-box' approach to empirical based energy assessment methods.

Application of computational energy assessment methods, in the context of a building stock, is subject to a probabilistic approach to modelling. The use of uncertainty modelling procedures becomes important in understanding the influence and sensitivity of the varying building characteristics that determine building energy efficiency.

2.4 Uncertainty Techniques in Building Energy Modelling

Empirical investigation relies on the use of statistical techniques to identify relationships between building type and energy use [55]. This requires survey of a statistically significant and representative set of buildings, that is a large, expensive task to carry out.

Simulation tools offer a more rapid and potentially more detailed energy assessment procedure for a building stock. The limitation of current simulation tools, however, is their deterministic nature. Without due consideration of parametric and resulting output uncertainties, modelling procedures are flawed [81].

Borchiellini and Furbringer introduce uncertainty analysis as one of the most important topics in simulation where input parameters can take on different values with equal acceptability [82]. This is a fundamental consideration in applying simulation tools to a probabilistic assessment of a given building stock.

Though uncertainty in building energy simulation tools is being given more theoretical consideration [83], De Wit highlights a rare account being made in general model use [84]. Consequently decisions about energy saving features are often made with false confidence in deterministic modelling approaches.

2.4.1 Model Uncertainty

Understanding parametric uncertainty distributions is paramount to the usefulness of the model. Further more model assumptions and abstraction related to the theoretical descriptions of physical relationships adds greater uncertainty. This is recognised in building energy model uncertainty studies by De Wit [85] and MacDonald [83]. De Wit summarises in [86] these two major sources of uncertainty as (i) building details (physical properties, occupant behaviour etc.) and (ii) model simplification (abstraction in thermophysical behaviour).

2.4.2 Parametric Uncertainty

Of the two identified sources of uncertainty, parametric uncertainty is the most applicable to a probabilistic energy assessment of a building stock.

Identifying parameter values and the probability distributions associated with them is key to successful uncertainty analysis [86, 87]. Issues arise where parameters are dependent on each other making it vital that all model parameters are given due consideration [55, 81, 87].

Cooke [81] highlights the practicality of parametric uncertainty:- where parameter values are not clearly defined, expert subjective probability judgements are required. Karatasou et al. conclude in [88] that application of distinct input parameters for a general model is "indefensible". De Wit [84] and more recently Hand et al. [56] acknowledge that there is limited availability of data containing relevant uncertainties, making it difficult to include rigourous uncertainty analysis in building energy simulation.

Accounting for uncertainty in building parameters during energy modelling increases the number of required simulation runs. With an exponential relationship to the number of uncertain parameters, uncertainty modelling can become computationally expensive with extremely large result sets for analysis [89]. Carrying out sensitivity analysis allows focus to be given to smaller, key parameter sets, deemed to be most influential to building energy performance [90].

Sensitivity analysis provides confidence to model behaviour and results, giving greater confidence in energy saving measures/design. Whilst important to confidence building Hamby makes a clear distinction between uncertainty and sensitivity analysis [91]. *Uncertainty analysis is carried out on variable parameters to which a model is sensitive. Sensitivity analysis is used to identify important parameters, whether uncertainty in their values exists or not.*

MacDonald et al. [92] are in agreement with Hamby [91]; that sensitive parameters are not always important to uncertainty. Sensitivity analysis becomes important where parameter values are unknown, for stochastic processes and for choice of algorithms in energy models.

The notion of parametric analysis is becoming increasingly important in building energy simulation as dynamic modelling tools become more sophisticated and computational power continues to grow. This is demonstrated in [93], where an interface tool to EnergyPlus has been developed for such purposes.

2.4.3 Methods of Uncertainty and Sensitivitiy Modelling

MacDonald [83] considers two methods for dealing with model uncertainty in building energy models. These are defined as:

1. External - Repeating the simulation N times with parameters varying in a considered or random approach. Treating the simulation tool as a 'black-box'.
2. Internal - Incorporating uncertainty into the model conservation equations, reducing the model to one simulation run. Using arithmetical methods.

The external methods are split into local and global methods. The local methods are linked to sensitivity analysis where uncertainty of each parameter is considered whilst all other parameters are held constant [94]. To account for interdependencies of parameters within the model a factorial approach can be considered.

The global method requires all parameters to be described by a probability distribution. The chosen method by MacDonald is Monte Carlo Analysis (MCA), where each parameter is randomly determined according to its probability distribution. Running the model N times, a probability distribution in model results reflects the probable influence of the parameters. MacDonald [83] explains that via the central limit theorem a Gaussian distribution in model results is always achieved.

MacDonald and Clarke [95] recognise that external methods of uncertainty analysis require considerable effort as multiple runs using local and global techniques are needed. To provide a more efficient approach to model uncertainty they explore the potential of internal methods.

2.4.4 Application of Uncertainty Analysis

To improve confidence in a building specific energy model, monitoring the building provides real data for validation. This combined effort of modelling and monitoring is applicable to cases of retrofit. Though real data exists, modelling gives greater understanding of existing behaviour and potential improvements by different retrofit scenarios.

Borchiellini and Furbringer provide an example study of the Monte Carlo and Fractional Factorial Analyses used in evaluating the COMVEN multizone air flow code in [82]. With several hundred simulation runs, MCA provided a global understanding of model uncertainty. Fractional factorial analysis was required to understand the model behaviour in relation to physical parameters.

MacDonald and Strachan state that uncertainty must be evaluated when assessing building thermal performance resulting from refurbishment. Accounting for the uncertainty acts as risk assessment to the success of different retrofit strategies [87].

An uncertainty analysis was carried out on the expected improved energy performance for the 1896 Charles Rennie Mackintosh Lighthouse Building in Glasgow as a result of refurbishment. An example of uncertainty modelling for deciding on heating plant size was given for the Lighthouse Building [87].

2.5 Decision Making by Statistical Analysis

For either method of energy modelling (empirical or computer based) applying a statistical approach to data analysis leads to a quantifiable level of confidence in assessed energy performance and energy saving potential.

Limitations in data sets used for statistical modelling will restrict the level of confidence associated with model results. For computer modelling Hand et al. discuss this issue as a case of "garbage-in-garbage out (GIGO)" [96].

Bruhns et al. [20], as part of the NDBS project raise the issue of better understanding estimates for a 15%-25% potential energy saving in non-domestic UK buildings. To understand the most effective energy saving strategies a detailed knowledge of the building stock is needed. At the time of publication of [20] (2000), it was recognised that little understanding of building stock characteristics existed and should be considered of great value as a field of research [20, 97].

2.5.1 Influencing Factors

Multiple factors influence the energy performance of a building that should be taken into account during energy rating and retrofit assessment [98]. These factors include building location, construction, use, size, building services and external environmental conditions [40, 99].

In [99], Steemers addresses the concentration of energy consumption within cities, highlighting the significance of urban form on the energy use of buildings and transport. Dense urban development is considered to reduce transport demands and therefore create a more energy efficient environment. Steemers addresses how this would effect (the more significant) building energy consumption.

When considering the demand side and micro generation opportunities, reducing density will increase solar potential. With heating demands as high as 60% for domestic buildings [41] passive solar gains is thought to positively impact on energy demands in the UK. Steemers addresses lighting issues as another beneficiary of reduced urban density.

It is concluded that a typical building's energy demand increases with increased density. Steemers notes, however, that specific building characteristics will influence the energy response of the building to its surrounding urban environment. These characteristics relate to building width-depth ratios, window-wall ratios and ventilation strategies (natural/mechanical).

2.5.2 Diversity in the ND Building Stock

The diversity of the non-domestic building stock presents the biggest challenge in ranking energy saving measures. Though building use has been identified for categorising buildings for energy assessment, non-domestic buildings do not always have clearly defined activities [20].

Building age provides a category for identifying structural characteristics (common to building periods as a result of economic climate and building controls) that influence energy performance. From the survey of buildings within the NDBS Project, table 2.3 gives a breakdown of the four major building use classes by age within England and Wales.

Table 2.3: England and Wales NDBS Age Distribution by Class: 1994 [3].

Age of Premises	Office		Retail		Warehouse		Factory	
	No. of Premises	Area %	No. of Premises	Area %	No. of Premises	Area %	No. of Premises	Area %
Pre 1900	109503	16	269469	32	39600	23	52571	1
1900-1918	26721	5	73995	9	14863	6	25011	7
1919-1939	25014	7	68957	9	17729	7	31896	12
1940-1954	10934	7	27308	4	15821	3	29174	11
1955-1964	20948	9	42869	8	16928	10	31456	14
1965-1970	17957	11	32922	7	14559	9	24671	11
1971-1975	9804	9	16752	5	10147	6	15126	7
1976-1980	8478	9	14269	5	11940	6	19038	7
1981-1985	10306	9	11735	5	16546	7	29677	6
1986-1990	24337	11	19383	10	18530	15	29585	7
1991-1994	12529	5	9847	5	7869	8	11764	3
Unknown	864	1	1098	1	2283	1	6020	1
Total Area 1,000 m^2	70736		94221		119372		213552	

The physical characteristics of a building (geometry, exposed wall area, floor area, construction type, etc.) are fundamental to energy performance. Specifically in the ND building stock these properties are subject to great variation, not necessarily influenced by building activity [100].

A survey within the ND building stock project resulted in 17 principal building forms being identified. These forms did not consider roof type, which is recognised to take several possible forms [101, 102]. From the study cellular sidelit (by daylight), open plan sidelit and a combination of these forms proved the most extensive in the surveyed buildings.

2.6 Conclusions

Assessment measures and the influencing factors of energy indexing and development of energy indicators have been considered in the context of Non-Domestic Building Stocks (NDBS). A review of existing energy surveys, the building stock of England and Wales and energy assessment techniques has been carried out.

The NDBS is recognised to be diverse in building use, structural characteristics, form, site and age. Along with variations in building infrastructure and occupancy patterns the variation makes energy assessment of ND buildings more complex than that associated with the domestic building stock.

Two methods of building energy assessment exist, one based on energy benchmarks resulting from building surveys, the other from theoretical computational analysis. The literature shows a divide in the use of these methods. Empirical assessment is focused on building stock energy performance whilst computational simulation is used for detailed, building specific energy assessment.

Empirical data sets lend themselves to setting up statistical tools for energy assessment, such as regression analysis. This offers a simple method for assessment of buildings within a considered stock. The approach is limited, however, by assumptions made to obtain statistical relationships between building characteristics and energy performance. Average values of energy use and potential savings resulting from this method lack an understanding of the range and distribution of energy performance and energy saving potential in a highly variable building stock.

Considering the variability of stock in greater detail would require a substantive data set that is currently not available and will require significant funding to be achieved. With such data, however, comes issues of quality, accuracy and level of detail that have and are proving problematic to current studies [32].

Computational methods provide a more detailed account of a building's energy performance, that can lead to more effective energy assessment and energy saving measures for the considered building. These methods require a more detailed understanding of the underlying physical theory influencing energy performance and require a high level of technical ability that limits the user market. The deterministic approach (where building characteristics are given exact values that by the applied calculations will have a pre-determined answer) commonly applied in computer simulation has been identified as a weakness in giving confidence to model results.

The literature identified several statistical techniques that can be applied to quantify uncertainty in computer modelling and therefore offer statistical confidence to results. Applying uncertainty analysis methods to building energy simulation tools offers a novel method for energy assessment of a building stock. The method relies on obtaining probability distributions of building characteristics in the ND building stock that influence energy performance.

The success of a probabilistic building energy simulation process is dependent on the sources of data available to identify the distributions in building characteristics. As computer simulation tools require detailed building data, it is necessary to introduce new data sources, beyond the scope of large scale surveys as carried out in the NDBS Project.

Current projects have identified building categories that are thought to influence energy performance. The influences include occupant activity, basic form, internal layout, period of construction and building services. In the Hellenic building stock project building practices and basic building controls were identified as sources for determining average values for two basic building characteristics (orientation and window-wall ratio, respectively).

Average values and potential ranges in values of energy influencing building characteristics in the building stock need to be identified for probability modelling. In instances where the ranges in building characteristics required for energy simulation are unknown, building controls offer a potential source for identifying these values.

Using building controls to identify building characteristics provides a basis for using control periods to categorise building energy performance. Combining the probability distribution of building energy performance within each control period, with the distribution of a ND building stock by period of construction (available from the NDBS Project) provides an opportunity to determine the influence of age distribution on total building stock energy demands.

The method offers the potential to understand how the probability distribution of building energy performance in the ND building stock effects the potential for energy saving measures.

Chapter 3

Methodology - Thermal Simulation and Statistical Method

A review of building stock and building specific energy assessment (for non-domestic (ND) buildings) has been carried out (chapter 2). For building stock assessment, large empirically based surveys are typically used, categorising buildings by common use and features to which individual buildings can be benchmarked against the surveyed stock. Building specific assessment utilises computational simulation programs to understand (in detail) the energy performance of a building.

Energy benchmarking utilises energy survey data that proves statistically representative of a given building stock. By regression analysis trends in energy performance and basic influencing factors can be identified. In computer based building energy simulation currently accepted theory of building physics is used to show the expected energy performance of the given building.

For simulation methods a traditionally deterministic modelling approach is recognised as offering no confidence in modelled and expected building thermal behaviour. Methods of uncertainty analysis exist to add statistical meaning to building energy modelling results.

As an area of research, this thesis considers the use of building energy simulation combined with uncertainty modelling techniques for thermal energy assessment of an existing (ND) building stock. The energy assessment is to offer an understanding of stock level variation of probable thermal performance as influenced by building laws/regulations used to guide structural design of buildings.

By utilising existing building energy modelling tools/methods a focus is given to identifying the data requirements and potential data sources needed for the probability modelling tool.

The modelling focuses on the thermal performance associated with building structure alone (termed as 'base level' thermal performance). This offers insight into a stock's structural thermal performance that would be difficult to achieve from empirical energy surveying due to uncertainty in building management and heating/cooling system efficiencies.

Building stock energy assessment categorises buildings by common use types and period of construction (see chapter 2). Therefore, the probability modelling approach (of this thesis) investigated sources for identifying structural thermal properties of buildings by period of construction for ND office buildings.

An overview of building energy modelling theory is presented in this chapter along with the parameters of concern to developing a probability assessment of ND building stock thermal performance. The design of the probability modelling procedure, in connection with the energy assessment tool is also introduced.

3.1 Building Energy Simulation Methods and Tools

Many building energy modelling tools exist as found in [75, 103, 73, 104]. These tools are used for both integrated whole building and building component thermodynamic modelling. Many other modelling software packages exist, of varying capability [77].

In dynamic simulation, energy concerns of a building are interdependent and have resulted in an integrated modelling process in many available simulation tools [75, 103, 73, 77]. The input to these models are extensive; model inputs relate to building geometry, construction, internal and external environment as well as building services [17, 4]. The applicability of these model inputs is influenced by the model approach taken to represent energy relationships.

Two main methods of simulation for dynamic thermal energy modelling exist. These are dynamic response methods and discretized solution space (finite) methods. Response methods are usually applied to low-order, time invariant problems whilst finite methods provide a better method for more complex, time varying high-order energy consideration.

3.1.1 Dynamic Response Methods

Response methods apply Laplace transformations to the differential equations describing the thermal flow in a building component. Two methods exist as time-domain and frequency domain functions. The time domain method determines the response of a system to a unit change in the model boundary conditions, that can follow a periodic or non-periodic time series.

The time domain response method was introduced by Mitalas et al. in [105, 106, 107] and can be used effectively in building energy simulation. Though less flexible and less accurate than finite methods, it is less computationally expensive and it offers an acceptable level of accuracy for dynamic building energy simulation. An example is its use in the US Department of Energy calculation engine - EnergyPlus.

Frequency domain response functions are dependent on a periodic cycle of changing boundary conditions and therefore cannot be applied for full year weather series in building energy assessment. This provides simplification for assessing thermal performance of building components, where the periodic energy concern of each component are summed together to assess overall building performance. The most widely used frequency domain response function is the Admittance method (see appendix A, BS EN ISO 13786 and [108]).

The admittance method, was used to assess variations in dynamic thermal properties of structural components. This provided reasoning for the inclusion of different component forms in the probability model when the thermal transmittance (see appendix A) of the varying forms was constant according to the controlling building regulations.

3.1.2 Finite Methods

Finite methods provide solutions to solving the partial differential equations used to describe heat conduction (Fourier equation - see appendix A) and fluid flow (Navier-Stokes momentum equation) to a discretized solution space. Solving these equations is required for a transient system (i.e. where boundary conditions and modelled behaviour of considered components are subject to change over time).

The discretized problem domain, to which applicable partial differential equations are approximated, is carried out by finite difference, finite volume or finite element numerical methods in dynamic energy simulation tools [17, 109, 110].

Finite difference applies Taylor series expansion to the identified partial differential equation. Future conditions at the considered node are determined by a weighted average of present conditions in all connected nodes (explicit), or by considering all present and future conditions for all connected nodes (implicit).

Finite volume integrates the governing partial differential equations over small volumes that combined represent the modelled system. This method allows greater complexity in boundary conditions, thermo-physical interaction in the model and easier consideration of multiple model dimensions. It is applied in computational fluid dynamics (CFD) analysis.

More detailed consideration of these numerical modelling methods can be found in [17, 111, 112].

3.1.3 Choice of modelling method on probability model

The probability modelling method developed for building stock assessment applied variation in the considered ND building stock to the input parameters influencing thermal performance. The method recognises an interdependent relationship between varying building characteristics and thermal performance. To account for the inter-relations of structural components on thermal performance and the transient nature of thermal loads and demands, a Dynamic Simulation Model (DSM) utilising either time domain response methods or finite calculation methods was considered necessary.

Use of frequency domain response function models do not allow for consideration of true weather variability across a full year. For this reason its use in probability modelling was rejected.

Within the design of the probability model (see section 3.3) the building energy model was treated as a black-box. This provided flexibility in the choice of energy modelling tool - provided it takes appropriate parameters into account and utilises a finite or time domain response approach to calculating the building energy concern.

3.2 Parameters of concern in Building Energy Modelling

From [17, 4, 89], five categories were identified as a complete description of factors influencing a building's energy performance. They are:

- Building Form
- Internal Gains (activity based)

- Building Construction
- Building Situation (site, orientation, climate)
- Building Services

These categories were assessed with respect to variation in the ND office building stock of England and Wales. Data sources were identified that could offer methods of inspection on stock distribution of the identified categories. Sources included existing data from large scale stock surveys such as the Non-Domestic Building Stock (NDBS) Project [3].

Detailed information relating to construction was required by the energy modelling tool used in probability assessment. Building regulations and historical controlling laws were used to provide varying construction information relating to periods of construction in the existing building stock.

3.2.1 Building Form

The NDBS project identifies 14 basic ND building forms for which there are many potential combinations. Table 3.1 provides a summary of floor area distribution for 13 of the 14 building forms (where open plan daylit strip 1-4 storeys and 5+ storeys have been considered as one group and 'railway arch' forms have been omitted as not of interest).

Table 3.1: Gross Floor Area (1,000m^2) of 3,400 Surveyed Premises by built form and structural type [3].

Built Form	Framed	Load bearing	Portable/Portakabin	Other
Cellular Sidelit Strip 1 - 4 Storeys*	353	639	13	1
Cellular Sidelit Strip 5+ Storeys*	426	78	0	0
Other Cellular daylit*	498	385	3	3
Open Plan daylit strip*	41	27	0	0
Open Plan continuous single storey	195	42	0.1	0
Open Plan artificially lit multiple storey	110	30	0	0
Open Plan Single Shed	141	71	0	1
Open Plan car Parking Deck	80	26	0	15
Single Room	6	18	1	0.5
Hall	26	28	1	0
Basement	82	335	0	1
Occupied Attics	23	20	0	0.4

*Most common to office class of premises

Standard office desciptions for modelling have been presented in [113], which identifies seven form features of a building given in table 3.2. Further to this, design style and age categorisation was taken from an office survey conducted by Ove Arup (1984) as in table 3.3. For modelling purposes [113] provided six detailed descriptions of office buildings within the civil estate. This source was considered too limited for representation of a building stock.

Reviewing these sources, two basic building forms were developed for the model. An open plan rectangular building and a cellular rectangular building. Excluding building shape and building services all other factors (such as dimensions, number of storeys, basic window-to-wall ratios, wall construction and other structural components) were varied as parameters within a building DSM. In each case the buildings were considered stand-alone, a recognised limit in representation of the UK NDBS.

Table 3.2: BEPAC Building Form Choices.

Form Features	Range	
Depth/Width	Deep	Shallow
Internal Layout	Open Plan	Cellular
Storey Height	Low Ceiling	High Ceiling
Construction	Lightweight	Heavyweight
Shape	Simple (rectangular)	Complex (varied)
Building Services	Air Conditioned	Naturally Ventilated
Age	New	Existing

Table 3.3: Ove Arup Design Style and Age Categorisation.

Construction Period	Design Style
1890-1920	Turn of Century' - solid or cavity load-bearing wall, 40-50% glazing.
1920-1950	Between Wars' - solid or cavity load-bearing wall, 40-50% glazing.
1950-1973	Post War' - steel/concrete frame and lightweight cladding. High level glazing (up to 75%).
1973-1984	Energy Conscious - Reduced glazing, improved thermal performance of building construction
Post 1984	Post-Arup survey. Introduction of Part L Energy regulations.

3.2.2 Internal Gains

Internal gains relate to occupant activity. Thermal loads associated with people depend on level of activity, occupant density, use of equipment and required lighting levels. The behaviour of occupants and the resulting internal gains are a large uncertainty that feeds into building energy use.

This investigation attempted to quantify the variation in structural thermal performance and as a result applied constant patterns and levels of internal gains to the model. These are considered in the model design chapter (chapter 7).

3.2.3 Building Construction

Method of construction and period of construction were identified as influencing building form types (see tables 3.2 and 3.3). Engineering knowledge, available building material and legislated performance criteria all control construction via building regulations, by-laws and British/European/International standards.

Historical regulatory documents were analysed in order to predict probable building forms and associated ranges in potential structural values. Basic (theoretical) probability distributions were applied to the identified ranges to account for the uncertainty in values at stock level.

The study introduced relationships between construction methods, materials and basic form according to identified periods of control. These relationships were applied to the logic of parameter setting in the developed model.

3.2.4 Building Situation

The surrounding environment influences a building's energy performance according to local climate and radiative interaction with its surroundings. Town planning, building regulations and design criteria were identified as influencing urban geometry. Assuming a typical urban form of a street canyon, the regulations/laws considered to influence urban form were used to develop a probable distribution for wall sky view factors.

A relationship of sky view to surrounding obstruction heights was developed, based on a street canyon layout, with relative infinite length. As a result the simulation tool was able to provide a more accurate account of insolation in an urban context.

The position of a building within the country will influence the typical weather conditions to which it is subject to. Degree-day regions show how this could effect the expected thermal performance of a building [2].

Weather data currently exists as Test Reference Years (TRYs) for a limited set of locations in the UK. The data consists of averaged data from approximately 20 years of records. This data has been compiled by CIBSE, using Met Office weather data.

Other weather data sources for locations in the UK and internationally exist. The International Weather for Energy Calculations (IWEC) developed by ASHRAE (using the DATSAV3 surface climatic database of the National Climatic Data Center [114]) provides weather data in forms acceptable to the considered energy simulation tools (see section 3.3.5). This data represents averaged hourly weather conditions over 18 years of data sets.

In either instance data is currently not handled in a probabilistic manner. The weather data file used is dependent on the coordinate position of the modelled buildings. A regional distribution of the office building stock is given in [3]. A probability factor was determined for the different available weather files by matching weather file location to the regional distributions of office premises.

The latitude position of a building will influence the yearly sun-path and potential for solar loading.

3.2.5 Building Services

The use of different HVAC systems, their management, maintenance and age will influence the energy usage of a building. A focus was given to base level thermal performance, ignoring these service factors. Its influence is highlighted for completeness.

3.3 Thermal Assessment of ND Stock by Construction Period

One of the stated aims was to assess the impact of period of construction on the base thermal loading of buildings in a ND building stock. In response to this aim, modelling buildings by use of DSMs was considered a more viable method of assessment than multiple building energy survey for the study time scale. Use of DSMs was also recognised to ensure variable factors such as building occupancy patterns (and associated gains), efficiencies of building services and building management could easily be discounted.

To assign building structural properties (for building energy modelling) according to the date of a building's construction, historical building by-laws/regulations/standards were identified as an available and manageable data source. Using these documents inherently provided construction periods to which the UK building stock could be assessed. Within each period, however, it was recognised that many of the regulatory values were stated as guides, subject to variation from different building design, size, use, loading factors and materials used.

The variability in buildings of the UK's ND building stock adds a level of uncertainty in stock level prediction of base thermal loads (categorised by construction period). With building control laws/regulations and associated engineering standards used as design and construction guides an assumption was made that these values provided a method of identifying more probable structural properties.

By identifying ranges in values of structural properties, combined with a prediction of most likely values, a probability assessment of base thermal loading within a ND building stock was carried out. In doing so the method could capture the uncertainty in using construction control period to categorise base thermal loading. The resulting probability distribution would, therefore, provide statistical confidence in associating building thermal loads with building construction period.

3.4 Statistical Modelling - Probability Modelling Procedure

The deterministic nature of energy modelling procedures can be avoided by introducing uncertainty concerns to modelling methods, applied theory and (as investigated in this thesis) parametric uncertainty.

From the literature, a common method to investigate the influence of model uncertainty is MCA. Monte Carlo methods are algorithms concerned with theoretical experiments that utilise random number sampling in order to capture a systems uncertainty [115]. Each considered variate has an associated probability density that governs the random sampling. This method is noted as easy to implement and flexible in application.

A noted disadvantage of the unstructured assessment provided by Monte Carlo methods is the slow rate of convergence in the probability distribution of the modelled system's output [116]. Two alternatives that reduce sampling and convergence rates are quasi-Monte Carlo methods, as in [117], and the direct method, as in [116].

Quasi-Monte Carlo methods require a low-discrepancy sequence that can be taken from a uniform distribution. Though uniform distributions were applied within the model of this thesis they are not solely used and so such quasi-random sequences have not been applied in this thesis.

The direct method applies transformations to the distributions associated with the input variables - directly calculating the distribution of the output variables. For dynamic thermal building models, however, the interdependence of variables on system behaviour is considered too complex for use of the direct method.

Monte Carlo methods were applied in this thesis as the most suitable method for capturing the influence of construction variability[1] on stock level uncertainty in building thermal performance. Understanding parametric distributions representative to the considered building stock was, therefore, paramount to the usefulness of the intended probability model.

Figure 3.1 provides an overview of the model design, based on the five identified categories influencing thermal and energy performance from section 3.2. Of the five categories a focus is given to those defining the base level thermal performance of the building. Figure 3.2 gives further detail on the breakdown of the model parametric probability.

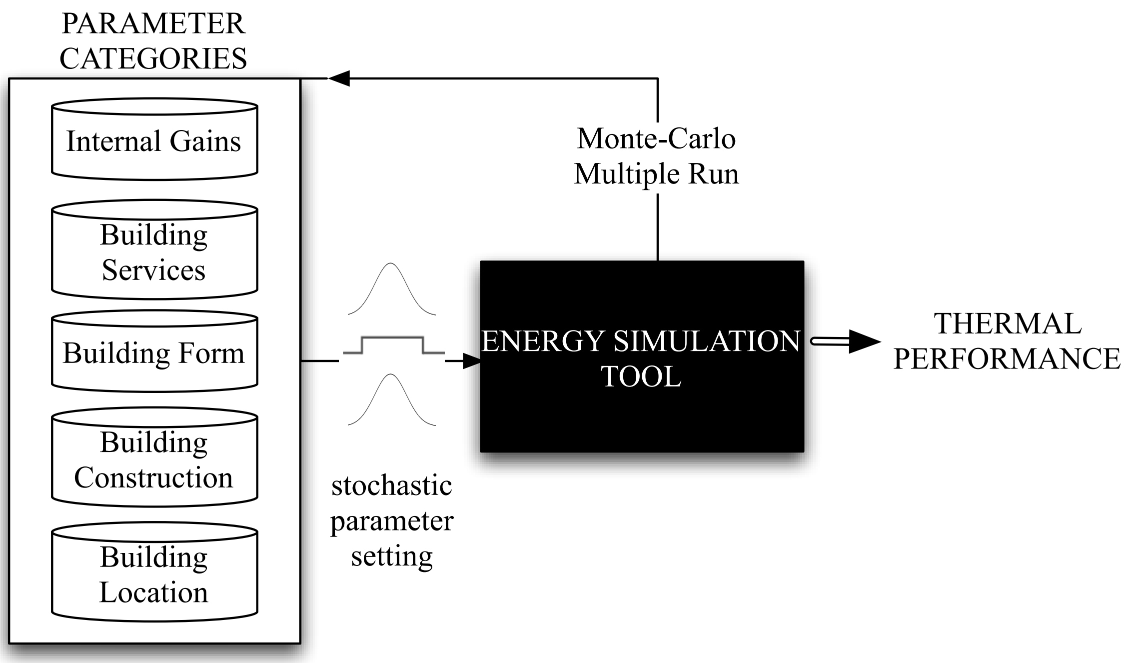


Figure 3.1: Basic Modelling Procedure by Monte-Carlo method.

3.4.1 Model Interface

The probability distributions associated with building characteristics were determined from a script based program using Mathworks' high level language, MATLAB [118]. The parameter values resulting from the probability model were designed for use in a whole building energy simulation tool that utilises numerical methods for solving thermal energy behaviour.

The parameter values were applied to the chosen energy simulation tool via a set-up interface. ESP-r provides a graphical user interface (GUI) as well as a text mode for set up. The interface utilised the text

[1] According to construction control periods.

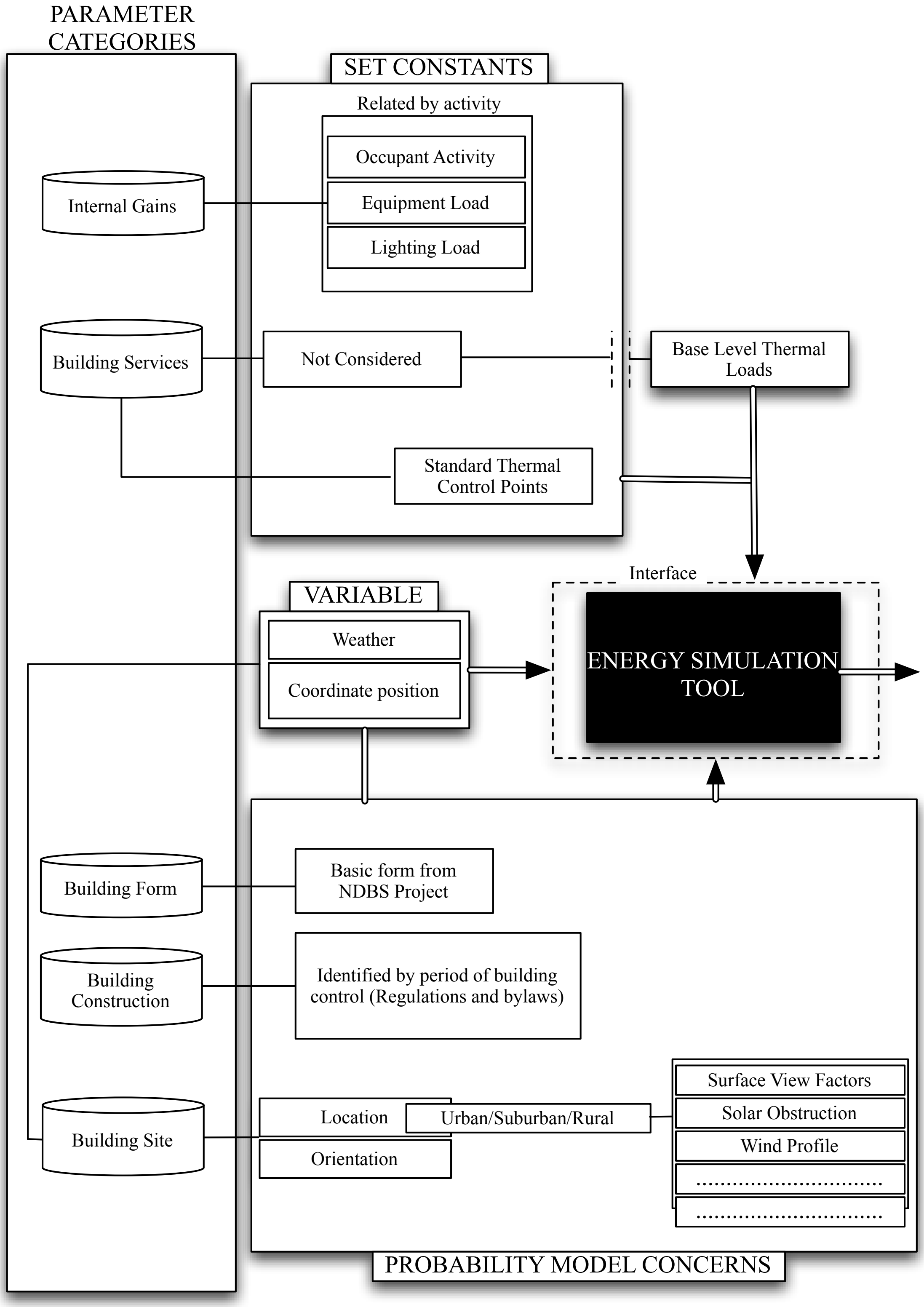


Figure 3.2: Probability Modelling Parameter Concerns.

mode control method, setting up shell scripts to automatically alter the base level models and associated databases. Only the interface for ESP-r was developed (see figure 3.3).

Each simulation run provides a detailed set of results for a representative year for the identified building conditions. The study focused on the base level thermal performance. The heating and cooling loads were extracted from the results file of each simulation run and normalised to kWh/m^2/year.

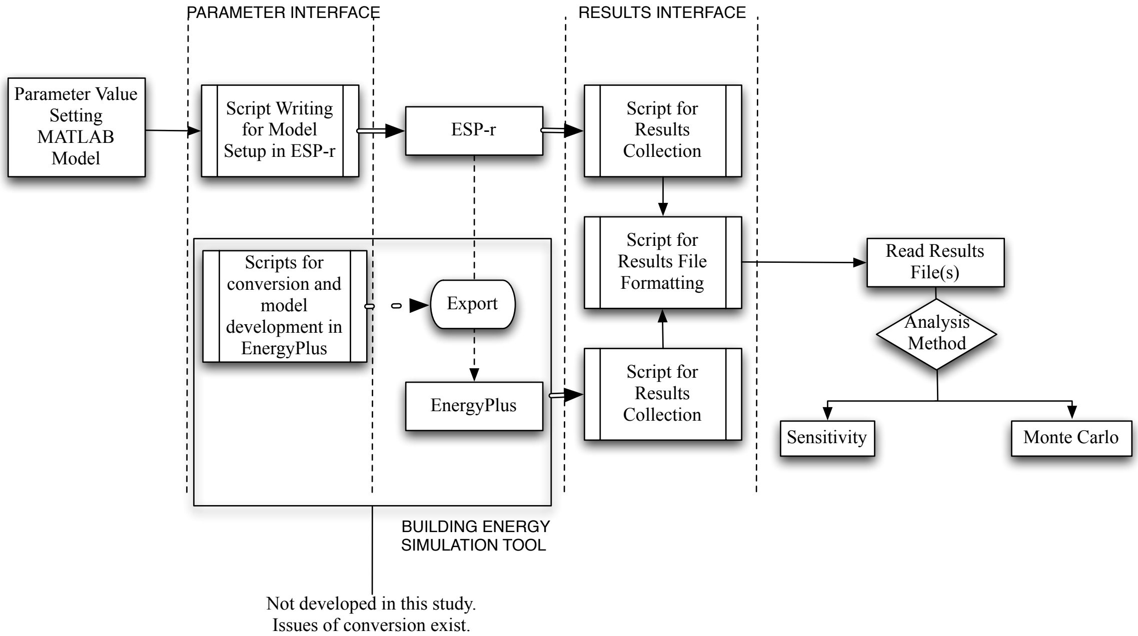


Figure 3.3: Probability Modelling Interface.

3.4.2 Sensitivity Testing

Influence of parametric probability distributions on the resulting distribution of predicted thermal performance depends on the sensitivity of the model to each parameter. To provide a better understanding of these influences sensitivity analysis was carried out (see Chapter 7).

The sensitivity of a model is dependent on the base case model to which the test is carried out. Categories for parameter values and probability distributions in energy modelling of the NDBS were developed according to periods of building control. Mean or modal parameter values for each control period provided several base case models on which sensitivity analyses were conducted.

3.4.3 Energy Simulation Tool

An important consideration to the probability model is the energy simulation tool. An early necessity realised from discussing modelling methods (section 3.1) was the use of numerical methods in energy simulation. Crawley et al. have carried out a study of 20 major building energy simulation programs, and was used to identify potentially suitable tools [77]. From the report, an evaluation of the 20 programs' considerations of internal loads, daylighting, insolation, thermal mass, infiltration, ventilation, HVAC systems and renewable systems was made.

ESP-r [75], EnergyPlus [103], IES [119] and Tas [120] provide the most comprehensive set of capabilities. The latter two are commercial software suites, while EnergyPlus and ESP-r are free to academic research and make source code available for development.

The user community and open source nature of ESP-r provided greatest flexibility and support for research purposes. Use of scripts in ESP-r's text editing mode presented a clear automated method for parameter setting for Monte-Carlo simulation.

ESP-r has an export facility to EnergyPlus that allows potential to develop the probability tool to use a two 'black-box' simulation process. This could enable the model to account for uncertainty resulting from different modelling methods. A two-simulation-tool method has not been applied in this investigation. Its application and potential use has been raised to highlight further benefit of adopting an external approach to probability modelling over an integrated approach.

Though assessment is on base level thermal energy concerns (i.e. passive influence), using a whole building energy modelling tool enables the probability model to be further developed to provide a probability model to assess building energy use for different heating and cooling systems.

3.5 Statistical Modelling - Parameter Distribution Setting

Regulations provide limits of acceptability in building design and construction. Applicable probability within these parameter ranges depends on how the regulations are treated during design and construction stages. An account of the British building industry in [33, 6] showed availability of materials, skills and economics all influenced construction.

The ranges associated with regulations were assessed from an economic stand point. Values deemed to minimise design and construction costs and maximise profits (for example maximising building density) were taken as most probable. Basic distributions were then applied to the limits associated with the considered parameter.

Three basic continuous distribution types were used in the probability model (as identified for uncertainty modelling methods by MacDonald [83]):

- Uniform (Rectangular)
- Triangular
- Gaussian (Normal)

Discrete probability was applied to clearly defined physical parameters, such as detailed wall construction.

Where data on stock distributions of building characteristics were unknown, theoretically derived distributions were applied from assessing building control documentation and other industry recognised data sources. As a result the model contains *a priori probability* that itself introduces uncertainty in the resulting model distributions.

In part, the research aim was to establish what data for a simulation approach to assessing a building stock is required, what data currently exists and whether approaching the modelling *a priori* provides realistic distributions in results.

3.5.1 Uniform (Rectangular) Distribution

The probability of occurrence of a value x in the range a to b is constant over the range for a continuous distribution. The probability function f(x) is represented as:

$$f(x) = \begin{cases} \frac{1}{b-a}, & \text{if a} \leq \text{x} \leq \text{b} \\ 0, & \text{otherwise.} \end{cases} \tag{3.1}$$

For discrete values in the range from a to b each value is given equal probability of occurrence so as number of simulation runs (n) tends towards ∞ , each discrete value has occurred an equal number of times. The probability of n discrete values in the range is given as:

$$f(x) = \frac{1}{n} \tag{3.2}$$

For each case the *rand()* function in MATLAB that provides a pseudo-random value between 0 and 1 was scaled to represent the considered range of a parameter. In the case of n discrete values the range was split into n equal and continuous components, with each sub-range representing a discrete value.

Rectangular distributions were applied to parameters when only the upper and lower limits of the potential range could be identified.

3.5.2 Triangular

Triangular distributions are relevant to continuous distribution ranges where only the mode and limits are known. It is used in instances where a non-uniform distribution is expected, but little/no data is available for determining the actual distribution. The probability function of a variable x in the range a to b, with mode m is given as:

$$f(x) = \begin{cases} \frac{m-a}{b-a}, & \text{if x = m} \\ \frac{(x-a)^2}{(m-a)(b-a)}, & \text{if x < m} \\ 1 - \frac{(b-x)^2}{(b-m)(b-a)}, & \text{if x > m.} \end{cases} \tag{3.3}$$

The distribution mean is given as:

$$\mu = \frac{m+a+b}{3} \tag{3.4}$$

and variance as:

$$\sigma^2 = \frac{m^2+a^2+b^2-ma-ab-mb}{18} \tag{3.5}$$

3.5.3 Gaussian (Normal) Distribution

Typically associated with normal distributions, a bell shaped curve describes the probability function associated with this continuous distribution. The curve is represented by the Gaussian function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \tag{3.6}$$

using the same notation as applied to equations 3.1 to 3.5.

This probability distribution was applied for instances where such a distribution in the building stock was predicted from existing stock surveys and for compiled data on building components (see air infiltration consideration). This is used by reasoning of the 'Central Limit Theorem' that states for a finite variance (σ^2) and mean (μ) in a given sample, the distribution approaches a normal distribution of variance $\frac{\sigma^2}{n}$ and mean μ as sample size (n) increases. Success of application of this theorem is dependent on the sample size used for obtaining the mean and variance.

As physical limits exist in the parameters under consideration distributions are often restricted. Where modal values are at or in close association to a given physical limit the distribution will contain asymmetry, termed skewness . For univariate distribution, skewness is calculated as:

$$\gamma = \frac{\sum_{i=1}^{n}(x_i - \mu)^3}{(n-1)(\sigma^2)^{\frac{3}{2}}} \tag{3.7}$$

3.6 Conclusions

The success of a probability model for energy performance indication of a building stock depends on the distributions applied to influencing parameters. Current sources for identifying distributions are incomplete and the method has not been applied to the NDBS before. The influence of the five identified categories affecting building energy performance in the ND building stock is unclear.

Surveys and remote sensing have and are being applied to give a better understanding of the variation in basic form for the building stock. Building regulations and control laws offer an approach to understanding the basic distributions of detailed building construction. A method for assessing the influence of building controls on probable base level thermal performance has been described.

The NDBS used activity to categorise buildings for energy assessment. It is recognised that many of these categories have significant variation in activity. Office buildings offer greatest 'homogeneity' in activity, though is understood that occupant behaviour does also vary within this activity type. As a significant ND building type in developed countries and due to less variation in occupant behaviour a focus is given to this ND building type.

Five basic areas were identified to account for all influencing parameters. The current method aims to assess thermal performance of the building, not its services, or the efficiency of heating/cooling/lighting systems and associated management. This allows the model to focus on the building stock's potential to use passive measures for improving thermal control and the uncertainty associated with that potential when applied to the building stock.

Understanding internal gains is a large uncertainty that is difficult to assess for probable behaviours in an office environment. The internal gains will be dependent on personal preference, internal layout (thermal control, lighting systems, etc..), occupant behaviour (i.e. use of controls on internal conditions, use of equipment, activity level). These factors are in turn influenced by human physical condition and reports suggest social factors such as job satisfaction are also of concern.

For determining the use of such probabilistic modelling as a methodology for large scale energy assessment in buildings these factors were fixed. This was intended to allow focus on the building structure and identifying methods for assessing building parameters in a probabilistic manner. Of the 5 identified categories, building form, location and construction gain the focus of this project.

Chapter 4

Parametric Assessment - Building Component Form

Building use and period of building construction were identified as two important methods of categorisation for energy assessment, according to [20, 121, 101, 54]. Focusing the study on ND office use; building regulations, historical building control laws and standards were used to identify ranges in expected structural properties by period of construction.

This chapter describes the variation in building form, captured by investigating historical building control documentation. The importance of varying form of basic building components (e.g. wall and floor construction and glazing proportion) to thermal loading was investigated in relation to dynamic thermal energy modelling. These initial investigations were used to determine the level of detail needed for modelling probable stock level variations in building thermal performance.

For each considered structural component a statistical distribution was associated with its potential variation. Physical limits were set for each distribution as a result of the studied building controls combined with existing data from stock survey data taken from the NDBS Project [29].

4.1 Division of Building Structure and Material Thermal Properties

The building structure was split into five basic components for assessment. These are:

(i) External Wall

(ii) Internal Wall

(iii) Floor/ceiling (ground/inter-storey)

(iv) Roof

(v) Openings (window type and glazing area)

Each component was assessed in terms of composition and variation in composition for the ND building stock. In cases of substantial variation in component composition only common forms were investigated to aid model development.

The proportion of structural component parts impacts the significance of each component to thermal performance. Where applicable, variations in such proportions (i.e. window area) were investigated.

4.1.1 Thermophysical Properties of Building Materials

The thermal nature of the structural building components is a result of the thermophysical properties of the materials used in their construction. For dynamic thermal assessment, conductance, density and specific heat are all required properties for determining thermal diffusivity (Fouriers law of Heat Conduction). Radiative properties (solar absorptance, opacity and surface emissivity) for both longwave and shortwave radiation are also required to model the impact of radiative heat sources on building thermal performance.

Thermophysical properties for standard building materials can be found in [122, 108]. The report [122] (summarised in [108]) evaluates national standard data-sets of building material thermophysical properties for several countries. Sources include ASHRAE handbook and CIBSE data as well as reference manuals/databases supplied with modelling tools such as DOE-2 and ESP-r.

The thermophysical properties are determined from experiments adhering to national standards. It is noted that the data provides steady-state thermophysical properties, for example BS EN 1745 uses a square-guarded hot plate method at fixed temperature and moisture content for determining thermal conductivity. Clarke et al., [122], also reports limited data for some materials only allows for their use in steady-state heat loss and condensation assessment.

The data supplied for materials that allows for dynamic thermal assessment has been used in this investigation. Clarke et al. offers the most comprehensive data on building material thermophysical properties in [122]. The data were used to provide expected properties of materials used in structures as identified via building regulations.

Variation in material properties, resulting from evolving technology for material manufacture and variation in the raw materials used for producing building materials [6], was not accounted for. Uncertainty in material values is not considered by the modelling work of this thesis.

4.2 Building Controls for Identifying Structural Component Properties

Having established a source for the thermophysical properties of building materials, an account of the construction of building components was needed. As empirical surveys had used periods of construction for grouping energy performance of a building stock, a similar approach was intended in the probability simulation model. Without carrying out large scale intrusive and potentially destructive testing on existing ND buildings, control laws were considered as an alternative solution for establishing ranges in building component construction.

A review of historical building controls showed efforts were made to standardize building control in UK Parliament from 1844 onwards. Model by-laws were introduced which local authorities were to use in controlling building construction. Little adherence to these controls was recognised and the laws were regularly changed with improved understanding of building requirements. A period of stability and greater national acceptance of the model by-laws occurred under the Public Health Act 1894 and London Building Act 1894 [13].

Based on an expected instability in building control prior to 1894, the building controls were only used in consideration of buildings built after this date. In doing so the existing building stock is not fully considered by the model. From the NDBS Project's evaluation of the Valuation Office Agencies data on building age, 75% of the ND floor space is accounted for between 1900-1994 [20]. A similar study [1] conducted ten years later showed a similar proportion post dating 1900.

4.2.1 Building Control Periods - Pre Building Regulations 1894 - 1965

Prior to the introduction of official building regulations as an instrument of building control, by-laws and British Standards were used to regulate building construction. For wall construction, wall thickness charts were used.

Three construction control periods were identified for the model as:

(i) 1894/1915 - 1938 [13]

(ii) 1939 - 1952 [123]

(iii) 1953 - 1965 [124]

The earliest period can be used to represent load bearing structures built from 1894. Building by-law controls for reinforced concrete and steel frame structures were only established in 1915 [39]. The use of these controls (depending on treatment of framed structures pre-1915) can therefore be applied to the ND building stock as far back as 1894.

The 1936 Public Health Act resulted in revised wall thickness charts and general building by-laws used up until the (government issued) 1952 Model Byelaws - revised in 1953 [123, 124].

It is recognised that up until 1952 the central government issued by-laws were subject to change under local authority guidance [125]. Introduction of standards and Codes of Practice in [124] made it possible for other methods to be used to determine required structural composition. These techniques for determining structural performance allowed introduction of new materials and building techniques, increasing diversity in building stock form.

The sources identified for determining wall structure between 1894 and 1965 can only be considered as guides. Uncertainty exists due to regional variation in adherence to the by-laws. The study of (and use of) regional building laws is an area of further research for developing the probability model.

4.2.2 Building Control Periods - Introduction of Building Regulations 1966 - 1984

The Building Regulations of 1965 (coming into force in 1966) were introduced by the Minister of Public Building and Works after consultation with the Building Regulations Advisory Committee. The regulations introduced control of thermal performance of the basic building envelope (walls, floors and roofs).

In 1972 a new Statutory Instrument of Building Regulations were brought out. The only noticeable change is the use of metric (S.I) units, rather than imperial units. This results in minor differences from rounding up or down of the converted values.

The oil crisis of the 1970's resulted in further tightening of building thermal efficiency regulations, that were introduced in the 1976 Building Regulations (coming into force in 1977).

Based on the minimum required standards set out in these regulations, wall structures of varying (yet common) material and construction method are given.

Three periods of control were identified for the ND building stock probability model as:

(i) 1966-1971 [126]

(ii) 1972-1976 [127]

(iii) 1977-1984 [128]

The regulations of these periods only state dwellings (i.e. not commercial buildings) needed to adhere to the thermal regulations. Other reports [113, 129], however, show commercial buildings applying thermal performance concern to building construction as a result of the 1970's oil crisis. The regulations have therefore been applied in determining ND building structure.

4.2.3 Building Control Periods - Post 1984 Building Act (Part L Energy Regulations)

The 1984 Building Act restructured the building regulations. Part L was introduced to regulate energy performance (by structure and efficiency of building services) - titled Conservation of Fuel and Power. This structure of regulations are still in use today.

Focusing on structural thermal efficiency requirements, the building components are regulated by minimum U-values . Review of Part L, showed changes to these regulations occurred in 1991, 1996, 2002 and most recently in 2006. For structural thermal regulations, there is no change to regulations for the 2002 and 2006 regulations.

Four periods of structural thermal control were identified for the model as:

(i) 1985-1990 [130, 34]

(ii) 1991-1995 [35]

(iii) 1996-2001 [36]

(iv) 2002-Present [37, 38]

4.3 Building Component Construction and Thermal Analysis

Based on the identified periods of building control, different structural component forms were analysed for use in the building stock probability model. Materials used in component construction and component dimensions were investigated to develop a database of expected component forms, of varying thermal behaviour.

The thermal regulations of building components (in-part 1966-1976 and fully post-1976) provide minimum accepted standards of thermal transmittance. Building to these standards suggests a uniform thermal performance associated with each building component. However, the identified component values were recognised as relating to a steady-state evaluation of thermal behaviour that can lead to misjudgement of expected thermal behaviour in buildings (as highlighted by [131]).

This arises as no account is made of the dynamic response of a building due to thermal storage capacity associated with building materials. It was shown in [132] that ignoring mass effects could lead to significant error in thermal performance prediction. Saparito showed a significant sensitivity of dynamic (by numerical methods) thermal building energy simulation to thermal mass [121].

In assessing varying structural composition in the ND building stock via building control, dynamic thermal assessment was carried out using the admittance method (see appendix A). This was used to determine the need to account for varying building component compositions in the probability modelling procedure.

4.4 External Wall Construction

Table 4.1, provides an overview of basic wall construction methods and common building materials used in wall construction in England and Wales. The NDBS project showed load bearing and frame construction to be equally represented in ND office buildings [3]. Common internal wall finishes considered were rendered plaster or plasterboard lining.

From [6], both plasterboard (introduced in 1917) and rendered plaster finishes have been available for the considered periods of construction. Plasterboard, however, only started to be more widely used as a wall lining in the 1950's (previously it was more commonly applied to ceilings) [6]. The thermophysical differences depend on the plasterboard density. In some instances an 'insulating plasterboard' is shown in the building regulations, where a maximum thermal transmittance is stipulated.

For periods pre-1953 a rendered plaster was applied to all modelled wall constructions. Post-1952 two plasterboard finishes were used, depending on the regulatory requirements. For constructions with an 'insulating plasterboard' a lightweight plasterboard was applied. In all other cases a more dense plasterboard was applied, based on values from [122].

The masonry wall components can be combined in layers, where common layer formations are brick-cavity-brick, brick-cavity-block, block-cavity-block and solid brick walling.

Fully glazed curtain walling was not considered in the examination of thermal performance of buildings. As high level glazing impacts thermal and visual performance, more bespoke (i.e. outside the scope of basic building controls) design considerations are made to control comfort levels. Understanding general forms and the distribution of those forms in the current ND building stock cannot be easily identified from historical building controls or other existing data sources.

Appendix B provides the basic wall construction of typical construction methods for the identified periods of building control. A focus was given to masonry wall construction (considered the most common construction in the UK building stock) and prefabricated panelling systems for later control periods. This simplification in building stock construction offers an area of further development in the model.

Table 4.1: Use and description of walling materials in buildings of England and Wales [6, 7, 8, 9, 10].

Category	Wall Component	S	C	LB	CF	Description
Masonry	Brick	x	x	x	x	Most common walling in the existing building stock. Variation in form (solid/hollow) influence thermal properties. The distribution of different forms in the building stock has not been assessed, though M. Bowley reported greater acceptance of hollow bricks post 1953. Recognised as the cheapest building material (1894-1960).
	Concrete Block	x	x	x	x	Varying in density, material and form - 29 types recognised by the Committee on Standardisation of Construction in 1920. The use across the country was influenced by the availability of brick and stone. Up to 1960, it was reported by M. Bowley as a more expensive material than brick. Though available throughout the considered period (1894 to 2008) their use as an internal-leaf for cavity walls became popular in the early 1960's according to UWE department of the Built Environment.
	Stone	x	x	x	x	A localised material, reaching a peak in use by the late 19th century (G Lott, Development of Victorian Stone Industry, English Stone Heritage Proc.). High costs result in more selective use of stone - associated with prestigious buildings. The properties of the material vary according to the petrological state of the area in which it is sourced.
Prefabricated	Steel Sheet-Insulation	x			x	A sandwich of micro-gauge metal sheets with a core of insulating material. New methods of metal sheet production in 1960, resulted in the development of insulated cladding panels, used in commercial buildings (R Barry, Construction of buildings).
	Aluminium Sheet - Insulation	x			x	
	Asbestos Cement Sheet				x	More typically used as a lining material, or roof panelling. Carcinogenic properties has and is resulting in replacement of asbestos in buildings.
	Fibreboard				x	Using waste wood material, boards used as a substitute for solid wood cladding. Its use in history of commercial buildings was low (M Bowley, 1960).
Reinforced Concrete	Precast Slabs /Cast on-site	x		x	x	
Curtain Walling	Glass - steel Stone veneer Prefabricated panels				x	A cladding of glass and/or steel with some form of insulation (usually an air gap). Typically used for cladding 'tall' (50 metres plus) buildings. Other materials, designed to clad frame structures are metal-insulation panels (see prefabricated section in this table).

S - Solid Wall C- Cavity Wall LB - Load Bearing Wall CF - Clad Frame Wall

4.4.1 Dynamic Thermal Assessment of Considered Wall Constructions identified in building controls

For the control periods between 1894 to 1965 wall thickness charts were identified for providing minimum thickness requirements according to wall length, height and construction material (see appendix B). Harmonic dynamic response factors (appendix A) and U-values were calculated for the wall thickness charts. A large variation in wall thermal property results from wall length and height that dictate wall thickness.

The results (tables 4.2, 4.3 and 4.4) for solid brick and brick-cavity-brick construction from the investigation show large variation in thermal transmittance (U-value). The greatest variation results from method of wall construction as well as wall height (divided into storeys of 3.05m [10ft] in height). Increased height required increased wall thickness for load bearing strength, so reducing U-value. Variation in wall thickness requirements between the three identified periods (1894-1938/1939-1952/1953-1965) results in differing thermal properties of equivalent wall components.

The admittance response factor is relatively consistent for the differing wall constructions.

The regulation periods (post 1965) provide thermal performance criteria of building components via steady-state thermal transmittance (U-values). The typical wall construction methods identified in the building regulations (Appendix B) were assessed by the admittance method. Table 4.5 provides the resulting values for brick-cavity-block walling (a common construction method of the considered stock) as set out in building regulations and documented in appendix B.

The study showed that whilst building to a maximum allowable (constant) U-value, the method of construction resulted in varying dynamic thermal properties.

Comparing all building periods showed a reduced wall U-value and admittance (Y-value) for later control periods. However, between the wall thickness controls (1894-1965) and the early building regulations (1966-1976) this trend is less clear. Thicker wall requirements for taller and longer walls (1894-1965) result in lower U-values (and higher Y-values) compared to the equivalent wall constructions of 1966-1976. This suggests reduced thermal efficiency in building construction for late 1960's, early 1970's buildings.

Of the considered wall constructions, variation in both dynamic and steady-state thermal properties exist within each specified control period. It was concluded that a database of the identified wall constructions associated with each period of building control was needed for energy modelling of the ND building stock. The variation in thermal property with wall height for control by wall thickness charts (1894-1965) required the model database to also provide different wall construction in relation to wall height.

Table 4.2: 1894-1938 steady-state and dynamic thermal properties relating to minimum regulated wall thickness.

	Minimum Wall Thermal Value by minimum wall thickness (1894-1938) - Solid Brick																													
Storey*	1			2			3			4			5			6			7			8			9			10		
	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f
1st	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.23	4.45	0.09	1.23	4.45	0.09	1.06	4.45	0.05	1.06	4.45	0.05
2nd				2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17	1.23	4.45	0.09	1.23	4.45	0.09
3rd							1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17	1.23	4.45	0.09
4th										2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17
5th													2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17
6th																1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17
7th																			1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
8th																						1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
9th																									1.77	4.47	0.32	1.77	4.47	0.32
10th																												1.77	4.47	0.32
	Minimum Wall Thermal Value by minimum wall thickness (1894-1938) - Brick-Cavity-Brick																													
Storey*	1			2			3			4			5			6			7			8			9			10		
	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f
1st	1.51	4.27	0.53	1.51	4.27	0.53	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	0.98	4.25	0.08	0.98	4.25	0.08	0.87	4.25	0.04	0.87	4.25	0.04
2nd				1.51	4.27	0.53	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15	0.98	4.25	0.08	0.98	4.25	0.08
3rd							1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15	0.98	4.25	0.08
4th										1.51	4.27	0.53	1.51	4.27	0.53	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15
5th													1.51	4.27	0.53	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15
6th																1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15
7th																			1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29
8th																						1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29
9th																									1.29	4.26	0.29	1.29	4.26	0.29
10th																												1.29	4.26	0.29

* Storey Height assumed to be 3m

Table 4.3: 1939-1952 steady-state and dynamic thermal properties relating to minimum regulated wall thickness.

	Minimum Wall Thermal Value by minimum wall thickness (1939-1952) - Solid Brick																													
Storey*	1			2			3			4			5			6			7			8			9			10		
	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f
1st	2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.21	4.45	0.09	1.21	4.45	0.09	1.06	4.45	0.05
2nd				2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17	1.21	4.45	0.09
3rd							2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17
4th										2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17
5th													2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17
6th																2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
7th																			1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
8th																						1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
9th																									1.77	4.47	0.32	1.77	4.47	0.32
10th																												1.77	4.47	0.32

	Minimum Wall Thermal Value by minimum wall thickness (1939-1952) - Brick-Cavity-Brick																													
Storey*	1			2			3			4			5			6			7			8			9			10		
	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f
1st	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	0.96	4.25	0.07	0.96	4.25	0.07	0.85	4.25	0.03	0.85	4.25	0.03	0.78	4.25	0.02
2nd				1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	0.96	4.25	0.07	0.96	4.25	0.07	0.96	4.25	0.07	0.85	4.25	0.03
3rd							1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	0.96	4.25	0.07	0.96	4.25	0.07	0.96	4.25	0.07
4th										1.29	4.26	0.29	1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	0.96	4.25	0.07	0.96	4.25	0.07
5th													1.29	4.26	0.29	1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15	0.96	4.25	0.07
6th																1.29	4.26	0.29	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15
7th																			1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15
8th																						1.1	4.25	0.15	1.1	4.25	0.15	1.1	4.25	0.15
9th																									1.1	4.25	0.15	1.1	4.25	0.15
10th																												1.1	4.25	0.15

* Storey Height assumed to be 3m

Table 4.4: 1953-1965 steady-state and dynamic thermal properties relating to minimum regulated wall thickness.

	Minimum Wall Thermal Value by minimum wall thickness (1953-1965) - Solid Brick																													
Storey*	1			2			3			4			5			6			7			8			9			10		
	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f
1st	2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17	1.23	4.45	0.09	1.23	4.45	0.09
2nd				2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17	1.44	4.45	0.17
3rd							2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17
4th										2.31	4.41	0.57	2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.44	4.45	0.17	1.44	4.45	0.17
5th													2.31	4.41	0.57	2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.17
6th																2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
7th																			1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32	1.77	4.47	0.32
8th																						2.31	4.41	0.57	1.77	4.47	0.32	1.77	4.47	0.32
9th																									1.77	4.47	0.32	1.77	4.47	0.32
10th																												1.77	4.47	0.32
	Minimum Wall Thermal Value by minimum wall thickness (1953-1965) - Brick-Cavity-Brick																													
Storey*	1			2			3			4			5			6			7			8			9			10		
	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f	U	Y	f
1st	1.51	4.27	0.53	1.51	4.27	0.53	1.51	4.27	0.53	1.51	4.27	0.53	1.26	4.26	0.27	1.08	4.25	0.13	1.08	4.25	0.13	1.08	4.25	0.13	0.96	4.25	0.07	0.96	4.25	0.07
2nd				1.51	4.27	0.53	1.51	4.27	0.53	1.51	4.27	0.53	1.51	4.27	0.53	1.26	4.26	0.27	1.08	4.25	0.13	1.08	4.25	0.13	1.08	4.25	0.13	1.08	4.25	0.13
3rd							1.51	4.27	0.53	1.51	4.27	0.53	1.51	4.27	0.53	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27	1.08	4.25	0.13	1.08	4.25	0.13
4th										1.51	4.27	0.53	1.51	4.27	0.53	1.51	4.27	0.53	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27	1.08	4.25	0.13
5th													1.51	4.27	0.53	1.51	4.27	0.53	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27
6th																1.51	4.27	0.53	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27
7th																			1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27	1.26	4.26	0.27
8th																						1.51	4.27	0.53	1.26	4.26	0.27	1.26	4.26	0.27
9th																									1.26	4.26	0.27	1.26	4.26	0.27
10th																												1.26	4.26	0.27

* Storey Height assumed to be 3m

Table 4.5: Steady-state regulated wall values and associated harmonic dynamic thermal response factors for brick-cavity-block wall construction.

Building Period	Wall Thermal Properties							Appendix 4A Construction key
	U	Y	f	s	φy	φf	φs	
	(W/m^2.K)					(h)		
1966-1976	1.7	3.47	0.76	0.65	1.97	-4.99	-1.34	D
1977-1984	1	3.78	0.21	0.59	1.65	-11.98	-1.36	E (i)
	1	3.6	0.36	0.62	1.8	-9.51	-1.34	E (ii)
	1	3.17	0.5	0.68	2.12	-7.96	-1.26	E (iii)
	1	2.6	0.67	0.76	2.43	-6.15	-1.03	E (iv)
	1	1.88	0.76	0.83	2.66	-5.01	-0.73	E (v)
1985-1990	0.7	1.25	0.3	0.87	2.39	-8.16	-0.42	A
	0.7	2.58	0.53	0.75	2.28	-7.41	-0.98	B
	0.7	3.57	0.47	0.67	2.26	-7.79	-1.52	C
1991-2001	0.45	1	0.27	0.92	3.41	-8.46	-0.42	A
	0.45	2.68	0.47	0.74	2.32	-7.96	-1.04	B
	0.45	3.66	0.42	0.66	227	-8.2	-1.59	C
2002-2008	0.35	0.95	0.26	0.94	3.89	-8.57	-0.43	A
	0.35	2.72	0.45	0.74	2.32	-8.16	-1.06	B
	0.35	3.69	0.41	0.66	2.26	-8.49	-1.6	C

4.4.2 ND Building Stock Probability Model Consideration

From the NDBS Project, wall construction is categorised by load bearing or framed structures of either masonry, heavy cladding, light cladding or glazed curtain wall material [11]. The data shows framed structures are more common than load bearing construction for buildings of large floor area.

For deep-plan and sidelit built forms (most common forms for office buildings) table 4.6 summarises the percentage share of framed and load bearing structures according to floor area size bands - taken from [11].

Of the four construction types given by [11], masonry walling for deep-plan and sidelit load-bearing or framed structures is most common. Table 4.7 shows the percentage of total surveyed floor area associated with the different wall construction categories.

These percentage distributions were considered representative of the ND office building stock and were applied to the probability model. No relationship between wall construction distribution and period of building construction was made. The same distributions were applied to all construction periods.

The building controls identified different wall constructions within the four basic construction types given by [11]. The varying wall constructions within the four basic categories of wall construction (identified by control laws and building regulations) were given equal probability of occurrence.

Wall Construction Variation within Periods controlled by Wall Thickness Charts

For the construction periods using wall thickness charts a range of wall thickness according to wall height was established from the minimum values associated with differing wall length. With potential variation in actual built thickness to these minimum thickness charts[1], the chart values were used to set likely

[1]Due to dimensions of basic building blocks and varying building design and construction practices.

Table 4.6: Distribution of building structure (framed/load bearing) according to building size bands by floor area [11].

Size bands for Floor Area (m^2)	Deep Plan (% of total surveyed floor area)		Side-lit (% of total surveyed floor area)	
	Framed	Load Bearing	Framed	Load Bearing
< 100	-	-	14	86
100 - 300	30	70	16	84
300 - 1,000	50	50	29	71
1,000 - 3,000	58	42	59	41
3,000 - 10,000	70	30	76	24
10,000 - 30,000	75	25	78	22

Table 4.7: Distribution of popular office type ND building structure by wall construction material groups [11].

Wall Construction Group	Deep Plan (% of total surveyed floor area)		Side-lit (% of total surveyed floor area)	
	Framed	Load Bearing	Framed	Load Bearing
Masonry	76	93	66	94
Heavy Cladding	10	7	14	6
Light Cladding	7	0	12	0
Glazed	7	0	8	0
Total	100	100	100	100

minimum and maximum wall thickness. With no understanding of the variation in thickness beyond that described by wall thickness charts a random selector was applied in the model to set the wall thickness. A rectangular distribution was associated to the thickness ranges determined from the wall thickness charts.

Wall Construction Variation for Periods of Building Regulation Control

For the regulation periods (post 1965), the wall constructions set out in appendix B were used. Equal probability was applied to the identified construction types within each of the four basic construction methods.

4.5 Floor and Ceiling Construction

The floor/ceiling influences the level of thermal isolation between a building's storeys. Three basic categories were identified as ground floor, inter-storey and top storey ceiling/roof. For each category two sub-categories were defined as:

(i) Ground Floor - Solid/Suspended (concrete/wood)

(ii) Inter Storey Ceiling/Floor - Wood boards/Concrete slab

(iii) Top Storey Ceiling - Ceiling to roof void/Roof to external environment

In each instance the thermal bridging associated with joists was ignored for simplification of construction for the DSM.

4.5.1 Ground Floor Construction

The two methods of construction (solid and suspended) were identified as possible in all of the considered building periods (1894 to present day). The building controls and regulations set minimum standards for each method. For suspended floors with exposure to external air, thermal regulations were applied in the 1965 Building Regulations. For solid flooring thermal regulation was introduced in the Part L regulations following the 1984 Building Act.

Table 4.8 summarises the dimensions associated with solid and suspended floor construction prior to thermal regulation. These are minimum values found in by-laws and regulations. Consistency in the controlling laws prior to the introduction of the 1965 Building Regulations is evident.

Table 4.8: Basic floor construction identified in regulations - without thermal regulation (1894-1990).

Control Period	Type	Concrete Base Thickness (m)	Suspended Floor Height (m)
1894-1938	Solid	0.1524	-
	Suspended	0.1524	0.2286
		0	0.381
1939-1952	Solid	0.1524	-
	Suspended	0.1524	0.2286
		0	0.381
1953-1965	Solid	0.1524	-
	Suspended	0.1524	0.2286
		0	0.381
1966-1971	Solid	0.1016	-
	Suspended*	0.1016	0.2667
1972-1976	Solid	0.1	-
	Suspended*	0.075	0.2774
1977-1984	Solid	0.1	-
	Suspended*	0.075	0.2774
1985-1990	Solid	0.1	-
	Suspended*	0.075	0.2774

*Construction required if not thermally regulated (i.e. not exposed to external environment by more than the required amount of ventilation for moisture control).

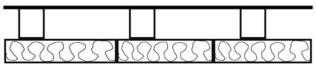
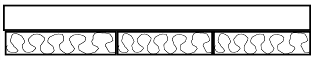
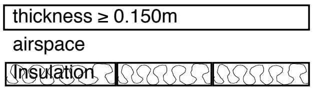
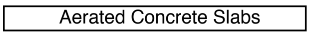
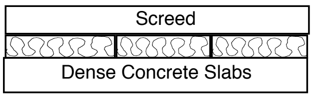
For suspended flooring exposed to external air, table 4.9 shows the maximum expected U-value for each period, along with expected construction identified in the building regulations. In all instances the airspace is considered as an unventilated air cavity with constant thermal resistance, R, of 0.18 $m^2.K.W^{-1}$.

For later control periods insulation levels are related to floor area and perimeter dimensions. Tables from Part L building regulations that control the insulation levels for ground floor construction are summarised in appendix C. The data given here and in appendix C was used in the logic of the probability model to determine the floor construction.

4.5.2 Inter-storey ceiling/floor construction

The level of thermal transmittance associated with inter-storey flooring is only considered in regulations post 2001. For earlier periods a consistent construction was assumed for both timber flooring and concrete slab flooring. Thermal bridging effects were ignored with construction layers representing the ceiling of the lower storey and floor of the upper storey.

Table 4.9: Floor Construction - controlled by thermal transmittance: regulations post-1965).

Control Period	U-value (W/m^2.K)	Type	Construction			
1966-1971 & 1972-1976	Exposed Floor 1.42	Suspended Wood		Tongue & groove timber ≥ 0.016m Joist Wood wool ≥ 0.038m thick		
		Suspended Concrete		Suspended Concrete Slabs Wood wool ≥ 0.05m thick or Expanded Polystyrene ≥ 0.019m Corkboard ≥ 0.025m thick		
1977-1984	Exposed Floor 1.0	Suspended Concrete		Suspended Concrete Slabs (high density)		
				Insulation	Minimum Thickness (m)	
				Airspace Size	0	>0
				Compressed straw	0.058	0.038
				wood wool slabs	0.043	0.028
				Fibre board	0.031	0.02
				Corkboard	0.023	0.015
				Mineral Fibre slab	0.018	0.012
				Expanded polystyrene	0.018	0.012
		Suspended Concrete		Thickness ≥ 0.150m	Density ≤ 650 kg/m^3	
1985-1990	Exposed Floor 0.6	Suspended Concrete		Thickness ≥ 0.075m Thickness ≥ 0.035m/0.046m/0.058m k = 0.03/0.04/0.05 W/m.K Thickness ≥ 0.100m	Density ≤ 650 kg/m^3	
1991-1995	0.45	All Ground and Exposed Floors	The required insulation is dependent on the floor perimeter to area ratio. The tables provided in Part L building regulations are summarised in Appendix 4B.			
1996-2001	0.45	All Ground and Exposed Floors				
2002-2006	0.25	All Ground and Exposed Floors				
2006-Present	0.25	All Ground and Exposed Floors				

Gypsum plasterboard was a recognised building material for all considered construction periods, see [6]. It has been applied as the initial layer for all ceiling constructions.

For later regulatory periods, inter-storey floors have a specified U-value according to Part L Building Regulations. The values of required insulation thickness to meet overall U-values are calculated by taking into account bridging effects of floor joists. In the regulations the joists are assumed to account for 12% of total floor area. As bridging effects are not accounted for in the constructions of the DSM, the insulation levels were recalculated to obtain the same U-value as stated in the regulations[2] (see appendix C).

4.5.3 Top Storey Ceiling and Roof

The top storey ceiling is either connected to the external environment (as a flat roof construction) or to a roof void. No account of pitched roof with sloping ceiling was made.

Table 4B-17 in appendix C summarises the insulation levels accounted for by building regulations from 1966 onwards. Pre-1965 building regulations, the basic construction is considered with no insulation. For pitched roofs pre-1965, only tiled roofing was considered.

4.5.4 Thermal Properties for steady-state and dynamic consideration

The harmonic response function (Admittance Method) was used to investigate the dynamic thermal response of the two basic categories of light and heavy weight floor/ceiling construction. Table 4.10 shows the results for each building control period's modelled ground floor form[3].

The calculation procedure did not include external surface resistance as the 'external' floor surface is considered in full contact with the ground (external environment). For the suspended floors no ventilation is considered and an air cavity thermal resistance, R, of 0.18 m.K/W was applied (as the default applied in esp-r).

The data in table 4.10 shows an increased U-value from pre-Building Regulation control periods to the periods between 1966 to 1990 when comparing like-for-like ground floor construction. This results from a reduced requirement in concrete base thickness that reduces dynamic response factors and time leads/lags.

Stability in U-value and Y-value appears in the later periods between the solid (heavy weight) ground floor and suspended (light weight) floor. This is a result of layer order, where insulation layer is on the upper side of concrete floor slabs and lower side of suspended wood flooring. Though not stated in the regulations as the required order (as U-value will be the same regardless), all examples found in the regulations use this order.

For simplification in the probability model, a fixed order of construction layers for flooring and ceiling (as given in construction examples in building regulation documentation) was used. In all instances in the model only one insulation material was applied. It is recognised that this simplification does not consider the potential difference of dynamic thermal behaviour of different insulating materials or layer order. Insulation material and layer order demonstrated in examples within regulatory documentation were used[4].

[2] This procedure was carried out for all structural components with implied thermal bridges in calculating U-value.

[3] Each form example resulted from study of regulatory or bylaw documentation.

[4] As assumed to be standard practice (i.e. most probable) within building construction.

Table 4.10: Ground Floor Construction - Thermal properties for minimum standards set by building controls.

Control Period	Solid							Suspended						
	U	**Y**	**f**	**s**	**Φy**	**Φf**	**Φs**	**U**	**Y**	**f**	**s**	**Φy**	**Φf**	**Φs**
	(W/m^2.K)					(h)		(W/m^2.K)					(h)	
1894 - 1965	**2.4**	**3.3**	**0.9**	**0.6**	**1.1**	**-3.3**	**-0.7**	**1.7**	**2.7**	**1**	**0.7**	**1.6**	**-3.8**	**-0.8**
	Hardwood Concrete				Thickness = 0.025m Thickness = 0.1524m			Hardwood Air Concrete				Thickness = 0.025m Thickness = 0.2286m Thickness = 0.1524m		
1966-1971	**2.7**	**3.3**	**1.1**	**0.6**	**0.8**	**-2**	**-0.6**	**1.8**	**2.7**	**1.1**	**0.7**	**1.5**	**-2.5**	**-0.7**
	Hardwood Concrete				Thickness = 0.025m Thickness = 0.1016m			Hardwood Air Concrete				Thickness = 0.025m Thickness= 0.2667m Thickness = 0.1016m		
1972-1990	**2.7**	**3.3**	**1.1**	**0.6**	**0.8**	**-2**	**-0.6**	**1.9**	**2.7**	**1.1**	**0.7**	**1.4**	**-1.9**	**-0.7**
	Hardwood Concrete				Thickness = 0.025m Thickness = 0.1000m			Hardwood Air Concrete				Thickness = 0.025m Thickness = 0.2775m Thickness = 0.075m		
1991-1995	**0.6**	**2.5**	**0.9**	**0.8**	**3.5**	**-3.3**	**-1.2**	**0.6**	**2.5**	**1**	**0.8**	**3.4**	**-2.7**	**-1.2**
	Hardwood EPS Concrete				Thickness = 0.025m EPS Thickness = 0.038m Thickness = 0.1000m			Hardwood EPS Air Concrete				Thickness = 0.025m EPS Thickness = 0.031m Thickness = 0.2775m Thickness = 0.075m		
1996-2001	**0.45**	**2.5**	**0.9**	**0.8**	**3.5**	**-3.3**	**-1.2**	**0.45**	**2.5**	**0.9**	**0.9**	**3.7**	**-2.8**	**-1.2**
	Hardwood EPS Concrete				Thickness = 0.025m EPS Thickness = 0.049m Thickness = 0.1000m			Hardwood EPS Air Concrete				Thickness = 0.025m EPS Thickness = 0.051m Thickness = 0.2775m Thickness = 0.075m		
2002-2008	**0.25**	**2.6**	**0.9**	**0.9**	**3.9**	**-3.7**	**-1.3**	**0.23**	**2.6**	**0.9**	**0.9**	**3.9**	**-3.5**	**-1.3**
	Hardwood EPS Concrete				Thickness = 0.025m EPS Thickness = 0.091m Thickness = 0.1000m			Hardwood EPS Air Concrete				Thickness = 0.025m EPS Thickness = 0.121m Thickness = 0.2775m Thickness = 0.075m		

Different insulation materials have different thermophysical properties. In the regulations the thickness of insulation required is dependent on the material's conductivity, κ , and desired U-value. In a dynamic thermal process, however, the thermal storage (dictated by density, ρ , and specific heat capacity, c_p) may vary. Table 4.11 demonstrates this dynamic thermal variation (by the admittance method) due to different insulating material, whilst U-value remains constant for a suspended floor construction that adheres to current regulations (see table 4.10).

Table 4.11: Suspended hardwood floor of differing insulation material but with the same U-value.

Insulating Material (Conductivity)	U-value	Admittance (Y)	Decrement Factor (f)	Surface Factor (s)	Admittance Time Lead Φ_y	Decrement Time Lag Φ_f	Surface Time Lag Φ_s
	(W/m^2.K)		-			(h)	
Expanded Polystyrene (0.03 W/m.K)	0.23	2.63	0.88	0.87	3.89	-3.45	-1.3
Corkboard (0.04 W/m.K)	0.23	2.81	0.43	0.81	3.32	-9.93	-1.34

4.6 Roof Type Variation

The NDBS Project identified six basic roof forms, [3, 100], as:

- Flat
- Gable-ended pitched
- Hip double pitched
- Multiple pitched
- Monitor
- Mansard

Different roofing materials are related to roof types, that effect conduction, radiative and permeability properties of the roof surface. How the roof geometrical and material variations effect overall thermal behaviour in a building energy model depends on the theory applied to modelling the roof thermal behaviour.

4.6.1 Modelling Radiative and Convective Considerations

Allinson [133] developed a model to evaluate roof thermal behaviour based on available theory for convective, conductive and radiative properties for a roof space. Allinson used a simplified equation for radiant heat exchange given in [134] (see equation 4.1), as used in ESP-r. Assuming equal surface temperature to surrounding surfaces (as by Clarke for ESP-r [17]), Allinson showed a significant effect of roof pitch on night-time unit area radiant heat losses.

$$q = A\xi\sigma_{SB}(S\nu\theta^4_{sky} + (1 - S\nu)\theta^4_{surroundings} - \theta^4_{surface}) \quad (4.1)$$

The sky view factor Sν refers to the proportion of the hemisphere which a surface sees (see chapter 6).

Allinson highlighted simplifications in ESP-r's consideration of convective heat transfer coefficient by not accounting for surface-air temperature differences. A sensitivity study of roof pitch to available convective models showed ESP-r convective heat flux was not sensitive to roof pitch.

The forced convection coefficient (h_c - [W/m^2/K]) within equation 4.2, is calculated by equation 4.3 in ESP-r [17]. This relationship has been determined empirically, as described in [135].

$$q_{conv} = h_c(\theta_{surface} - \theta_{air}) \tag{4.2}$$

$$h_c = 5.678(a + b[\frac{294.26V}{0.3048\theta_{air}}]^n) \tag{4.3}$$

The coefficients (a and b) and the exponent (n) in equation 4.3 are empirically derived [17].

The roof geometry will effect the surface area, view factors and roof space volume. Sky view factors for roof surfaces (Sν_{rs}) are based on a simple relationship of surface angle to sky view applied to vertical surfaces (Sν_{ws}) in the model (see equation 4.4 and figure 4.1). ESP-r does not take into account self-view factors evident for complex roof geometry such as multiple pitch or monitor roof types.

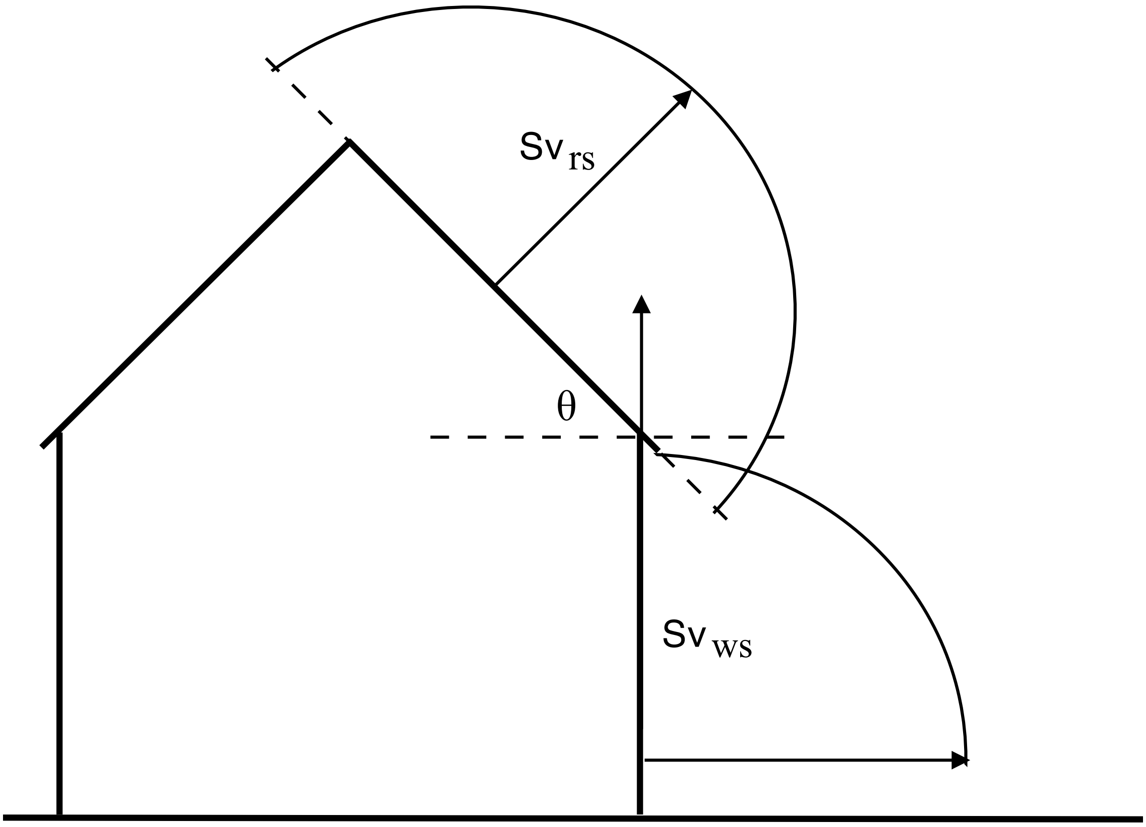


Figure 4.1: Roof Sky View Factor.

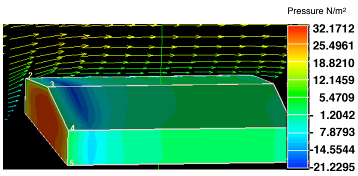
$$S\nu_{rs} = 1 - S\nu_{ws}\cos(\pi/2 - \theta) \tag{4.4}$$

4.6.2 Modelling Air Infiltration Considerations

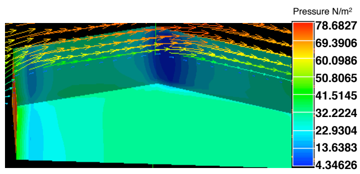
The infiltration/exfiltration in a loft space is dependent on the permeability of the roofing material, temperature differences across the surface and pressure differences that drive air flow. The construction of a flat roof means any air infiltration will directly impact the occupied building space, whilst a pitched roof (with roof void) will have an indirect effect. A pitched roof, commonly uses tiling that results in greater air permeability than other roofing methods.

Pressure driven air infiltration is dependent on the pressure distribution over the roof surface. The pressure distribution is dependent on prevailing wind speed and the roof geometry in relation to wind direction (as demonstrated in figure 4.2). Figure 4.2 shows the results from three Computational Fluid Dynamics (CFD) models of varying roof geometry and orientation in relation to wind direction.

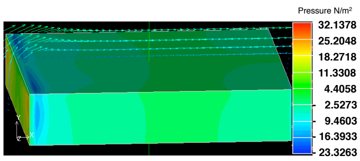
Each model consisted of a flow field region of 500m x 500m x 500m and a building of 20m x 20m x 3m at the centre of the flow field. A uniform free stream velocity of 10 ms^{-1} was used to represent a moderate flow rate at which greater surface pressures (and therefore greater infiltration) started to occur.



(a) Gable ended pitched roof with flow parallel to the roof apex



(b) Gable ended pitched roof with flow perpendicular to the roof apex



(c) Flat roof

Figure 4.2: Surface Pressure for three roof geometry - differing in roof type or orientation in relation to wind direction.

Whole building energy simulation tools do not account for local flow fields and geometrical influences on pressure distribution and resulting air infiltration. The method used in the whole building energy model is to apply a fixed volumetric air change rate (i.e air changes per hour ACH). The relation of this to roof component is discussed further in chapter 5.

4.6.3 Model Sensitivity to Roof Geometry

Though in reality roof geometry influences radiative, convective and infiltration based thermal loading, simplifications in a whole building energy model mean that geometry is only considered to influence radiative calculations. The radiative concern is affected by sky view factor (from roof pitch) and solar gain (from surface orientation).

To determine the sensitivity of the building energy simulation tool to the different identified roof geometry (listed earlier) a model of each type was developed in ESP-r. Each roof geometry was connected to a zone with equal footprint area, air infiltration rates and (in the case of pitched roof types) pitch. Pitched roofing were oriented so the main pitch was along the North-South axis. In all cases the roofing material was kept constant. In this way each model was representing a different roof structure for an otherwise consistent model.

The modelled zones were not thermally controlled[5], so zone temperature was measured along with surface flux (short and long wave radiative and external forced convective flux). These thermal values were compared for models of a:

- Gable-ended pitched roof
- Hip pitched roof
- Multiple pitch gable-ended roof
- Multiple monitor roof

Each model was simulated over a year.

Comparing surfaces of the same orientation and pitch the annual radiative and convective gains/losses (per m^2) were the same, regardless of roof geometry. Table 4.12 shows these annual surface gains/losses for the four models listed above.

Table 4.12: Thermal Flux for different roof type models.

Roof Type	Surface Flux (kWh/m^2/year to nearest integer)			
	External Forced Convective		Longwave - Sky Radiative	Shortwave - Solar Radiation
	Gains	Loss	Loss	Gains
Gable-ended pitched roof	87	290	403	615
Hip pitched roof	87	292	408	615
Multiple pitch gable-ended roof	87	292	408	615
Multiple monitor roof	87	292	408	615

Figure 4.3 shows the monthly temperature variation for each modelled zone. The plot shows the monthly statistical variability of temperature for each zone, highlighting the maximum temperature range as well as the standard deviation (σ) associated with the fluctuating temperatures.

The data in figure 4.3 shows little variation in σ between roof types. Greater model variation in the maximum temperature ranges is evident in figure 4.3. This is most significant during the summer months. With varying total surface area, increased peak temperatures coincided with increased total solar loading.

[5]As was the case for modelled roof voids in the probability modelling process.

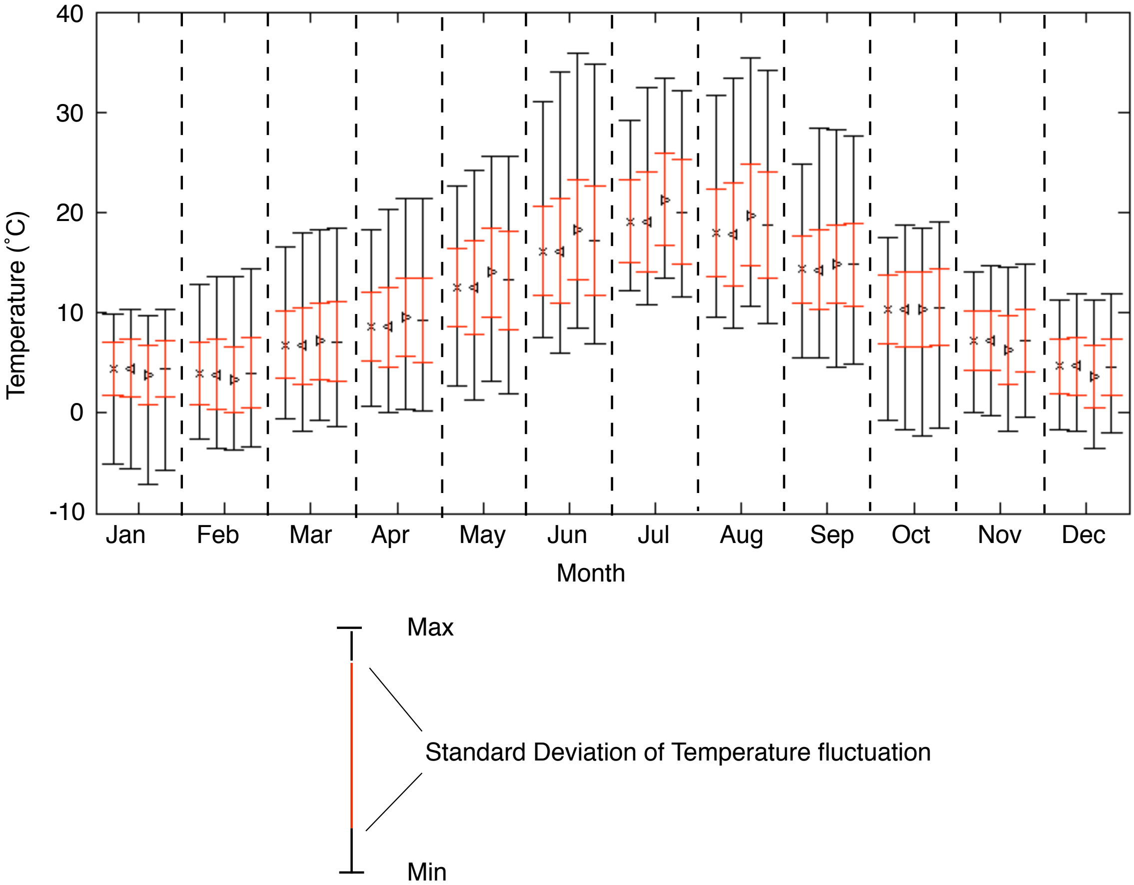


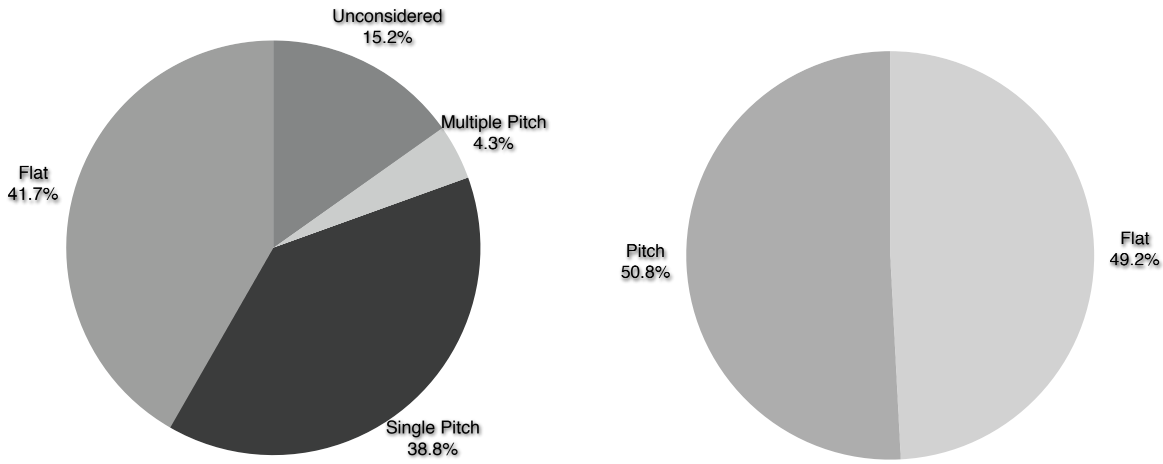
Figure 4.3: Zone Temperature statistics for modelled roof geometry in ESP-r. (x) Gable-ended pitched roof, (◁) Hip pitched roof, (▷) Multiple pitch gable-ended roof, (+) Multiple monitor roof.

4.6.4 Modelled Roof Types and Associated Stock Distribution

The investigation into ESP-r's theoretical consideration of surface flux and the sensitivity to the different geometrical roof types, suggests the probability model can adequately represent roof forms in 2 groups. These are flat (no roof void) and single apex pitched roofing.

From the NDBS building site survey, flat roofs account for 41.7% of the roof plan area and double pitch gable-ended account for 31.5%. Hip, double pitch roofing accounted for a further 7.3% and monitor and multiple pitch 4.3% combined. Other types have been excluded as unlikely for office buildings. Mixed roof types accounted for 4.9% of the surveyed premises, but potential variation of mixed types and modelling complexity put them beyond the scope of the probability modelling procedure.

Combining unconsidered roof forms and double pitch hip and gable-ended forms gives a percentage distribution as seen in figure 4.4. Ignoring the unconsidered proportion and combining pitched and multiple pitch forms (due to insensitivity in ESP-r) gives higher probable percentage of occurrence to the two modelled roof types.



(a) Stock distribution of roof types (b) Modelled stock distribution of simplified roof types

Figure 4.4: Roof Geometry - stock distribution.

4.7 Glazing Properties and Window Wall Ratios

A review of building control documentation was carried out in order to determine the potential range in Window Wall Ratios (WWR) of ND office buildings. The regulations/laws were also used to apply an expected mean WWR by building control period, to which a stock level probability distribution of WWR could be applied.

The type of glazing (i.e. single/double/triple) influences the impact of WWR on thermal gains and losses. Different glazing types were associated with ranges in WWR according to periods of building control.

4.7.1 Window Wall Ratio

For all considered control periods (1894 to present) minimum window area is set as 10% of the total floor area of each room in a building (unless the room is intended for use for building services). In identifying the range of potential WWR for the building stock, 10% of floor area was used to set the minimum ratio. The minimum WWR is, therefore, dependent on the ratio of floor area to exposed wall area.

For the periods up to 1984 a maximum WWR of 50% was set for standard walling construction. Higher WWR were allowed provided pier-wall construction was used to increase structural stability. Pier walling results in thicker wall construction than otherwise required by regulations. To aid model development such measures were not considered, so setting an upper limit on WWR of 50%. For post 1984 control periods this upper limit was increased to 66%, in structural regulations (Part A of Building Regulations).

For buildings built up until 1950 a study by Ove Arup (1984), as documented in [113], showed commercial buildings to typically have glazing ratios between 40-50%. Those buildings between 1950 and 1973 were expected to have higher glazing ratios (as high as 75%) and between 1974 and 1984 the typical glazing area was reduced due to energy concerns.

Higher levels of glazing are feasible as part of 'curtain-walling' systems, where it is acknowledged that 100% glazed walling exists in the considered building stock [136]. However, only metal panel insulated cladding systems have been accounted for as consideration of curtain walling and development of other curtain walling systems (including high level glazing) is seen as an area for further research and model development.

For ease of modelling windows were considered evenly distributed across all external walls of the building model.

4.7.2 Glazing Type

Prior to 1977 (introduction of 1976 Building Regulations) no thermal consideration of window-wall ratio was given in building control. Single glazing is the only considered glazing type pre 1977. Between 1977 and 1984 thermal regulations introduced limits on use of single glazing in a wall adhering to minimum thermal transmittance value. For periods post 1984 the thermal transmittance of the glazing unit is linked to WWR. The regulations stipulate (in absence of manufactures values) level of glazing (single,double,triple), glass surface properties relating to radiative control, air spacing in multiple glazed units and types of framing combining to influence the unit U-value.

In the 1976 Building Regulations [128] a standard single glazed unit was given a U-value of 5.7 $W/m^2.K$ and 2.8 $W/m^2.K$ for a double glazed unit. The combined wall and window U-value could not exceed 1.8 $W/m^2.K$. With a minimum wall component U-value of 1.0 $W/m^2.K$, single glazing is restricted to ~18% WWR and double glazing to ~50%.

For Part L Building Regulations (1985 to Present) standard glazing units of given U-value have maximum allowable WWR (see table 4.13). A glazing unit of appropriate U-value was applied in the probability model according to the randomly applied WWR and period of construction. The building energy model does not include door openings or roof lights and so window U-values represent the averaged U-value requirement of all these components according to building regulation requirements.

For the building stock probability model three basic constructions were identified as single, double and triple glazed. The model was designed to apply a construction representative of the required window unit construction according to the relationship to WWR - identified by building regulations.

Table 4.13: Standard Glazing Unit, U-value and maximum WWR according to period of building control.

Control Period	U-value ($W/m^2.K$)	Maximum WWR (%)	Description
1894-1976	5.7	50	Single glazed unit
1977-1984	5.7	18	Single glazed unit
	2.8	50	Double glazed unit
1985-1990 Standard considered U-value of 5.7$W/m^2.K$ for a maximum WWR of 35% for single glazed unit.	5.7	35	Single glazed unit
	2.8	-	Double glazed unit
1991-1995 Standard considered U-value of 5.7$W/m^2.K$ for a maximum WWR of 35% for single glazed unit.	5.7	35	Single glazed unit
	2.8	70	Double glazed unit
	2	-	Double glazed with low emissivity coating or Triple glazing (applied in model)
1996-2001 Standard considered U-value of 3.3$W/m^2.K$ for a maximum WWR of 40% for double glazed unit.	5.0 - 4.7	25 - 27	A standard Single glazed unit is expected to have a U-value between 5.8 and 4.7, depending on type of framing. (A standard single glazed unit is applied in the model).
	4.2 - 2.4	30 - 58	Double glazed U-value ranges between 4.2 and 2.4, depending on material of frame, gas fill, glass spacing.
	2.3 - 2.0	60 - 74	Either double glazing or triple glazing of different glass spacing, gass fill, emissivity coating and unit framing.
2002-2008 Standard considered U-value of 2.2$W/m^2.K$ for a notional building maximum WWR of 40% for double glazed unit.	3.3 -2.3	25-38	Double glazing of varying spacing (6/12/16 mm), argon filled.
	2.2-1.7	40-55	Double Glazed 12mm spacing, and low emissivity to double glazed, low emissivity argon filled 16mm spacing. Or triple glazing of 12 or 16 mm spacing.
	1.6-1.3	58-75	Triple glazed 16mm spacing (argon filled) to Triple glazed 16mm spacing (argon filled) with low emissivity coating

4.7.3 Distribution for probability modelling of ND Building Stock

As part of the NDBS Project, Gakovic reports on types of glazing and other openings for ND buildings in [137]. Categorising surveyed buildings into six forms, the 'traditional' (load bearing), 'framed, curtain walling', 'framed, deep plan' and 'framed, other' forms are of greatest relevance to office buildings. Regression analysis on glazing area to floor area and glazing area to wall area was carried out in this study and showed a strong correlation in these variables for the relevant building forms.

From the building regulations a minimum glazing area to floor area ratio of 0.1 is expected. From [137] a minimum ratio of 0.08 was observed for deep plan buildings. The 0.02 variation in observed and theoretically considered minimum window to floor ratio is likely to result from service areas (e.g. lifts and plant rooms) that do not count for glazing requirements in building regulations. Higher average window-to-floor ratios for the other building forms are observed.

The regression analysis carried out in [137] provides typical glazing ratios for different built forms, but offers no account of probable distribution in the building stock. As building controls have been identified as a source of influence on building window-wall ratios, they were used to develop *a priori* probability distributions of WWR for each period of building control.

In each case a basic triangular distribution was applied (see chapter 3), where the limits were set to a minimum of 10% of the floor area and a maximum of 50% WWR pre-1985 and a maximum of 66% WWR post-1984. From [38] the 'traditional' buildings surveyed result in an expected glazing area to floor area ratio of 0.13. Of the surveyed buildings 74.9% of the total floor area is attributed to building built prior to 1960. For the building control periods 1894-1938, 1939-1952, 1953-1965 the minimum value in the range (0.1 of floor area) was considered as the modal value.

For framed buildings within the study by Gakovic [137] 77.3% of the surveyed floor area was attributed to buildings built between 1961 and 1980. For framed curtain walling, framed deep plan and other framed structures the expected WWR were calculated to be 0.6, 0.15 and 0.25, respectively. Considering these methods as typical of the time (but with no distinction between these 'framed' structural types) an averaged modal value of 0.33 was applied to the model for periods between 1966 to 1984.

For buildings built under Part L Regulations - Conservation of Fuel and Power (post 1984) the elemental approach to thermal regulation sets maximum WWR (as a percentage) for different glazing types. In each of the identified periods post-1984 the regulations use a notional building to which a maximum thermal transmittance of any building structure is set. For the WWR the maximum value associated with a typical level of glazing is used for the notional building. As a guide for good thermal design, these WWRs are considered as the most likely within the given control periods.

For the two periods between 1985 and 1995 a WWR of 35% is used. For post-1995 periods a WWR of 40% was given as the modal value in the applied distribution to the probability model.

Figure 4.5 represents the applied distributions in determining the WWR for the probability model. As a ratio of window area to floor area is used to determine the minimum WWR, the minimum WWR potentially could exceed the maximum WWR. In such circumstances the model logic set the WWR to the maximum limit considered.

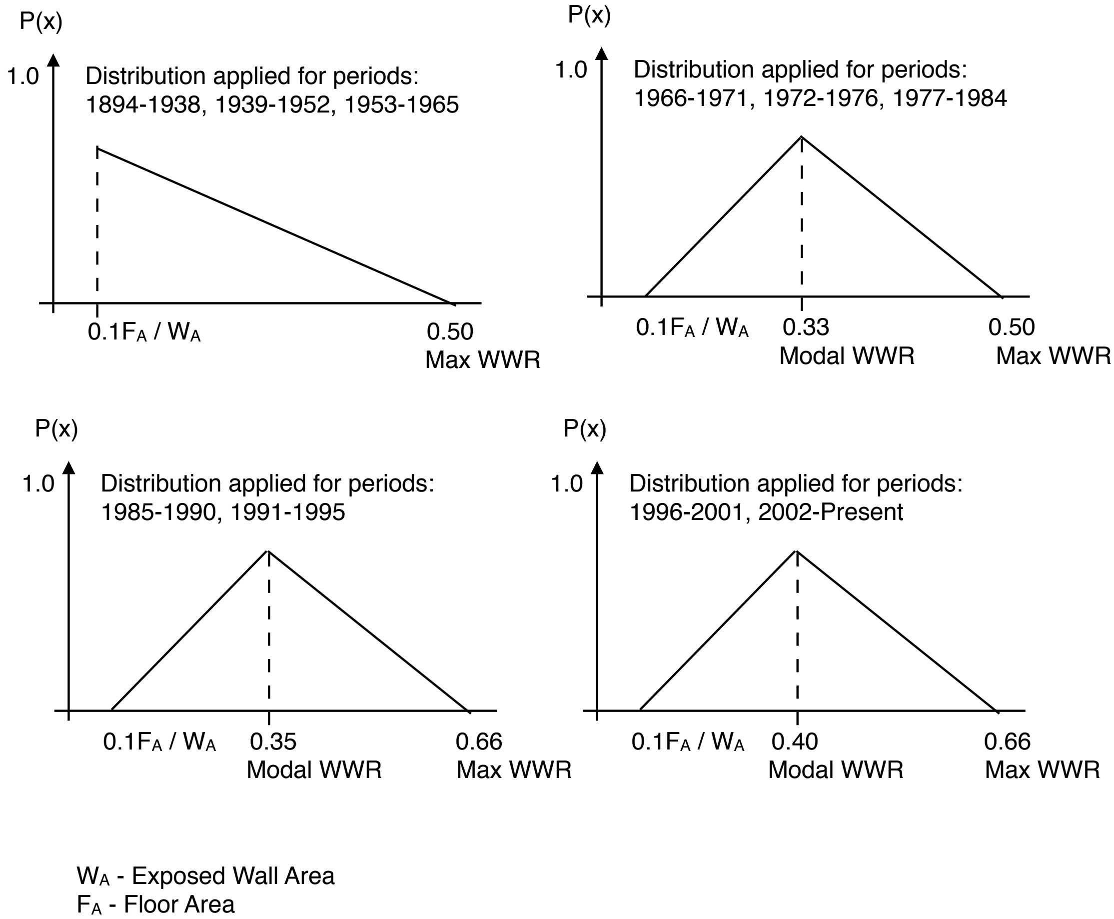


Figure 4.5: Triangular distribution for determining glazing area in ND building stock probability model.

4.8 Construction Database Template

To minimise the size of the construction database and reduce the complexity of the set-up scripts associated with the energy modelling tool, a construction database template was developed. A template construction database for each identified period of construction control was developed. Figure 4.6 provides a description of the basic construction database template used for all periods.

For each component (x) a number of layers N_x existed to allow for composite structures and divide thick constructions into thin layers for improved accuracy of modelling by finite volume methods (see chapter 3).

For earlier periods it was identified that wall thickness varies with wall height. Using zones to represent storeys, a wall construction component for each potential storey of a building was provided by the database template.

For flooring, two inter-storey components were developed as wood and concrete construction. Reverse components were also developed as the ceiling equivalent of the floor to the storey below.

Three roof components were developed: one to represent flat roof construction and the other two for pitched roofing - either traditional tiling or panelling/cladding systems.

Three basic window components were developed as single, double and triple glazed to be used for thermal regulations stipulating different glazing requirements for different WWR.

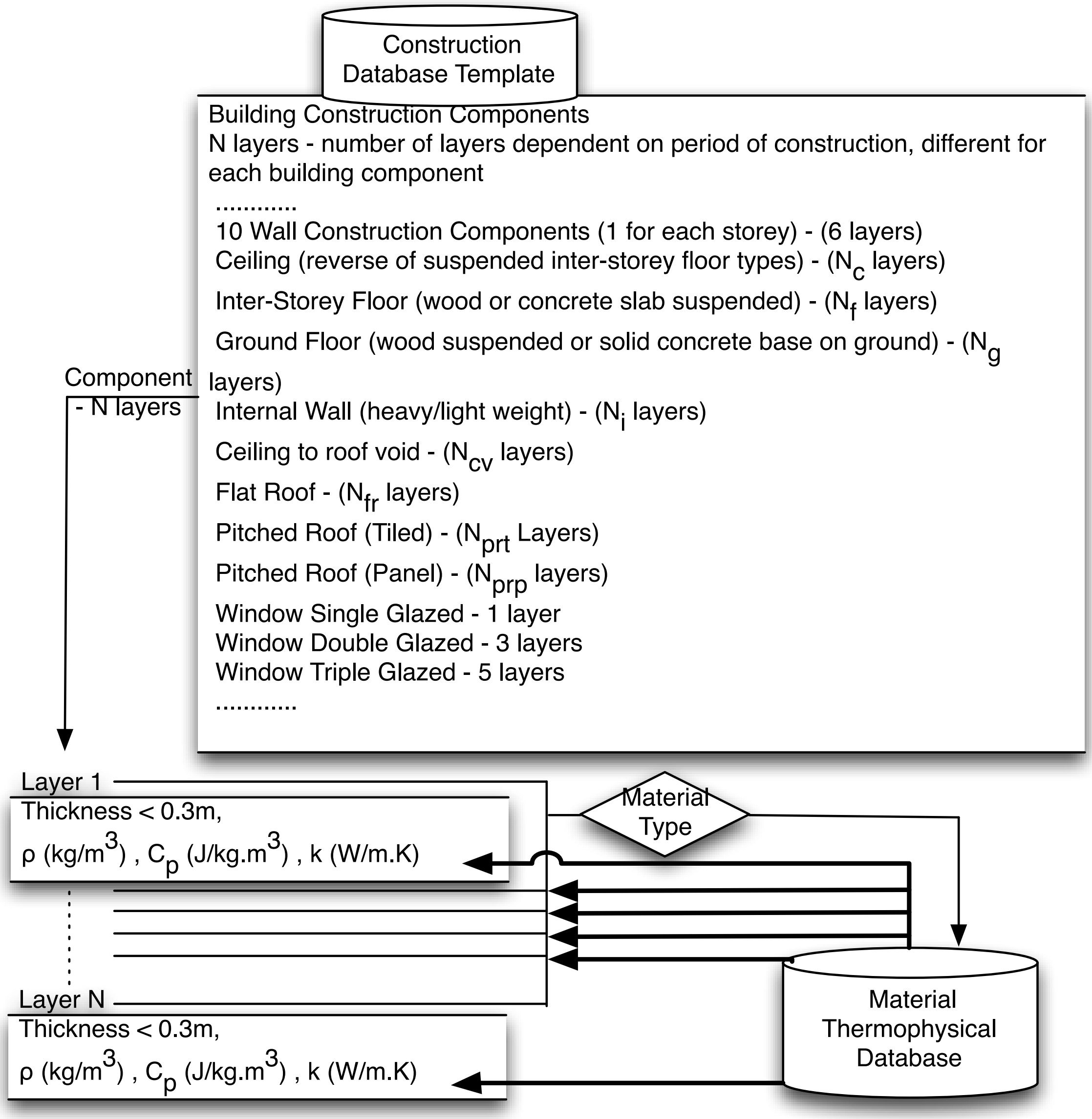


Figure 4.6: Construction database template.

4.9 Conclusions

Building controls, combined with published survey data from the NDBS project have enabled a probabilistic thermal energy modelling approach to the ND building stock to be undertaken. An *a priori* probability of the building stock structural characteristics results from theoretical evaluation of building controls, by-laws and published data.

Consideration of dynamic thermal behaviour of building components showed detail of component construction and uncertainty in construction can effect thermal properties. Accounting for varying construction is, therefore, necessary to a building stock energy model assessment.

In some instances (for example roof geometry) the energy modelling tool used in this investigation proved insensitive to variation in building form and structure. Separate studies showed these variations could significantly effect the boundary conditions which influence thermal behaviour. The model abstraction leading to this insensitivity is unavoidable without further development of existing building energy modelling tools.

Chapter 5

Parametric Assessment - Adventitious Leakage

Adventitious leakage is recognised as a significant influence on energy consumption, particularly in buildings with improved insulation in walls, floors and roofs [138]. Restrictions on uncontrolled air infiltration/exfiltration, however, were only introduced to Part L of the building regulations in 2002. As buildings undergo refurbishment and retrofit of technologies to reduce their carbon load it is important to understand the resulting impact on expected leakage rates.

Carrying out air leakage tests can be expensive and is complicated according to a building's size and design. It is not practically possible to expect a leakage test to be carried out on every building undergoing energy efficiency improvements. Currently there is limited data available from building air leakage tests, making it difficult to show any statistically significant relationship between air leakage rates and building age, form or use [139].

The study carried out by Persily [139] utilises data from pressure leakage tests carried out on buildings of different (non-domestic) use and in different countries in order to obtain a large enough data set for analysis. The study suggests that only building height influences air leakage rates, with increasing airtightness with increased height. Persily concludes that the data set is too small to show any statistically significant relationships between building attributes and adventitious leakage.

Persily's evaluation of the data requires the assumptions that the use of building has no effect on the design and resulting leakage rates and that building controls and building methods do not vary between the different countries or regions in America used for the study. The second assumption is critical to the conclusions made, as where height is related to leakage rate it could equally be shown that greater leakage could be attributed to buildings built in a warmer climate (majority of the low level buildings in Florida whilst the majority of taller buildings are from a Canadian study).

A study into air leakage of apartments and commercial buildings was carried out by the Indoor Environment Department at Lawrence Berkley National Laboratory (LBNL) for the California Energy Commission [140]. The study also highlights the limited data sets available for predicting air leakage rates associated with buildings. A comprehensive list of air leakage tests carried out on commercial buildings in five countries was presented.

The study highlights that building use, construction type and country could all influence the adventitious leakage associated with the building. As not all combinations of these parameters are covered in the collated data (and those which are have limited sample sizes), Bayesian Hierarchical Modelling (BHM) is adopted to allow sharing of information between the building categories. The data from each study is then standardised to provide an expected air leakage rate associated with buildings of a given use, construction method and geographical area.

Taking into account the biases towards potentially influencing factors it was concluded in the study of 267 commercial buildings that the sample size was too small and not representative of building stocks for statistically sound conclusions. So whilst it is possible to carry out a similar BHM procedure on the international data set for representing UK commercial buildings' air leakage, the conclusion that a larger, more statistically representative data set is needed will still exist.

Adventitious leakage is attributed to small gaps and cracks in the shell of the building that to some extent are unique to each building as a result of its design, method and quality of construction, the conditions to which it is subjected to and level of maintenance over its life. In general, however, the shell of a building can be split into common components; each of which has an associated weak point for air leakage (e.g. the perimeter of a window/door in the building façade).

A study of the expected leakage coefficients for different building components is given by Orme et. al [12]. The data presented in [12] is held by the Air Infiltration and Ventilation Centre (AIVC), an annex of the Energy Conservation in Buildings and Community Systems (ECBCS) agreement of the International Energy Agency (IEA). For creating a probabilistic representation of air leakage for the ND building stock energy model (developed in this thesis) the data represented in [12] was used.

5.1 Theory of Air Leakage

Uncontrolled air infiltration and exfiltration to a building are the result of a pressure difference across a building's envelope. Pressure differentials occur via the stack effect and wind effect.

The stack effect occurs due to temperature differences between the outside and inside air. As the internal air heats and rises the pressure at the lower levels drops and it increases at the top. The pressure increase causes exfiltration and the decrease results in infiltration. Buoyancy effects are mainly associated with tall buildings where vertical columns (such as stair cases and atriums) connect the lower building levels with the upper building levels.

The unit force exerted on the external surface of a building due to the wind incident upon it creates a pressure difference across the outside to the inside. This results in infiltration of the outside air. On the leeward side of a building the flow of air causes a negative pressure difference resulting in exfiltration.

For both causes of air leakage the rate of air flow, Q (m^3/s) in or out of the building is proportional to the pressure differential , ΔP (Pa). The relationship between these two components is dependent on the flow path shape and dimensions. In the case of adventitious leakage these paths are described as small cracks.

Some debate over the theoretical description of the relationship between pressure and air flow through cracks is evident in the literature [141, 142, 143, 144]. Currently two theoretical relationships exist, a quadratic relationship and a power law relationship. The literature suggests significantly greater accuracy associated with the quadratic equation at the low pressure differences associated with infiltration and exfiltration. The power law (equation 5.1) is shown to provide an approximate representation of the more accurate quadratic equation [142, 145]. As current standards and available data from air leakage tests utilise the power law it was used for this modelling study.

$$Q = C.\Delta P^n \tag{5.1}$$

In equation 5.1, C refers to the flow coefficient ($m^3/s.Pa^n$) and n is the flow exponent. The exponent value, n, is dependent on the flow type; ranging from 0.5 (turbulent flow) to 1.0 (laminar flow).

For energy modelling purposes it is important to determine the flow coefficient and exponent for the shell of a building (or the components of that shell).

5.2 Building Component Air Leakage

In the first instance it is important to identify the different components that will potentially contribute leakage pathways to a building envelope. An envelope can be broken down into 4 main components: wall, floor, roof and openings. A detailed review of air tightness tests in buildings demonstrates that wall and roof construction methods influence the air tightness associated with them [146]. Further more wall/floor/roof joints should also be considered as a separate component to building air leakage.

Openings in the building envelope fall into two main categories: windows and doors. The join between the wall and window/door unit has an obvious potential for leakage pathways. The design of the units themselves may also contribute to leakage around any opening components within the units themselves.

Orme et al. [12] have compiled data from the Air Infiltration and Ventilation Centre's (AIVC's) numerical database to determine the leakage characteristics associated with buildings and building components. The data comes from different organisations within the International Energy Agency (IEA), so relating to buildings within OECD (Organisation for Economic Co-operation and Development) countries. All sources are referenced, but in some cases the data is unpublished.

Test data were compiled and analysed to provide the lower quartile, median and upper quartile ranges for the values of C and n. No distribution is associated with these ranges as sample sizes are small. For the purpose of this study it was assumed that component air permeability has a normal distribution defined by the median and quartile values. This assumption is based on the central limit theorem (see chapter 3).

Table 5.1 provides a summary of the values of C and n associated with the building components identified by Orme et al. Some of the components identified in [12] relate to penetrations of building services, trickle ventilators and fireplaces/flues that are liable to change/modification over the life of a building. Trickle ventilators provide uncontrolled ventilation but are purposeful and so shall not be included in determining adventitious leakage.

Other components omitted for simplifying the description of building forms are revolving and sliding doors, wall-to-wall interfaces, fireplaces and flues.

The number of penetrations of building services in a building's envelope are independent of building type. Penetrations were omitted from this study.

Table 5.1: Experimental data for air leakage coefficient ranges for Building Components [12].

Component	Lower Quartile		Median		Upper Quartile	
	(C = $dm^3.s^{-1}.m^{-1}.Pa^{-n}$)					
	C	n	C	n	C	n
Hinged Window (weatherstripped)	0.086	0.6	0.13	0.6	0.41	0.6
Hinged Window (non-weatherstripped)	0.39	0.6	0.74	0.6	1.1	0.6
Sliding Window (weatherstripped)	0.079	0.6	0.15	0.6	0.21	0.6
Sliding Window (non-weatherstripped)	0.18	0.6	0.23	0.6	0.37	0.6
Hinged Doors (weatherstripped)	0.082	0.6	0.27	0.6	0.84	0.6
Hinged Doors (non-weatherstripped)	1.1	0.6	1.2	0.6	1.4	0.6
Interface of wall to window/door frame (uncaulked)	0.053	0.6	0.061	0.6	0.067	0.6
Interface of wall to window/door frame (caulked)	0.00033	0.6	0.0025	0.6	0.012	0.6
Brick wall (bare)	0.022	0.84	0.043	0.8	0.094	0.76
Brick (plastered)	0.016	0.86	0.018	0.85	0.021	0.84
Brick (wall board)	0.01	0.88	0.042	0.81	0.18	0.72
Cladding (ungasketed)	0.01	0.88	0.032	0.82	0.1	0.76
Cladding (gasketed)	0.0069	0.9	0.012	0.87	0.015	0.86
Concrete block (bare)	0.082	0.77	0.13	0.74	2	0.59
Concrete block (plastered)	0.021	0.84	0.021	0.84	0.021	0.84
Concrete Panels (pre cast)	0.05	0.8	0.11	0.75	0.12	0.74
Metal Panel Walls	0.076	0.77	0.09	0.76	0.13	0.74
Curtain Walling	0.089	0.76	0.12	0.74	0.14	0.74
Timber Panel (with wall board)	0.27	0.7	0.52	0.67	2.7	0.58
Timber Floor (suspended)	0.11	0.75	0.15	0.74	0.45	0.67
Masonry Wall - Concrete Floor Interface (caulked)	0.005	0.6	0.024	0.6	0.11	0.6
Timber Wall - Timber Floor Interface (caulked)	0.0066	0.6	0.011	0.6	0.015	0.6
Timber Wall - Concrete Floor Interface (caulked)	0.052	0.6	0.083	0.6	0.11	0.6
Masonry Wall - Concrete Floor Interface (uncaulked)	-	-	-	-	-	-
Timber Wall - Timber Floor Interface (uncaulked)	0.008	0.6	0.023	0.6	0.03	0.6
Tiled Roof	2.1	0.59	2.3	0.58	4	0.55
Shingled Roof	0.6	0.66	0.7	0.65	1.1	0.63
Metal Roof	0.49	0.67	0.63	0.66	0.98	0.63
Pipes	0.63	0.6	0.74	0.6	0.84	0.6

Table 5.1 demonstrates a large number of potential leakage points exist within a building. The incomplete list of potential building components and the uncertainty associated with the component values of C and n, are a good indication of the complexity involved in determining adventitious leakage. To see the potential variation in leakage of a commercial building stock a study of ranges in building form is required.

The referenced work used to compile the sets of leakage coefficients in table 5.1 are from laboratory tests and field studies. The data is indiscriminate of the OECD country where tests where carried out. For field studies both domestic buildings and commercial property studies have been analysed. This lack of consideration assumes that building components used in each testing country and for buildings of different form should adhere to similar standards.

For masonry wall components no differentiation is made for the method and dimensions of wall construction (i.e. solid or cavity, wall/cavity widths). Orme et al. [12] notes, however, in cavity wall construction the inner leaf is normally more airtight and so dominates cavity wall leakage rates. Plastering of internal walls is probably a key factor (see table 5.1).

5.3 Component Model for Determining Building Air Leakage

An air leakage prediction tool was developed using a random number generator with normal distribution for the flow coefficient (C) and exponent (n) of each identified building component. Infiltration/exfiltration rates were normalised to leakage per unit area of the building envelope (S) per hour. To account for this normalisation the components in the model are given as ratios of the envelope surface area (equation 5.2).

A MATLAB program provides a description of the building envelope, split into three main parts:

1. Ground Floor
2. Walls
3. Roof

For calculating the probable unit leakage rate for the building, each part is considered separately. The contribution of each part is then determined as a factor of total surface area (equation 5.2). Using this method requires knowledge on a building's footprint area, building height, number of storeys, roofing type and pitch, split between exposed and unexposed wall and ratio of opening areas to wall area.

Figure 5.1, on page 73, describes the model developed for determining normalised leakage rate at any given pressure difference (Q_T). Q_T is measured in $m^3.h^{-1}.m^{-2}$.

$$Q_T = Q/S = Q_R.F_R + Q_F.F_F + Q_{We}.F_{We} + Q_{Wu}.F_{Wu} \tag{5.2}$$

where,

Q_R = Roof Unit Leakage , Q_F = Floor Unit Leakage

Q_W = Wall Unit Leakage = (Q_{We}+ Q_{Wu}) , Q_{We} = Exposed Wall Leakage

Q_{Wu} = Unexposed Wall Leakage , F_R = Roof Factor = (A_R/A_T)

F_F = Floor Factor = (A_F/A_T) , F_W = Wall Factor = $(F_{We} + F_{Wu})$

F_{We} = Exposed Wall Factor = (A_{We}/A_T)

F_{Wu} = Unexposed Wall Factor = (A_{Wu}/A_T)

and where,

A_R = Roof Area , A_F = Footprint Area

A_W = Wall Area = $(A_{We} + A_{Wu})$, A_{We} = Exposed Wall Area

A_{Wu} = Unexposed Wall Area , A_T = Total Envelope Surface Area = A_F+A_W+A_R

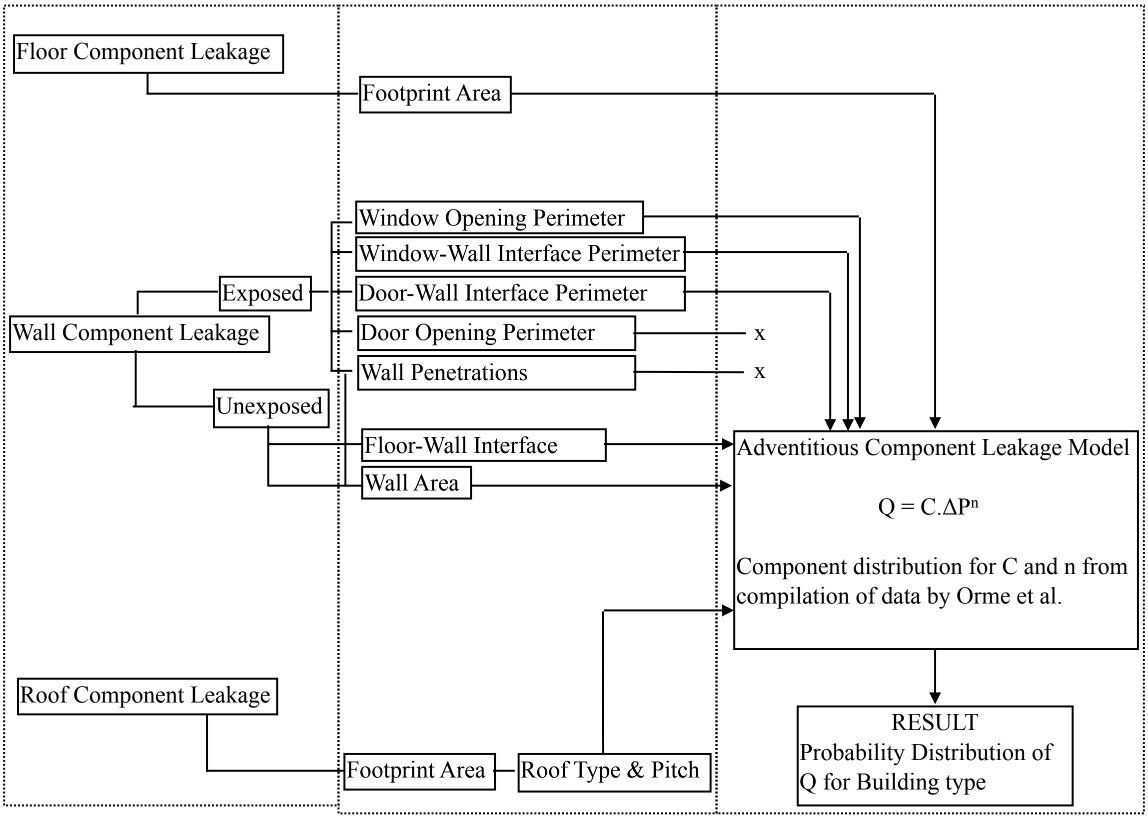


Figure 5.1: Flow chart description of Component Leakage calculation tool.

The wall constitutes the majority of the leakage components given in table 5.1. The wall needs first to be considered as exposed or unexposed. The unexposed leakage component made of floor-wall interfaces, ceiling-wall interfaces and the unexposed wall (i.e. party walls). Exposed walls are expected to contain openings and interface leakage points, with penetrations and trickle ventilators currently excluded. For openings a further simplification was made where doors were not considered - assuming the window components and window-to-wall ratios (WWR) account for their leakage contribution.

Window-wall interfaces are calculated from the area of windows per unit surface area of wall. The window area is a direct relationship to the WWR and assuming a rectangular shape the window perimeter is determined.

The window perimeter (P_r) is dependent on its length-width ratio (LWR) and for a given WWR for a unit area of the building envelope is given by equation 5.3. Figure 5.2 shows the influence of WWR and LWR on the window-wall length per unit area of wall. This method assumes that window units on average can be defined within a unit area of wall surface.

The study will assume no window to have a greater LWR than 10:1, where for a WWR of 0.2 and 0.7 the unit length/width would be 1.4m/0.15m and 2.65m/0.26m, respectively.

$$P_r = 2.(LWR + 1).\sqrt{WWR/LWR} \qquad (5.3)$$

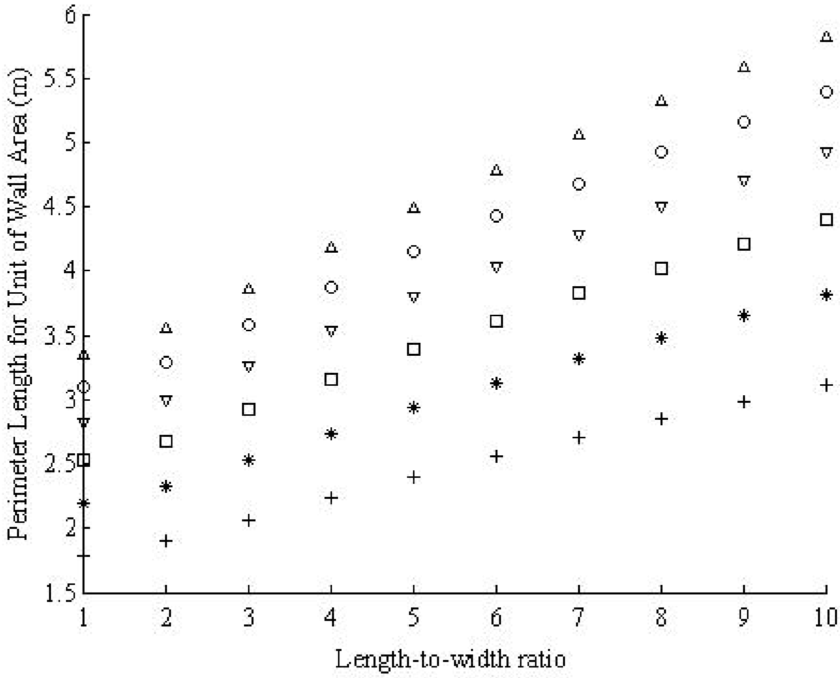


Figure 5.2: Relationship of WWR and LWR to window-wall interface length per unit area of a buildings wall. The WWR are represented as + is 0.2, ∗ is 0.3, □ is 0.4, ▽ is 0.5, ∘ is 0.6 and △ is 0.7.

Once the WWR has been identified a random LWR is determined (between 1:1 and 1:10), so the perimeter length for window-wall interface is calculated from equation 5.3.

Applying this process to identifying potential distribution of air leakage for large sets of buildings, the building description must be as simple as possible with the model accounting for any associated uncertainty in that description. Equation 5.2 highlights the need to know the influence of each building part (ground floor, wall, roof) to the value of Q_T. If a floor footprint area (FFA) and building height are known and it is assumed the building can be described as rectangular, then wall perimeter and total wall surface area can be calculated using equation 5.3 (substituting FFA in for WWR).

With the LWR unknown, randomly selecting a ratio (with equal probability) between 1 and 10 results in further uncertainty consideration in the model developed to determine the normalised air leakage of building types.

Considering the potential ranges in building form adds complexity to the process of identifying expected leakage rates in a building stock. To simplify the task and to provide focus to the most influential variables to air leakage a sensitivity analysis of the component model is required.

5.4 Sensitivity Analysis

To carry out the sensitivity analysis a notional building is required. The building form (described in table 5.2) results from assessing typical building form for office buildings observed in the Non-Domestic Building Stock (NDBS) project (see section 5.6). It has not, however, been possible to determine typical values for certain form aspects (e.g. WWR, LWR, roof type and window types). The values chosen are taken as mid-points in the potential range for these building parameters as estimated by assessing building controls (see section 5.6).

Table 5.2: Notional Building Form for Air leakage Sensitivity Analysis.

Building Description	Side lit (day lit). Detached brick plastered walls. Square building (LWR of floor = 1:1)
No. of Storeys	4
Storey Height (m)	3
Footprint Area (m^2)	400
Windows	WWR - 0.4 LWR - 5:1 Sliding - 50% Opening
Floor Type	Solid Concrete
Roofing	Flat - (no leakage)
Roof Pitch (°)	0

Running the air leakage model for the notional building (described in table 5.2) 5000 times, a mean air leakage of 14.9 $m^3.h^{-1}$ (to 1 decimal place) per surface unit area was given. A normal distribution of the expected leakage results (see figure 5.3) with a standard deviation (σ) of 2.3 $m^3.h^{-1}.m^{-2}$ (to 1 d.p). This is expected by the central limit theorem.

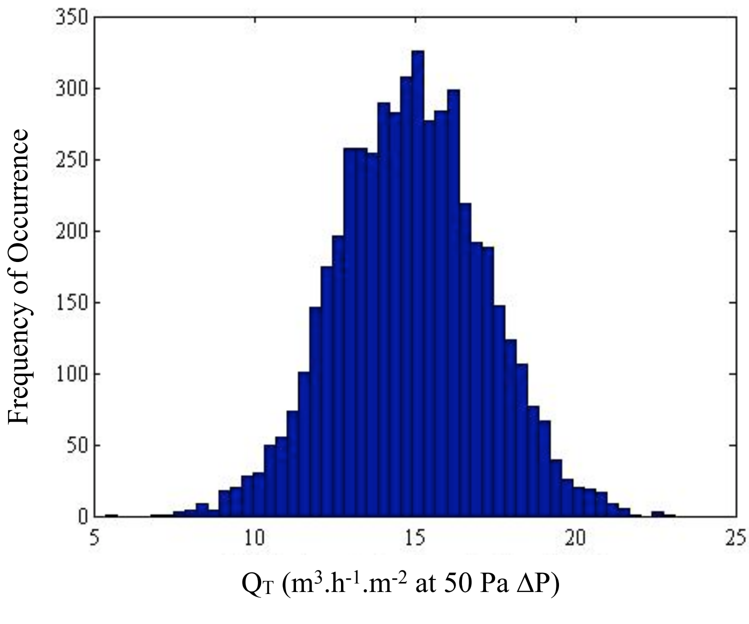


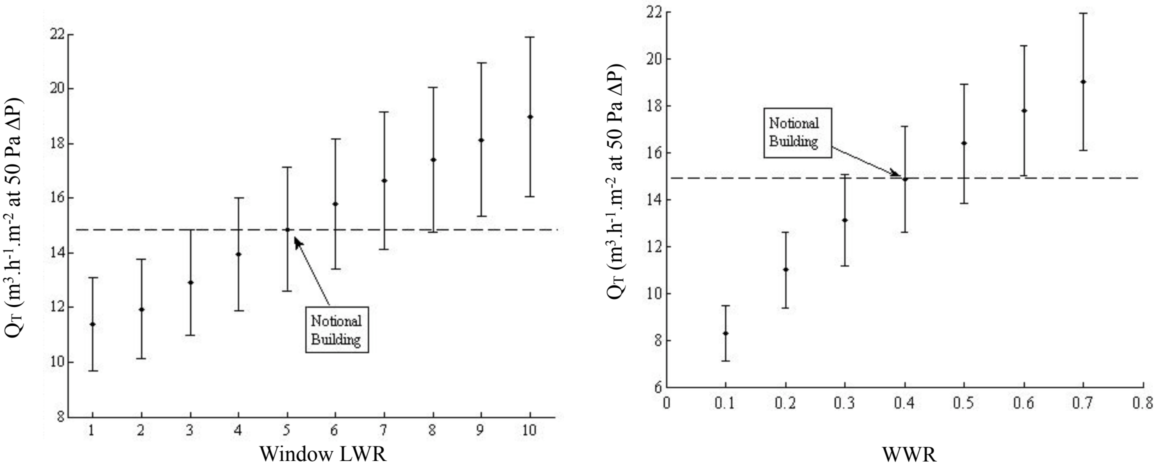
Figure 5.3: Distribution in expected unit surface air leakage for the notional building.

Figure 5.4 shows the influence of a window's LWR and the WWR at a LWR of 5:1. Varying LWR and WWR causes significant variation in the mean and σ of Q_T. As the mean value increases with increasing LWR or WWR σ also increases.

The notional building assumes windows to have an opening area half of the window total area (as set by early control laws 1894 - 1965). The window opening mechanism is described as sliding. Varying this to a hinged opening and a non-opening window shows a significant variation in Q_T (table 5.3). These results suggest the window component and its proportion of the building surface area are key factors in the air leakage of a building.

Table 5.3: Influence of window opening mechanism on Q_T of notional building.

Window Opening Mechanism	Q_T mean ($m^3.h^{-1}.m^{-2}$)	Q_T σ ($m^3.h^{-1}.m^{-2}$)
Sliding	14.86	2.27
Hinged	31.35	8.36
Non Opening	5.28	0.44



(a) Sensitivity for LWR.

(b) Sensitivity for WWR.

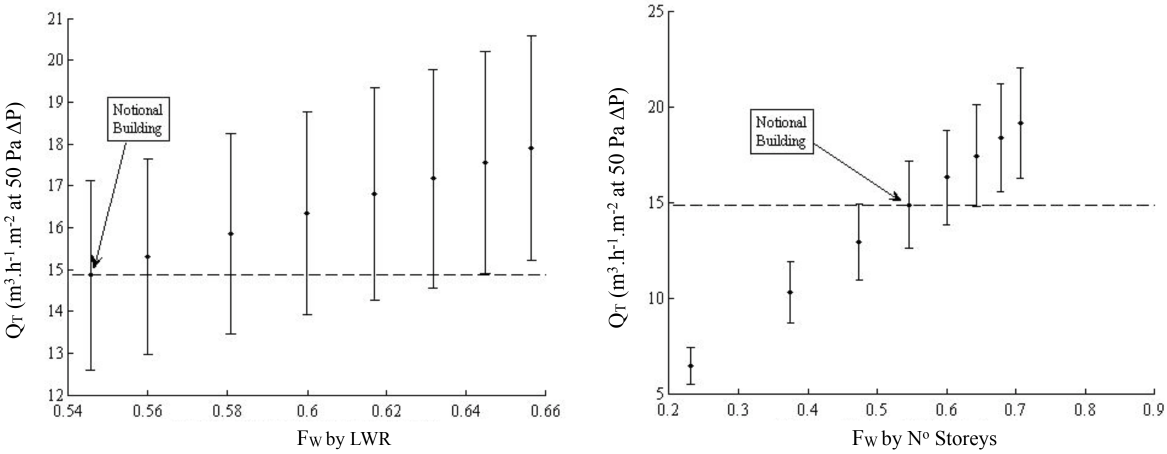
Figure 5.4: Sensitivity of mean and 1 σ of Q_T for LWR and WWR.

Figure 5.5 shows the sensitivity of wall area as a ratio of total envelope area, varied according to: (a) the LWR of the floor footprint and (b) the number of storeys in the building. The variation of LWR is from 1:1 to 8:1 increasing the wall area ratio (F_W) by 0.1 (20% of the notional building F_W).

Varying the number of storeys from 1 to 8 shows a greater variation to F_W than by varying LWR. The effect on Q_T is therefore more noticeable, suggesting greater sensitivity to number of storeys than the LWR of the floor footprint. As the number of storeys increases the increment in F_W reduces. The significance of further storeys becomes less and less and as building methods are likely to be different for taller buildings, [10], assessing the influence beyond 10 storeys in a building is considered unnecessary.

The roof of the notional building is considered to be airtight and flat. Table 5.4 shows, without increasing the roof surface area, how the other identified roofing methods can significantly increase Q_T for the notional building. These other roofing methods require a slope which will also increase the roof area as a ratio of total surface area (F_R).

For a tiled, gable-ended pitched roof figure 5.6 shows how increasing F_R by increasing roof pitch influences Q_T. Increasing the roof pitch to 60° from flat increases Q_T by 30% (on the value stated in table 5.4) and increases F_R by 47% of the flat roof value for F_R.



(a) Variation of LWR.

(b) Variation of Storeys.

Figure 5.5: Influence of F_W on component leakage model due to a) variation in LWR and b) variation in number of storeys.

The sensitivity of the roof leakage assumes that the roof cavity is considered to be open to the rest of the building. In model validation this assumption was highlighted as problematic (see section 5.5).

Table 5.4: Influence of Roof Type on Unit Surface Air Leakage at $\Delta P = 50$ Pa.

Roofing Type (Flat)	Q_T mean ($m^3.h^{-1}.m^{-2}$)	Q_T σ ($m^3.h^{-1}.m^{-2}$)
Concrete slab (no leakage)	14.86	2.27
Shingles	23.62	2.78
Tiled	38.15	5.31
Metal	22.49	2.84

The wall is itself considered as a leakage component and will therefore influence Q_T. Table 5.5 shows marginal variation in the mean and σ of Q_T for the majority of tested wall constructions. For curtain walling systems (usually associated with multi-storey, modern office buildings) Q_T is significantly reduced. Curtain walling refers to a glazed walling system attached to a load bearing (usually steel) skeleton structure. Few openings are expected in such a structure and so all opening-related leakage components were discounted when calculating Q_T.

Table 5.5: Influence of wall construction method on notional building's Q_T.

Wall Construction	Q_T mean ($m^3.h^{-1}.m^{-2}$)	Q_T σ ($m^3.h^{-1}.m^{-2}$)
Brick (Plastered)	14.86	2.27
Brick (No Plaster)	15.84	2.34
Brick (Plasterboard)	16.81	2.69
Cladding (Gasketed)	15.41	2.38
Metal Panel	16.1	2.22
Curtain Walling*	4.23	0.63

*WWR = 0.0 as considered as a glazing system.

Increasing the footprint area for the notional building will reduce the wall area ratio F_W which is

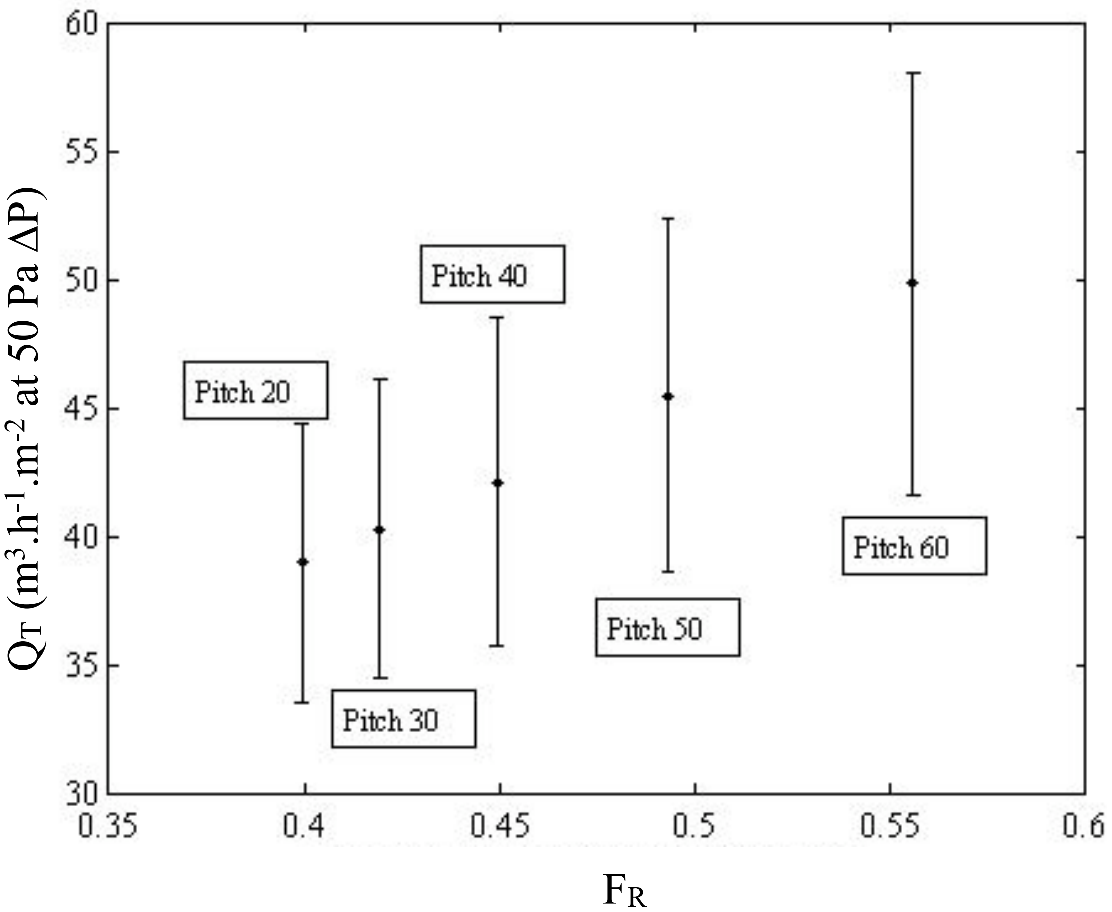


Figure 5.6: Sensitivity of Q_T to F_R - varied by roof pitch for a tiled roof.

providing the majority of the component leakage to this building. Table 5.6 shows little sensitivity to small variation in footprint area for the notional building. In the building stock, however, the variation in footprint can be quite large and as seen in table 5.6, Q_T will be sensitive to large variations.

Table 5.6: Influence of Building Footprint on notional building's Q_T.

Footprint Area (m^2)	F_F:F_W:F_R	Q_T mean ($m^3.h^{-1}.m^{-2}$)	Q_T σ ($m^3.h^{-1}.m^{-2}$)
400	0.23:0.54:0.23	14.86	2.27
500	0.24:0.52:0.24	14.13	2.12
600	0.25:0.5:0.25	13.5	2.03
800	0.27:0.46:0.27	12.52	1.88
1000	0.28:0.44:0.28	11.75	1.76
5000	0.37:0.26:0.37	6.92	1.04

5.5 Leakage Model Validation

A study on air leakage of 12 office buildings was carried out by BSRIA [147]. The normalised leakage rate at 25Pa and 50Pa is given for each building. A basic description of each building's size, form and year of construction is also given in [147]. No information is given on the WWR or LWR of windows.

With an assumed WWR of 0.4 and a fixed window LWR of 5:1, the model was run with a description of the BSRIA studied buildings. Table 5.7 shows good agreement of the model to flat roof buildings, assuming windows are all opening and applying a sliding window opening mechanism. For an Elizabethan building, reported to have been refurbished in the Victorian era (1840-1900), the model severely over predicts the expected normalised leakage rate.

The most noticeable difference is the inclusion of a tiled roof component, rather than the flat roof (non-contributing) elements as in the other buildings. The leakage rate of a roof will only be fully noticed in a leakage test if the roof cavity is directly linked with the rest of the building. For closed loft spaces the total leakage rate of the roof does not directly effect the leakage rate of the inhabited building interior.

Removing the effect of the roof leakage from the model showed better agreement with the experimental data. Further still reducing the WWR to 0.1 as a more representative WWR for buildings of this period brings the model results inline with the leakage test results.

It should also be noted that the Elizabethan building underwent a refurbishment program in the Victorian era. The impact of refurbishment on leakage coefficients is not understood by the model. In this instance, however, as the renovation is over 100 years old, it is not considered a significant factor for explaining the measured leakage rates.

The other buildings in the leakage study by BSRIA are complicated by irregular design and use of components such as atria that have not been leakage tested as building components. For these reasons it was not considered possible to use them to validate the model. This highlights a current limitation of the component leakage model in estimating the probability of leakage rates in buildings.

Validation with the BSRIA data required assumptions to be made about certain aspects of the form of the tested buildings. These assumptions are significant to the model results. A more detailed description of the form of the building than could be obtained from [147] was required.

For identifying the potential range in leakage rate for a building stock a survey of a statistically significant proportion of the buildings would be required to understand the variation in form and probability distribution of those forms. Building regulations, by-laws and other controlling measures (see chapter 4) were used to identify expected ranges in the building components and proportional contribution to the building envelope.

Table 5.7: Summary of BSRIA studied Buildings, normalised pressure leakage test results and the model results.

Building Description	BSRIA Leakage Test Results		Model Predicted (WWR = 0.4)	
	Q_{25}	Q_{50}	$Q_{25}(\sigma)$	$Q_{50}(\sigma)$
	($m^3.h^{-1}.m^{-2}$)			
Date of Build - 1970 Roof Pitch - Flat - assumed no leakage Wall - Prefabricated Walling System Window Type - Single Glazed openable (assumed sliding mechanism, WWR of 0.4 and all opening) Height (m) - 6.1 Storeys - 2 Footprint Area (m2) - 308 Estimated Floor LWR - 5:1	6.61	10.11	7.12 (1.08)	11.02 (1.69)
Date of Build - 1963 Roof (Pitch) - Flat - assumed no leakage Wall - Precast Panelling Window Type - Openable with secondary glazing (assumed sliding mechanism, WWR of 0.4 and all opening) Height (m) - 14.5 Storeys - 5 (7 in central column - ignored) FootPrint (m2) - 1,111 Estimated Floor LWR -10:1	9.86	15.08	8.54 (1.28)	13.15 (2.10)
Date of Build - 1986 Roof (Pitch) - Flat - assumed no leakage Wall - Frame with brick block cladding Window Type - double glazed (assumed sliding mechanism, WWR of 0.4 and all opening) Height (m) - 20 Storeys - 6 FootPrint (m2) - 814 Estimated Floor LWR -2:1	27.63	40.1	19.16 (7.28)	30.25 (11.85)
Date of Build - Elizabethan, renovated in Victorian era Roof (Pitch) - Tiled (49˚) - assumed single apex and gable ended Wall - Solid brick and internal plaster Window Type - openable (assumed sliding mechanism, WWR of 0.4 and all opening) Height (m) - 8.5 Storeys - 3 FootPrint (m2) - 1,486 Estimated Floor LWR -17:1	7.69	11.77	35.86 (5.89)	53.60 (8.75)
Elizabethan building with no roof leakage component	-	-	12.28 (3.26)	18.78 (4.81)
Elizabethan building with no roof leakage component and WWR = 0.1	-	-	6.54 (1.62)	9.98 (2.46)

5.6 Building Forms in the Non-Domestic Building Stock

The Non-Domestic Building Stock (NDBS) Project [27] was a comprehensive study carried out on Britain's non-domestic buildings. Data on the building stock has been collected via several sources, notably the Valuation Office Agency, and used to describe distributions of building floor space relating to use, age and energy consumption. In [3] tables showing age distribution of the NDBS categorise buildings as Pre-1900 and then in periods of 5 to 20 year intervals, up until 1994.

The NDBS Project identified 16 basic forms of building (table 5.8), with recognition that diversity in building fabric, roof types and potential composites of the basic forms leads to greater diversity in building form. A survey of 3,400 premises clearly relates activity to building form. CS4 and CS5 make up 56% of the floor area of surveyed office premises and a further 32% attributed to the composite forms CDO, CDS and CT1.

Table 5.8: Building Forms identified in NDBS Project [3].

Key	Building Form
CS4	Daylit (Sidelit) Cellular Strip. 1 to 4 storeys
CS5	Daylit (Sidelit) Cellular Strip. 5 or more storeys
OD4	Daylit (Sidelit) Open Plan Strip. 1 to 4 storeys
OD5	Daylit (Sidelit) Open Plan Strip. 1 or more storeys
CT1	Toplit Cellular, Single Storey.
HD	Daylit Hall, Sidelit, Toplit or both.
HA	Artificially lit Hall.
OS	Open Plan Single Shed
OC1	Open Plan Continuous Single Storey
OG	Open Plan Car Parking
OA	Artificially lit Open Plan, Multi-storey.
SR	Single-room Form
SSR	String of Single-room forms
RA	Railway Arch
CDO	Composite of CS4/5 and OA
CDS	Composite of OS and CS4

Vital to the leakage performance is the proportion and type of components considered for air leakage rates.

A review of the building regulations between 1840 and 1914 by Harper [13] shows instability in building regulations leading up to 1900. In this period leading up to 1900, acts to unify building control within England and Wales were put through Parliament as large city authorities were previously creating and enforcing their own building control.

The data collected in the NDBS Project shows that in 1994 82% of the surveyed office floor space post-dated 1900 [3] . The survey is thought to cover 70% of the total commercial office floor space. In theory reviewing building regulations between 1900 to the present day, combined with data from the NDBS Project, provides a method for estimating the component composition of a significant proportion of England's Building stock.

From sensitivity analysis the key considerations are wall construction type, floor footprint area, building height, number of storeys, WWR, window opening mechanism and roof shape and pitch.

Table 5.9 summarises relevant building component data found in a review of historical and current building laws, regulations and standards. The table shows overlap of component values between periods of building control.

From [3] a survey of wall, floor and wall opening dimensions at 122 buildings showed for load bearing (CS4 and OD4) buildings an opening-to-wall ratio of 0.13 is expected. For framed (CS4, CS5, OD4 and OD5) buildings the opening-to-wall ratio was averaged as 0.19 and 0.58 for cladding and curtain wall systems, respectively.

Based on this data and the building regulations a minimum WWR of 0.1 is expected for all office based buildings. Above a WWR of 0.66 (identified as the maximum for standard brick-block walling) a curtain walling system is assumed.

Identifying floor footprint area in relation to building height requires an extensive survey of commercial buildings. The most obvious approach would be to use a 3D-GIS tool, however, current data sets on

Table 5.9: Summary of Building Control for most sensitive air leakage components.

Period of Control	1894-1938	1939-1952	1953-1965	1966-1971	1972-1984	1985-Present
Floor	Suspended or Solid					
Roof	Tiled Pitched (45°-75°)		Pitched or Flat			
Typical Wall Construction	Brick Wall - Plastered		Brick Block - Plastered		Brick Block Plaster Board Cladding	
Window	Minimum Window Area ≥ 1/10th total floor area, opening window area ≥ 1/20th total floor area Maximum WWR - 0.5 if load bearing else 0.67				Maximum WWR 0.66 if load bearing. (Considered Curtain walling above 0.67 WWR)	
Building Height (m)	24.38 (80')	30.48 (100') if framed 15.24 (50') load bearing		No limit		
Storey Height (m)*	Min 2.59 (8'6")	Min 2.44 (8')	Min 2.29 (7'6")		Min 2.3m	

*Maximum storey height 3m (~10') for upper storeys as wall thickness of 8.5" is 1/14th of 3m. For 13" thick walls the limiting storey height is 4.55m for load bearing walls.

building use and dimensions are limited and require extensive surveying to populate GIS databases. The time required for such a survey put it beyond the scope of this investigation and highlights an area for further work.

5.7 Influence of Building Form Uncertainty on Adventitious Leakage

With a large deviation in building forms for the ND building stock, an analysis of varying component make-up on airtightness was conducted. The impact of the uncertainty in building form and component leakage rates were considered for conceivable office buildings in the UK NDBS.

Tables 5.10 and 5.11 summarise the ranges in expected values of building components significant to air infiltration rates. The values are derived from building controls, the NDBS project and the component leakage data given in [12].

Buildings only to 10 storeys in height are considered within the model as above this they are considered tall buildings by the Council on Tall Buildings and Urban Habitat [10]. Tall buildings require specific construction methods and components to withstand greater wind pressures and other loads that could considerably affect component air leakage coefficients. There occurrence in Britain is small compared to smaller building forms, so for these reasons they were excluded from the component leakage assessment.

The NDBS project identifies floor area of office premises in ranges from <50m^2 to 25,000m^2 plus. Noting that this refers to floor area and premises rather than building footprint, a range between 50m^2 and 10,000m^2 was considered.

Table 5.10: Range in building component parameters influencing expected airtightness.

Component Consideration	Minimum	Maximum
WWR	0.1	0.67
Roof Pitch ($^\circ$)	0	75
Ground Floor Construction	Solid	Suspended
Number of Storeys	1	10
Footprint Area (m^2)	50	10000
Window LWR	1	10
Footprint LWR	1	10

Table 5.11: Window and Wall construction methods influencing building airtightness.

Component Consideration	
Window Type *	Non-opening (minimum leakage potential)
	Sliding
	Hinged (maximum leakage potential)
Wall Construction	Brick only
	Brick and Plasterboard
	Brick and Plaster
	Brick and Block
	Brick and Block with Plaster
	Cladding
	Concrete Panel
	Metal Panel

*Half of window area assumed openable with same LWR as window

Just considering the extreme values for each type of wall construction and window types gives rise to 3072 combinations of building forms. Of these combinations some offer unrealistic options in building form, for example a 50m^2 footprint area for a 10 storey building. With such scenarios eliminated the model was run for 725 unique and representative combinations of the extreme values of the leakage components.

Figure 5.7 shows the mean Q_{50} against dispersion of probability distribution for the 725 combinations run in the component leakage model. The results show a large range in mean Q_{50} from 0.54m^3.h^{-1}.m^{-2} to 69.80m^3.h^{-1}.m^{-2}, with greater occurrence at lower values of Q_{50}. The uncertainty in the model results increases for forms displaying greater average airtightness.

The range in Q_{50} and variance highlights the difficulty in identifying a few built forms to predict the air leakage expected of a building.

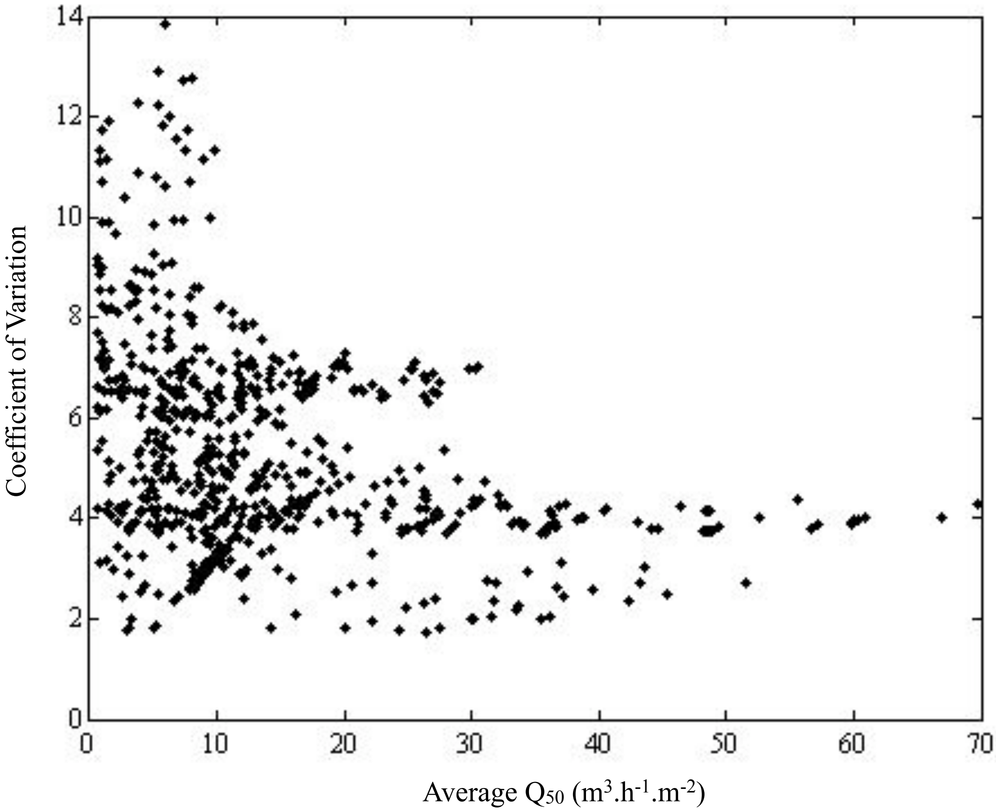


Figure 5.7: Uncertainty in building form and component leakage - Coefficient of Variance against Q_{50}.

5.8 Application in ND Building Stock Probability Model

The ND building stock probability model sets component values such as building size, construction and WWR that can be used to determine adventitious leakage via the component leakage model described in this chapter. This was applied to determine the air permeability of the model building envelope for all control periods pre-2002. Buildings built to regulations post-2001 are regulated to have a surface permeability (at 50Pa pressure difference) of no more than 11.5 $m^3.h^{-1}.m^{-2}$. The regulations set an expected value of 10 $m^3.h^{-1}.m^{-2}$ for typical ND office buildings and a low value of 2 $m^3.h^{-1}.m^{-2}$.

A triangular distribution was applied in the model for determining the permeability of a building post-2001. The minimum and maximum limits were set to 2 and 11.5 $m^3.h^{-1}.m^{-2}$, respectively. A modal value of 10 $m^3.h^{-1}.m^{-2}$ was used.

On determining the air permeability at 50Pa the air change rate per hour was calculated for the model building's surface area and volume. According to [12], a reasonable constant value of air change per hour (ACH) for energy calculation can be taken from that calculated at 50Pa pressure difference. This is done by dividing ACH_{50} by 20. This was applied in the stock level probability model.

5.9 Conclusions

The leakage in a building is the result of the leakage associated with the components that make the building form. Orme et al. compiled all measurements of the leakage coefficient (C) and exponent (n) of building components undertaken in OECD countries. The limited test data only allowed for median and quartile values to be established, but with no distribution. A normal distribution was applied to the leakage component and exponent values to investigate the probable effect of component make up on building leakage.

Developing a building air leakage predictor by component leakage requires knowledge of the building form (in terms of relevant component types and their proportion of the total building envelope).

Insufficient building air leakage tests has made it difficult to show any relationship between building type and airtightness. Using component leakage values (with a probabilistic consideration) combined with potential variation in building form has shown a large potential variability in air leakage within a building stock. Of the considered forms, relative variance in predicted air leakage distribution is greater where the mean predicted Q_{50} falls below the $10m^3.h^{-1}.m^{-2}$ expected value of current building regulations.

Providing a description of a building by its components can be used to calculate a probable leakage rate, to which statistical confidence can be applied. The validation process showed a need to isolate roof voids from the calculation tool to avoid over prediction of probable air leakage rates.

The merit of following a component leakage method is that it allows for a more rapid assessment of the building stock, reducing the need for pressure leakage tests that are expensive and disruptive to carry out. The large uncertainty in leakage associated with this method, however, means it cannot be used in practice to determine whether a building meets minimum standards of airtightness. The model would prove useful in combination with air leakage testing to demonstrate a relative leakage rate to buildings of similar component form within a building stock.

Chapter 6

Parametric Assessment - Weather, Sky View Factors and Solar Obstruction

A building's thermal energy demand is influenced not only by the required internal environment, but also by the relationship to its external environment. This refers to typical weather conditions and surrounding topology. Modelling a building stock, therefore, requires an understanding of the variation in both typical weather conditions and topology.

To account for the influence of a variable external environment, a probability distribution associated with representative climatic conditions of ND buildings was developed. This was considered in two parts:

(i) Variation in typical weather conditions by location

(ii) Variation in surrounding urban environment - affecting thermal influences and behaviour

6.1 Weather Conditions

Weather data (designed for use by DSMs) currently exists as Test Reference Years (TRYs) for a limited set of locations in the UK. The data consists of averaged data from approximately 20 years of records. This data has been compiled by CIBSE, using Met Office weather data.

Other weather data sources for locations in the UK and internationally exist. The International Weather for Energy Calculations (IWEC) files have been developed by ASHRAE (using the DATSAV3 surface climatic database of the National Climatic Data Center [114]).

The latitude range of England and Wales (50-56°N) results in different annual sun-path patterns (see figure 6.2). Figure 6.2 shows the sun-path lines at the summer and winter solstice and on an approximate heating season-cooling season crossover day at latitudes of 50° and 56°. As sun-path varies with latitude, the relationship of solar loading to occupied hours, surrounding obstructions and building orientation are all dependent on latitude position.

Both climate location and latitude are considered in relation to the regional distribution of office buildings identified from the NDBS project [3]. Figure 6.1 shows a distribution of degree-day regions (taken from [2]) in the UK, overlaid with latitude lines and the CIBSE and IWEC weather data locations relevant to England and Wales.

The economic cost associated with CIBSE data was reason for utilising the less geographically detailed IWEC[1] set of weather files. The sensitivity of the model to these files is considered in chapter 7.

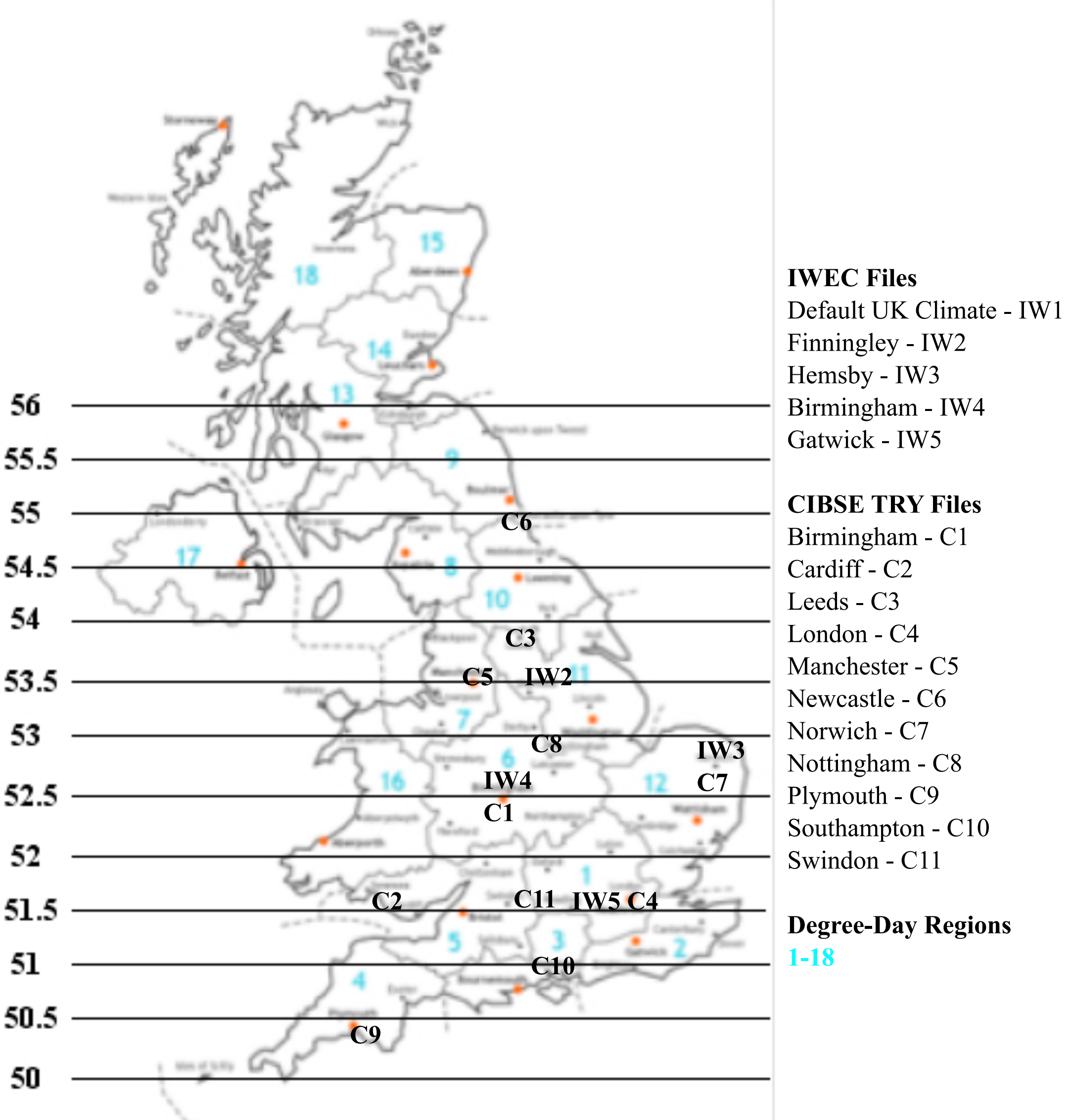


Figure 6.1: Degree day regions for the UK and distribution of available weather data files for building energy modelling [2].

Nine regions were identified in the NDBS to show the distribution of ND floor space and premises by bulk class (office, retail, warehouse and factory). Focusing on office buildings the distributions have been used to give a probability to the weather file to be used within the model. A range in latitude for each

[1]These files come as standard with ESP-r and can be downloaded from the US DOE website.

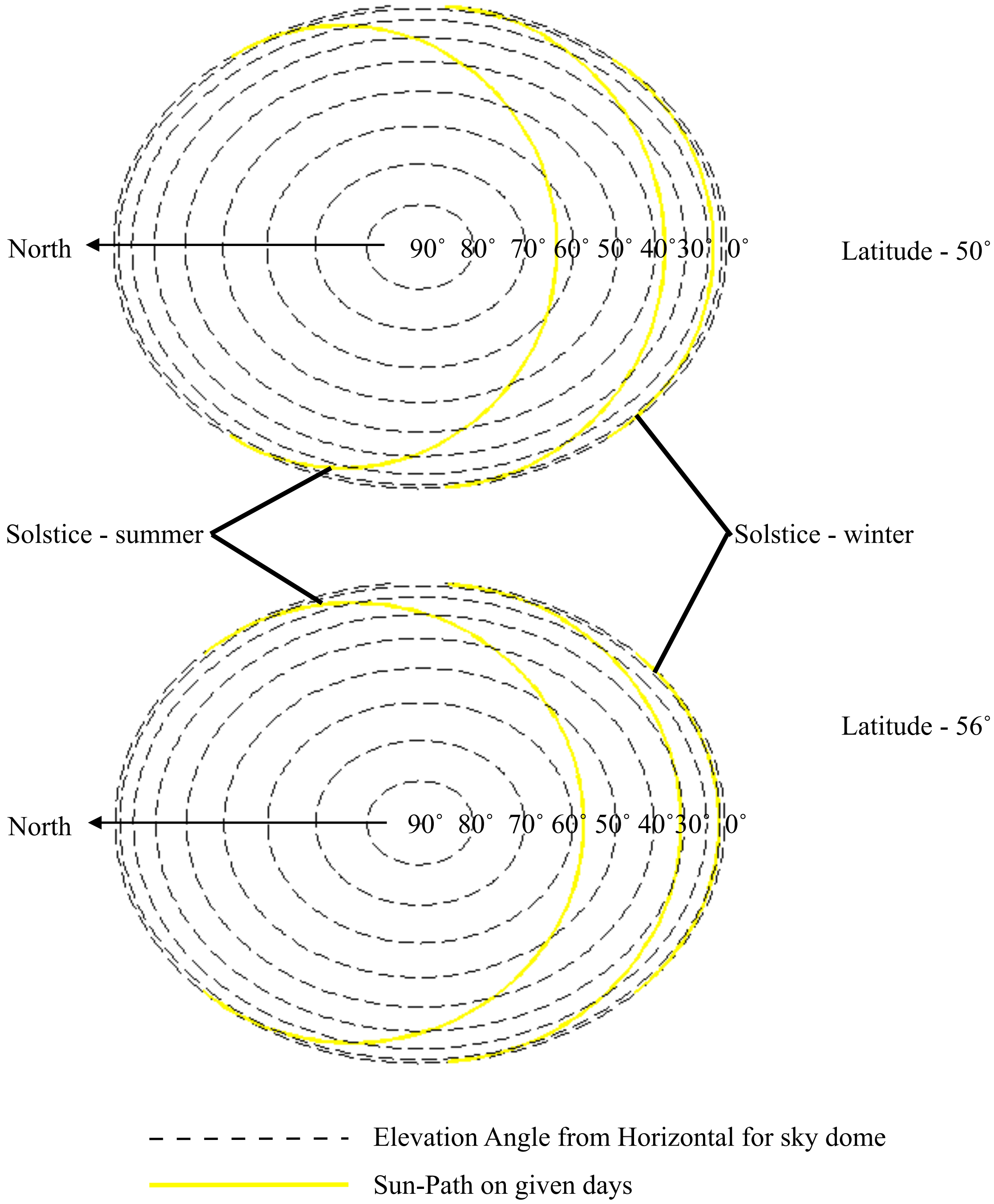


Figure 6.2: Spherical polar co-ordinate plot of sun path lines for solar angle from ground horizontal plane.

region was identified to which a random value (within the range) is applied to the model for each weather region.

Two values (floor area and premises) are available to identify the probability of an office building within the ND stock being associated with a given weather region. Figure 6.3 shows the percentage distribution by region as determined by both methods. Floor area provides no understanding of the number of office buildings, equally multiple premises can exist within a shared building.

Comparing stock distributions by premises and by floor area, discrepancy in the percentage share of the stock exists between these two measures. A maximum discrepancy of 7.8% is found within the South East region of England. All other regions have a floor-area-to-premises percentage share discrepancy within 2.25%.

The percentage distribution associated with premises was applied to the ND stock probability model. It is clear from figure 6.3 that the South East weather region is a dominant region when considering the National ND building stock. The probability modelling can, however, be applied regionally so avoiding any bias in weather region to model prediction (see chapter 8).

The stock distribution was applied as a probability weighting for assigning a weather file to the model. Using the available IWEC files, the limited distribution of these weather files resulted in grouping of regions and probability weighting. IW5 is applied to the South East and South West regions, IW4 for Wales, West Midlands and East Midlands, IW2 for North West and Yorkshire regions. The default UK climate file (1967 test reference year) was used for the Northern region as it provides a colder climate than experienced by all other available weather files.

Utilising CIBSE TRY files would allow a greater breakdown in the distribution of stock in relation to weather regions. The NDBS data provides stock distribution by county that would allow for a more detailed probability weighting for each CIBSE TRY location.

Both the CIBSE and IWEC weather files available during the study were developed using historical weather records. Recent research has stated the importance of future climate files in building energy modelling that should be considered in future work [148, 149, 150].

6.2 Radiation - Longwave and Shortwave influenced by the Built Environment

Both shortwave (i.e. solar) and longwave radiation processes are recognised as important factors in the thermal energy performance of a building [17, 151].

For solar loading concerns the surrounding environment can provide shading against direct beam solar radiation and impact on the level of diffuse daylight entering a building.

The longwave radiation emitted by a body is proportional to its temperature to the power of four (Stefan-Boltzmann Law). The net radiation exchange (q) between the considered building surface and surrounding bodies is given by:

$$q = A\xi\sigma_{SB}(\theta_o^4 - \theta_b^4) \tag{6.1}$$

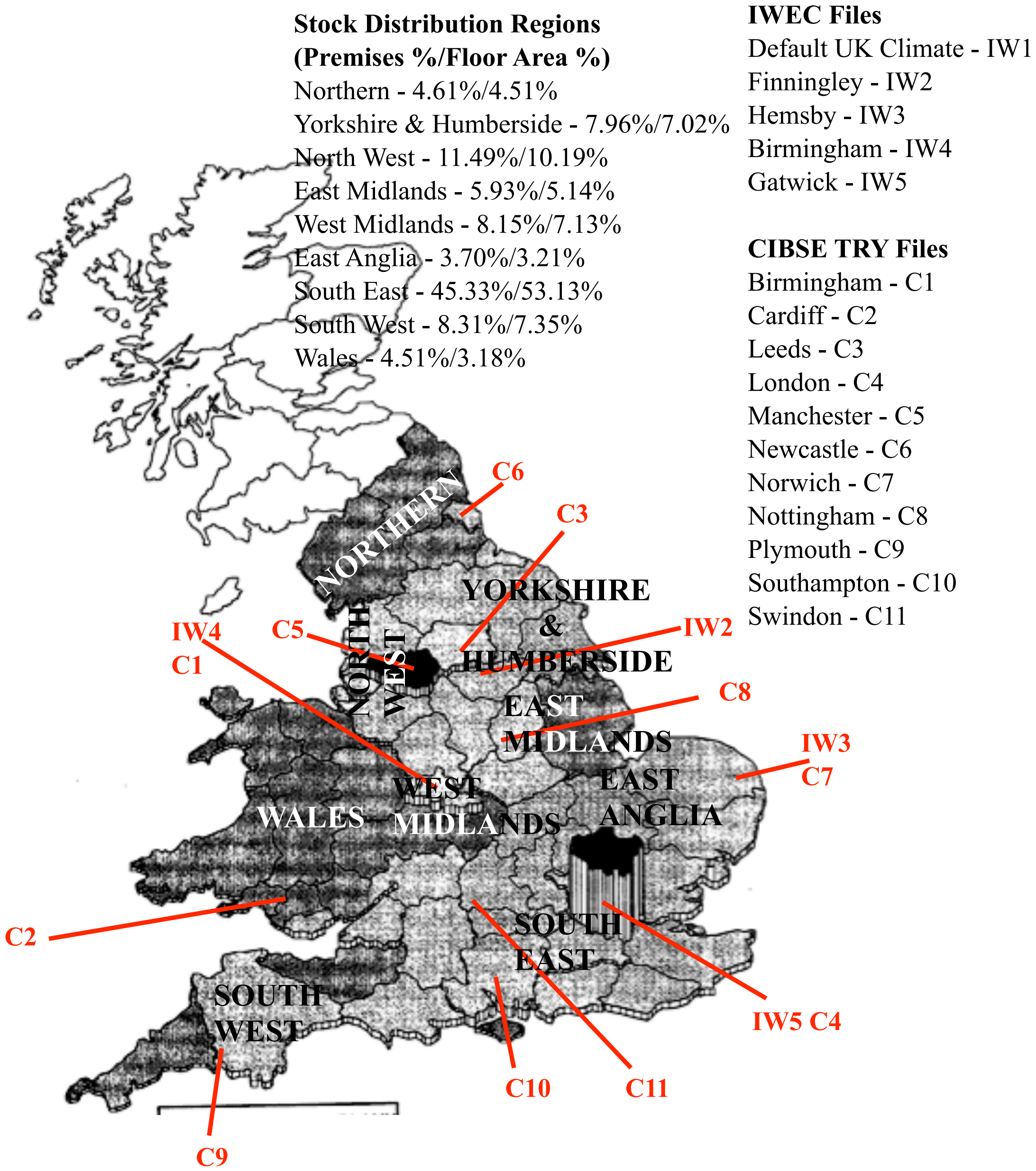


Figure 6.3: Distribution of National building stock in relation to available weather files for energy modelling [3].

where θ_o is the surrounding bodies surface temperature and θ_b the considered objects surface temperature. The surrounding bodies are of different temperature and occupy different proportions of the considered surface's view field.

In an urban environment buildings/built structures, vehicles, vegetation and the ground all radiate between one another. With similar surface temperatures the net radiant exchange between these urban objects is small. Treating the sky dome as another exchanging body, the sky temperature (θ_{sky}) for clear sky conditions is related to screen air temperature (θ_s) by:

$$\theta_{sky} = 0.05532\theta_s^{1.5} \tag{6.2}$$

according to [152]. At night this reduced radiating temperature (of already cool night-time air) makes the sky a significant factor in radiation heat losses of a building. Sky View Factor (Sν) is, therefore, considered important in properly accounting for the net longwave radiant exchange experienced by a building.

The effect of the urban environment on shortwave and longwave radiation processes of a building can be related to the geometric relationship between the considered building and its surrounding environment.

For shortwave radiative concerns, the angle of elevation between the considered building and the obstructing objects can determine for every hour of every day whether the building is subject to direct solar load. By determining the proportion of visible sky dome from obstructing elevation angles the level of diffuse sky solar radiation can also be determined.

For longwave radiation the Sν can also be determined from the description of surrounding obstructions by angles of elevation within the horizontal view field of the considered building façade.

6.3 Sky View Factor (Sν)

Considering the surface of an object, its field of view can be represented as a hemisphere, described by spherical polar coordinates. Objects within the hemisphere can be described as a solid angle that can be projected onto the surface of the considered hemisphere. This projected area can then be represented as a proportion of the total hemispherical surface area.

In the case of external building surfaces the basic hemisphere is represented by a mix of sky dome and ground. Sν refers to the proportion of the hemispherical field of view, attributed to the sky. A maximum of 1.0 results for a surface horizontal to the ground (with surface normal towards the sky), with no view of the ground and no obstructing objects within the field of view.

The principle is depicted in figure 6.4 that shows the sky dome to the ground. For the point of consideration at the axis origins with surface normal in the y-axis, the shaded regions (labelled O) represent obstructions projected onto the sky dome hemisphere. Each obstruction is related to the considered point by elevation angle (Φ) and horizontal angular displacement (θ) while r is set to unity.

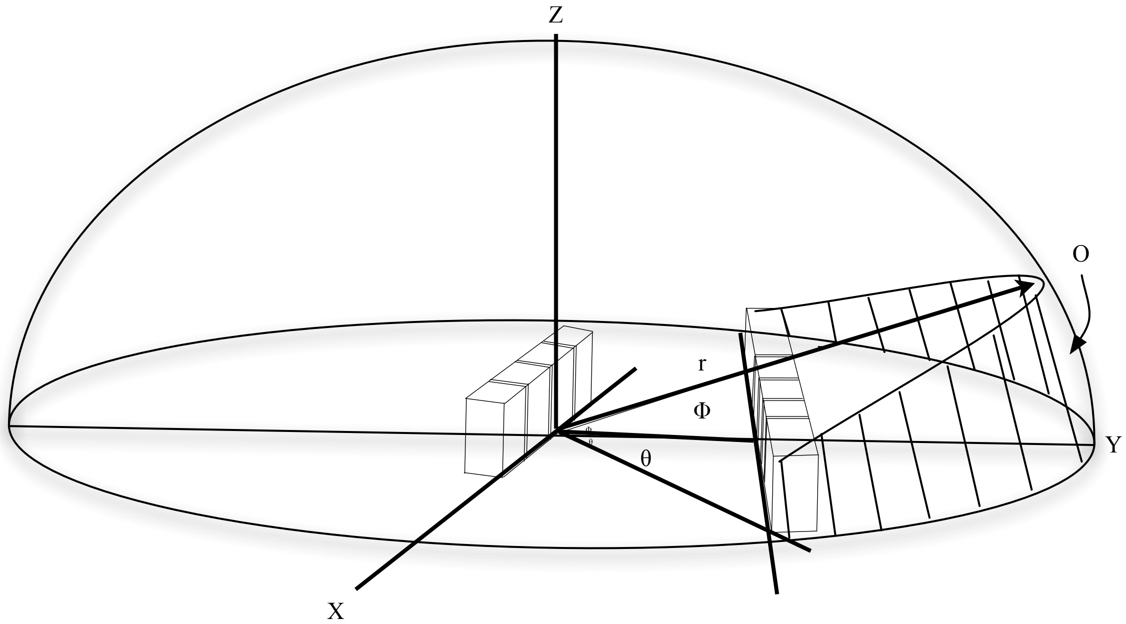


Figure 6.4: Sky Dome considered for a whole building - depicting sky view obstruction in a street canyon.

6.4 Building Controls determining radiation view factors in the Built Environment

In an urban environment Sν can vary from building to building. Considering a building stock or a single building in an unspecified urban environment, Sν is uncertain and representative values are usually applied in energy models such as ESP-r [75] and EnergyPlus [103]. In these circumstances adding a probable distribution to Sν can give greater confidence in model results [83].

Determining Sν is currently done using different digital imaging and remote sensing technologies [153, 154, 155]. Using these technologies to carry out large scale studies on a statistically significant proportion of a regions/countries urban environment is a time consuming process.

Sν can be calculated from a geometrical description of the surrounding environment. Factors such as street width, building heights and variation in height are needed for such an approach. Town planning laws and building regulations are sources of urban control, influencing urban geometry and, therefore, Sν.

After a brief review of current methods used to measure Sν a theoretical approach was examined. The theoretical approach focused on determining a representative Sν for commercial buildings in urban regions with an associated probability distribution in Sν. The values were derived using building and town planning controls considered to be most influential to urban layout.

6.5 Current Measurement Methods

Determining the expected Sν of an urban environment is useful for generic modelling of a building stock. To determine the mean Sν and associated probability distribution that can be applied to building stock assessment, large data sets are required to be statistically representative. For large scale studies an economical and time effective measurement technique is required.

Three methods of calculating Sν have been identified as:

(i) Site Monitoring - Geometric evaluations [156]

(ii) Digital Image Analysis [153]

(iii) 3D Remote Sensing and Geographic Information Systems (GIS) [155]

6.5.1 Site Monitoring to Evaluate Sky View Factor

Measuring the basic geometry of the environment surrounding a building requires two basic measurements: elevation angle to height of obstructing object and azimuth angles in relation to the side edges of the obstructing objects. These values can be determined from measuring height and width of obstructing structures and their position relative to the considered building.

Graphs have been developed by Watson et al. [156] to estimate Sν based on measured elevation and azimuth angles (see figure 6.7). Though data capture and calculation of Sν is relatively straightforward in dense urban regions that tend towards a street canyon layout (see figure 6.5), the task becomes complicated by less dense and less uniform commercial districts (see figure 6.6).

Figure 6.5: Influence of different urban layouts on sky view factors - Street Canyon.

Figure 6.6: Influence of different urban layouts on sky view factors - Offset building units.

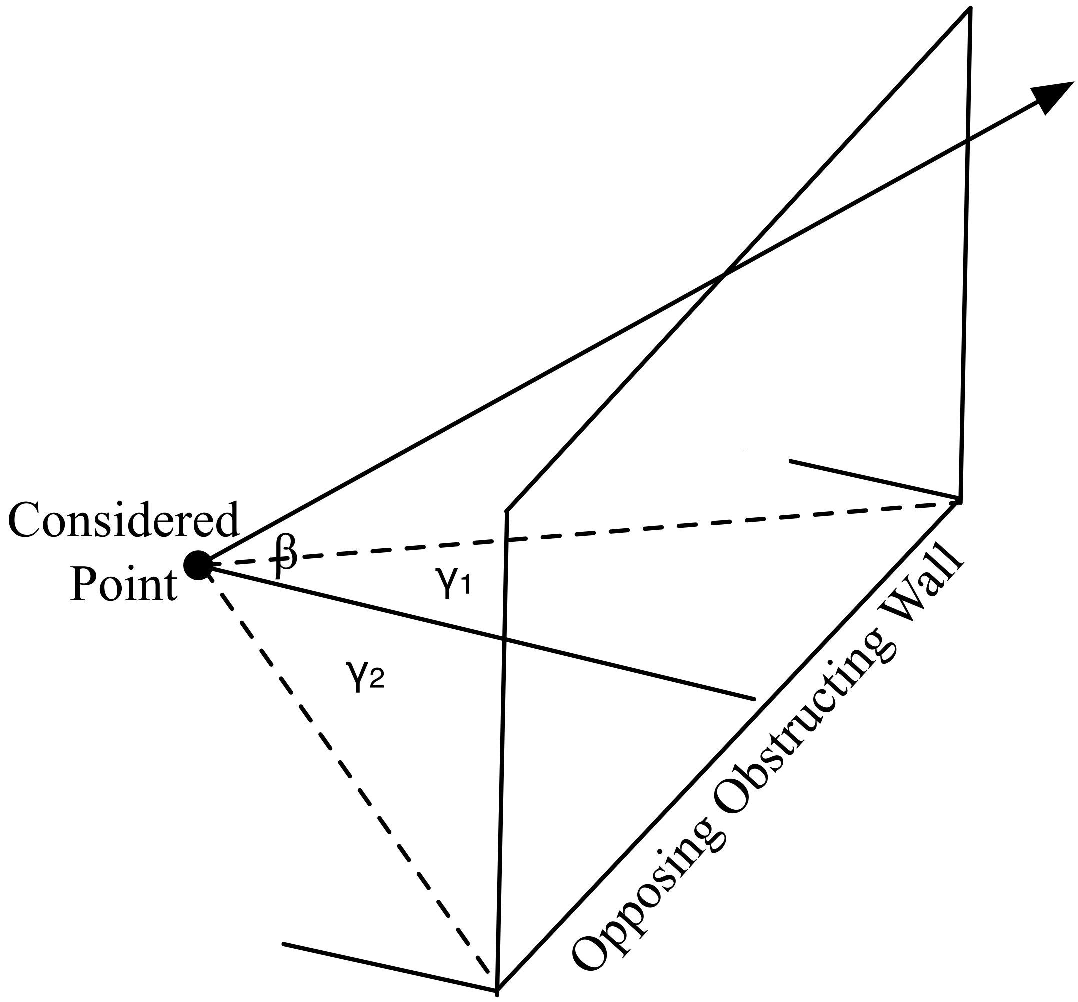


Figure 6.7: Azimuth angles γ at ends of object causing sky view obstruction with elevation angle β.

6.5.2 Digital Image Analysis to Evaluate Sky View Factor

Another approach to identifying Sν is to use an optical device combined with a fisheye optical sensor or lens, followed by post processing of the recorded data. Using the fisheye lens/sensor provides a 180° view of the environment that can be used to determine Sν. Of all optical measurement methods an approach with a digital camera affords greatest accuracy due to a more complete field of view and insensitivity to environmental conditions [153].

Image manipulation combined with a program (utilising equation 6.3) is used to determine the resulting Sν for street canyons in [154]. γ_1 and γ_2 refer to the azimuth angles of the ends of the opposing wall to the point under consideration and β is the angle of elevation to the top of the surrounding buildings (see figure 6.7). Image analysis, still requires site monitoring/geometric evaluation.

$$S\nu = 1 - (\frac{1}{2\pi}[(\gamma_2 - \gamma_1) + \cos\beta(\arctan(\cos\beta\tan\gamma_1) - \arctan(\cos\beta\tan\gamma_2))]) \tag{6.3}$$

In large studies image manipulation and processing can become a time consuming process, where [153] reports approximately 10 minutes per image is required to obtain Sν. For a regional or national study of urban Sν an order of 10^2 or 10^3 images would be required, making data processing alone a time expensive task.

6.5.3 Geographic Information Systems for Sky View Analysis

Souza et al. ,[155], present a novel use of Geographical Information Systems (GIS) combined with 3D CAD modelling to provide location specific Sν. The method provides high level of detail of an urban area. The system relies on pre-compiled data of urban sites, collected as digitised cartographic data.

Using this method currently requires extensive development of algorithms within GIS. The technology involved in remote sensing also requires greater development before the theoretical capability can be met.

6.6 Theoretical Assessment of Urban Form influencing Sky View Factors

Digital image analysis is at present the most effective way of determining Sν, but carrying out a statistically significant survey for a large building stock would be very time consuming. Providing a theoretical approach to evaluating Sν could reduce the dependancy on large data sets, potentially bringing confidence to results of smaller surveys.

Building regulations, model by-laws and town planning laws have been responsible for shaping the urban environment experienced today. Ensuring adequate daylight, ventilation and appropriate vehicle access have all influenced urban topography. As urban form dictates Sν, the controls on urban form will have an influence on the values of Sν.

Review of such documentation was carried out to predict modal[2] values of Sν for commercial regions in an urban environment. As regulations have changed over time the Sν is characterised according to periods of control.

6.6.1 Modal Urban Form

It is assumed that a street canyon represents the most likely urban context for a building. In the first instance the controlling laws are applied to a uniform, infinite street canyon where the ground storey of the building's façade can be considered as a point. In this situation identifying the angle of elevation normal to the wall (Φ_n) to the top of the opposing canyon wall is only required.

A summary of the expected elevation angles for street canyons (built to different periods of building control) is given in table 6.1. The control documentation used to obtain these values is discussed in section 6.6.2.

For an infinite street canyon the angle of elevation (Φ_i) varies with horizontal angular displacement (θ) by equation 6.4 (see figure 6.4 also). This shows the shading influence of the opposing canyon wall reduces to zero at the extremes of the 180° horizontal field of view associated with the building façade.

$$\Phi_i = \arctan(\cos\theta \tan\Phi_n) \tag{6.4}$$

The assumption of an infinite street canyon introduces an artificial restriction on urban form. The potential inaccuracy depends on the length of a finite street canyon and the form of obstructing objects beyond the bounds of the street canyon. Consideration of finite street canyons and greater variation in urban form will be addressed later on.

6.6.2 Predicting Urban Form by Historical Building and Town Planning Control Laws

Different requirements of the built environment have gained importance with changing scientific and engineering knowledge. This is most evident with the current increasing focus on energy performance

[2]Considered in a statistical sense as the most frequently occurring value.

Table 6.1: Summary of Expected Elevation Angle for different a building, related to the period of the surrounding urban development [13, 14, 15, 16].

Control Period	Range of Most Likely Elevation Angle normal to Ground storey of building facade (°)	Influencing Control
1840-1894	45	Building height limited to street width.
1894-1932	45 - 58	Maximum building height 24.38m (80') for street width 15.24m-18.29m (50' - 60'). Below width of 15.24m (50') elevation angle restricted to 45°
1932-1947	31-37	Adjusting limiting angles of elevation. Minimum width between opposing buildings of 10.97m (36') requires 45° elevation angle 4.57m (15') from ground floor. Maximum elevation at street centre line of 56°.
1947-1972	35-44	Daylighting factors - Influenced by study by Allen et al. Range in angle resulting from influence of street width.
1972-1992	20-37	Minimum Visibility of 0.97% of Sky Dome within vertical angular range of 20° to 40° and horizontal angular range 45° either side of the surface normal.
1992-Present	32-37	Minimum 25% of probable sunlight hours. 5% received during winter season.

of buildings. Controlling laws on building form and urban layout reflect this knowledge and have been subject to change over time.

A review of historical control documents revealed four periods of significantly differing control laws/guides on urban development. The laws, regulations and standards of building and urban design applied to these periods were used to predict modal geometric urban form that could be used in determining modal Sν.

Sky View Factor determined by Building and Town Planning Laws: 1840 - 1947

Between 1840-1947 building and town planning model by-laws provided limits on street widths and building heights. Angles of elevation were used to restrict the heights of buildings according to street widths. To maximise development profits buildings were more likely to be built to maximum allowable limits, according to [33, 6]. The restricting angles are therefore taken as the most likely elevation angles associated with urban regions of the period of development.

Between 1840 and 1947 three periods of control have been identified as 1840-1894, 1894-1932 and 1932-1947. Table 6.1 provides a summary of the elevation angles used as a building/planning control, expected at the ground storey level of a building's façade. A summary of each control is also given.

Sky View Factor determined by Daylight Design: 1947-1972

Within the consideration of an infinite and uniform street canyon each point on a building's surface[3] will have equivalent levels of obstruction. The restrictions of urban form associated with window regions and daylighting can, therefore, be considered applicable to all points on the surface of a wall. Daylight design was used under these conditions to predict probable values of Sν.

Post war a significant effort was placed on redevelopment of urban areas rather than urban growth. In 1947 the Ministry of Town and Country Planning issued guidance to Local Authorities on redevelopment [157].

[3] At a fixed height.

Daylight factors were seen as a good parameter for controlling urban development. Waldram diagrams along with daylight factor protractors provided new methods for assessing the influence of urban form on daylight. Studies using these tools carried out by Allen et al. [15, 158] showed preference in an 'open' layout over the traditional 'closed' street canyon.

Based on daylighting factors Allen et al. [15] demonstrated for a standard window size in an office building that the maximum vertical angle of obstruction for a street canyon would be 35°. This value is based on a daylight control factor at 3.66m (12') inside the building. For narrow streets (narrowest street allowed in [157] is 9.75m (32')) adjusting the control to the façade of the building effects the angle of elevation, giving a maximum angle of 44° to the nearest degree.

Greater complexity in determining expected values of Sν arises as daylight indicators consider daylight coming from above and to the side of other urban structures. This demonstrates potentially greater diversity in urban layout than in previous periods of control. Allen et al. [15] suggests better daylight can be met by an offset open plan layout of buildings and the resulting indicators used by Town Planning aimed to encourage such developments.

Sky View Factor determined by Daylight Design: 1972-1992

The daylighting criteria for buildings and the method of determining adequate levels progressed to the British Standard's draft for daylight design, valid until 1992. It stated non-residential buildings should have a daylight criterion with 0.97% of the total sky dome visible at any point 2m high on all sides of a building. This component also had to be between a vertical elevation of 20° to 40° and within the region 45° either side of the surface normal of the building's side. The area of consideration accounts for approximately 7.5% of the total sky dome [159, 160].

Sky View Factor determined by Daylight and Solar Load Requirement: 1992-2008

The British Standard [16] introduced in 1992, provides the current methods for determining that daylight criteria and solar loading criteria are met. Greater use of glazed walling systems affords further flexibility in urban layout making daylight criteria a nonviable control method.

A source for determining Sν comes from the criteria of sunlight duration, stipulating that a minimum of 25% of probable sunlight hours should be received at a window, with at least 5% being received between the 23 September and 21 March. To use this standard to formulate expected sky obstructions it was assumed that this criteria must be met for all sides of the building not facing North ±22.5°. A 180° view in the horizontal plane was assumed for each window (i.e. no recess).

The probable sunlight hours is defined as the long-term averaged total number of hours during the year that direct sunlight would reach the unobstructed ground. The values are, therefore, dependent on location. The standards state that using sunlight statistics for London provides reasonable accuracy for sunlight assessment throughout Britain and so was used to determine the expected sky obstruction for buildings within an urban development post-1991.

With a latitude taken as 51.5° figure 6.8 shows the spherical projection of the yearly sun-path across the sky dome, with the winter-summer line clearly indicated. In figure 6.9 the solid line represents the obstruction path for a South facing wall in an infinite street canyon. The angle of elevation at the normal to the wall is 30° resulting in a maximum (i.e. under clear-sky conditions) winter sunlight of 8% of the total available unobstructed sunlight. In total the South facing wall (at ground level) would receive nearly 55% of available sunlight.

An algorithm to determine the maximum angle of elevation for an infinite street canyon was developed in relation to the sunlight criteria stipulated in [16]. The area below the winter-summer line and above the canyon obstruction line is calculated as a percentage of total unobstructed sunlight.

Table 6.2 provides a summary of the maximum angle of elevation at the surface normal for East, South and West facing façades to meet the minimum criteria for unobstructed sunlight. The North face is not considered as cannot satisfy the sunlight criteria and is assumed to adhere to the restrictions for other wall orientations.

The results in table 6.2 show that as orientation moves away from South, greater dependance on meeting the sunlight requirement is placed on the winter sunlight. The variation in maximum elevation angle was only considered for East, South and West facing vertical walls.

Table 6.2: Maximum angle of elevation of surface normal of East, South and West facing walls to meet 25% of clear-sky unobstructed sunlight.

Wall Orientation	East	South	West
Maximum Angle of Elevation (°)	37	32	35
Percent of Total Sunlight (%)	25	51	25
Percent of Total within winter (%)	12	5	12

6.6.3 Variation in Urban Layout

Applying an infinite street canyon provides simplicity in determining Sν when elevation angle from the base of a building (normal to the building's wall) is known. By equation 6.4 the angle tends to zero at the extremes of the 180° horizontal view plane. A street canyon, however, is not the only urban form and even if the most probable form it will rarely be long enough to be considered infinite.

In order to take into account the potential variations in urban form, the 180° view plane should be segmented. To determine appropriate sectioning a brief review of the controlling factors is needed. In the following sections a calculation of the geometrical factors determining Sν are given in relation to the identified controlling periods discussed in section 6.6.2.

Horizontal View Plane Sectioning: 1840-1947

The sectioning of the sky dome (illustrated in figure 6.10) will vary according to a building's position within a street canyon. This variation is demonstrated in figure 6.11 where extremes in angles associated with sections 1 and 3 are encountered at the end of streets (or at street junctions). Towards the centre of the street the angles of these two sections become equal.

The distribution of the angles associated with the three sections depends on the street length and width. Figures 6.12 and 6.13 show the variation in angle for sections 1 and 3 for a 30.48m (100') and 91.44m (300') long street, respectively.

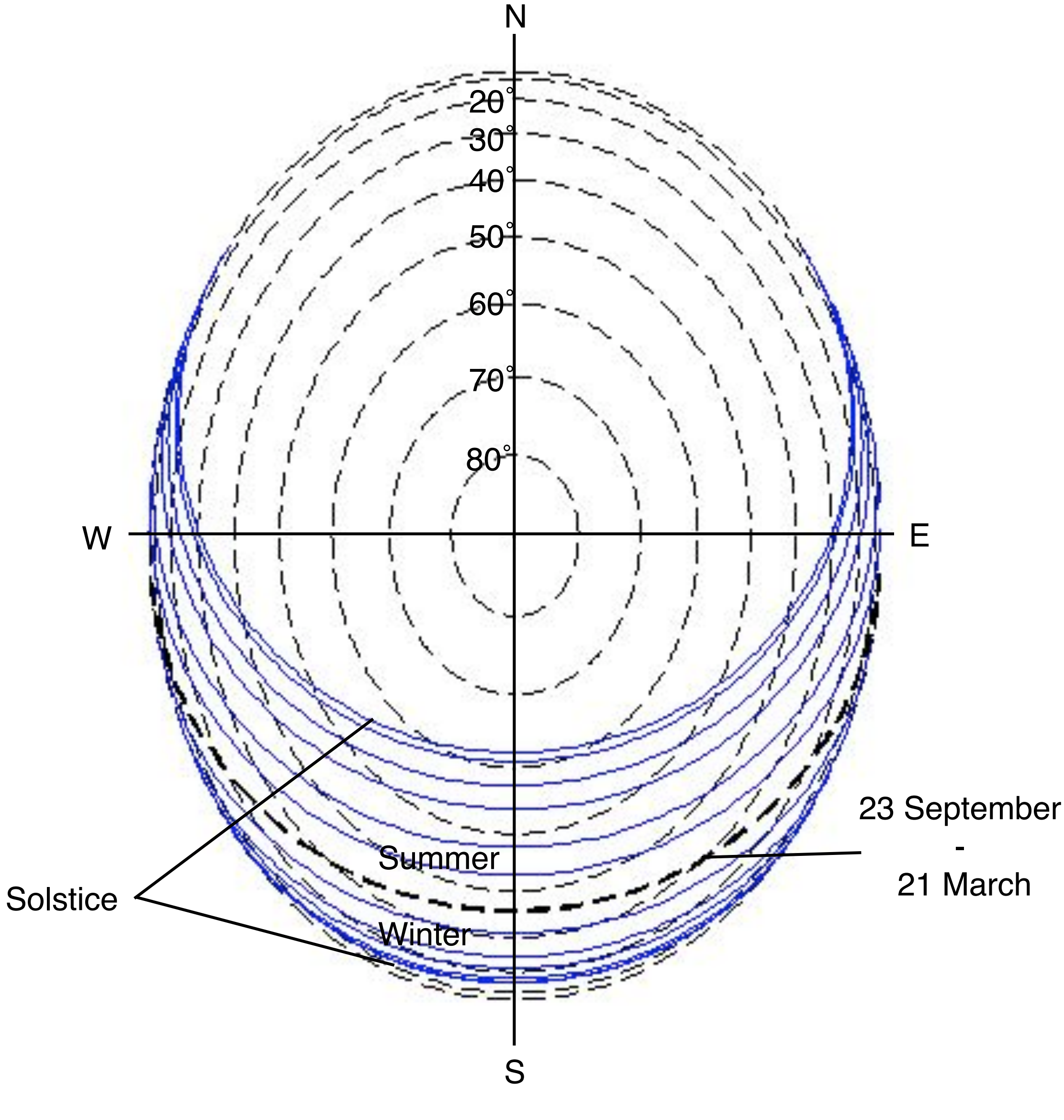


Figure 6.8: Sun-Path diagrams highlighting method to determine available sunlight to a south facing wall in a street canyon - Sun-path Diagram at 51.5° Latitude.

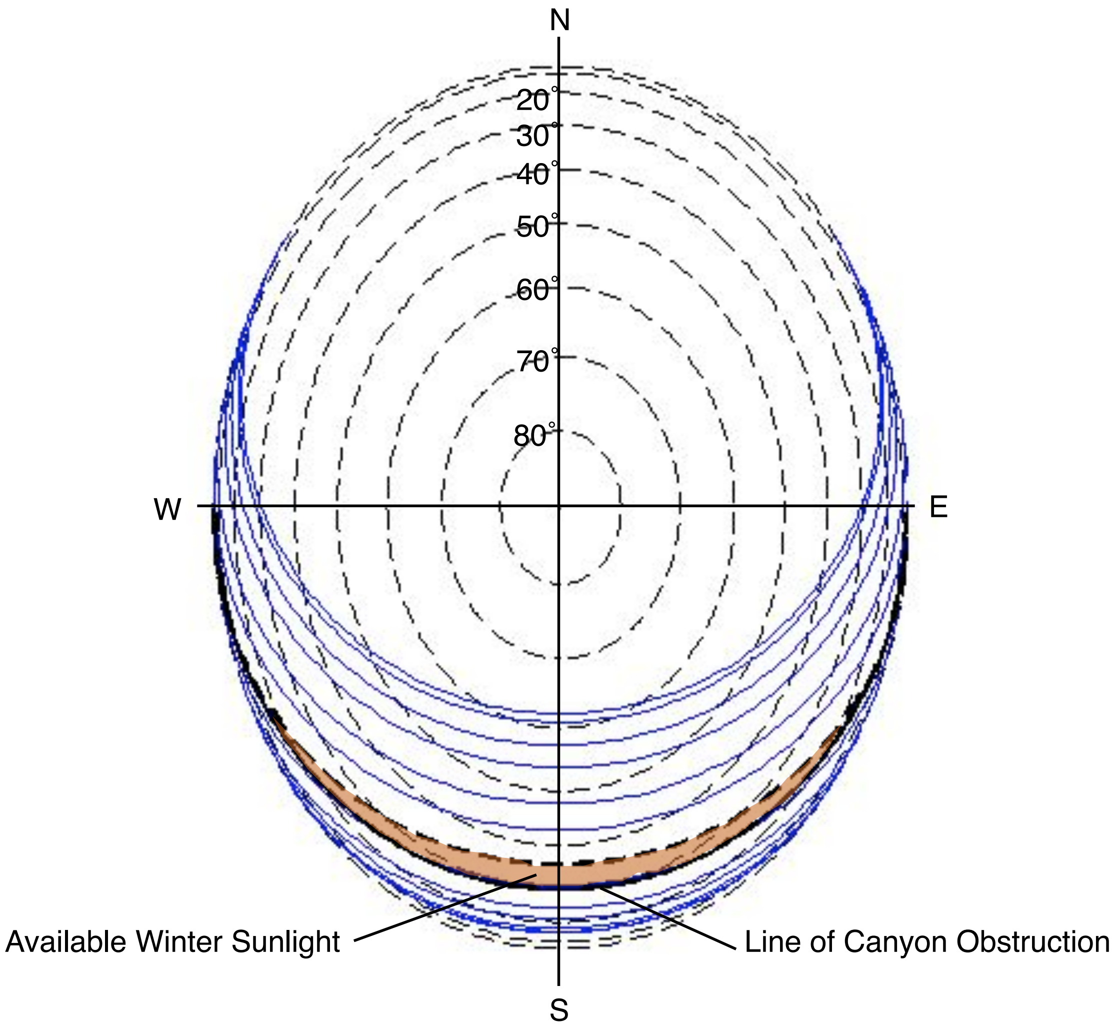


Figure 6.9: Sun-Path diagrams highlighting method to determine available sunlight to a south facing wall in a street canyon - Maximum winter sunlight available.

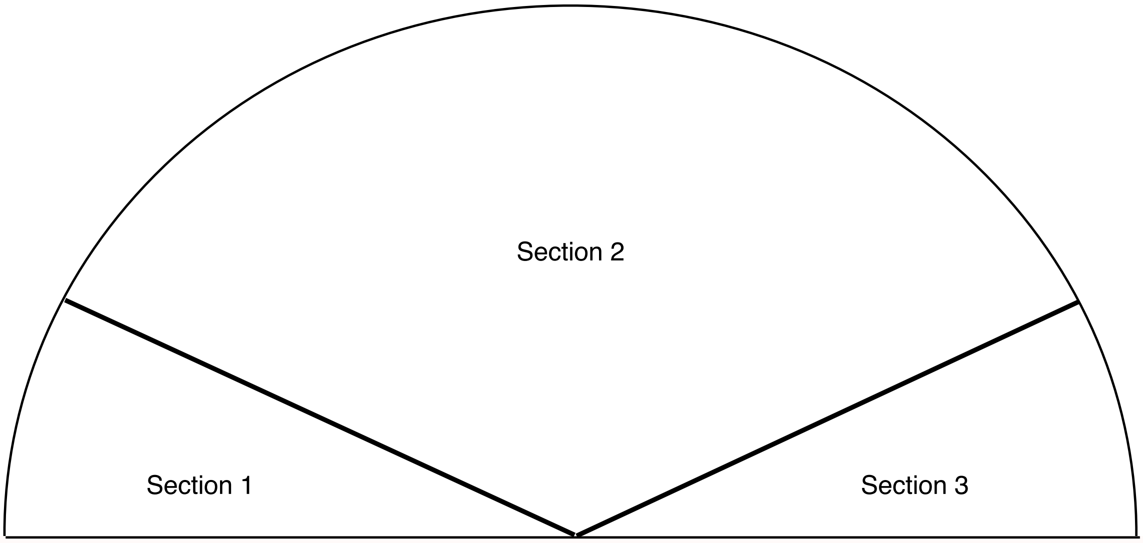


Figure 6.10: Split of the considered sky dome for determining expected Sν for development between 1947 and 1972.

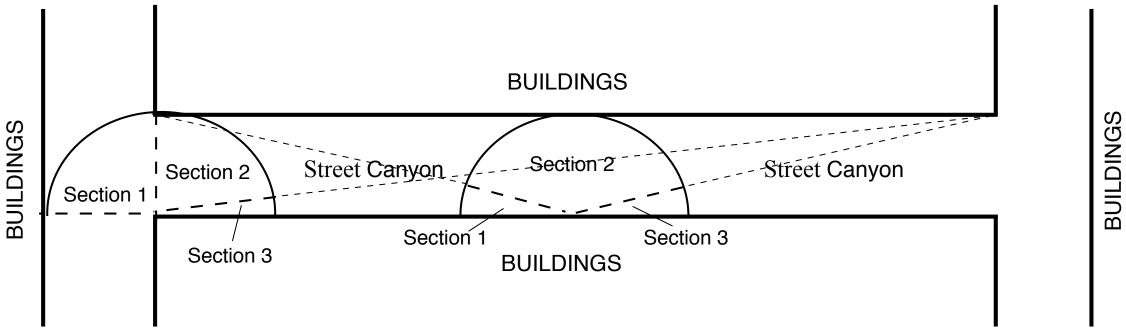


Figure 6.11: Variation in Horizontal Plane Sections at different points along the buildings making up the Street Canyon.

It can be seen from figures 6.12 and 6.13 that an exponential decay in angle occurs as you move away from the "near end" sections of the street. As the street gets longer the central region (defined as both sections 1 and 3 having angles below the mean value) increases in its proportion to total street length. Within this region the angles for sections 1 and 3 are in close agreement.

To simplify this concern, angular equality between these two sections was only considered. The median angle at each street length was calculated for section 1 and 3 and the averaged value applied (see figure 6.14). Street lengths from 30.48m to 304.8m (100' - 1000') are considered, assuming equal probability for all street lengths.

The same procedure was used for the period from 1932-1947, resulting in a sectional angle of 18° to the nearest degree (see figure 6.14).

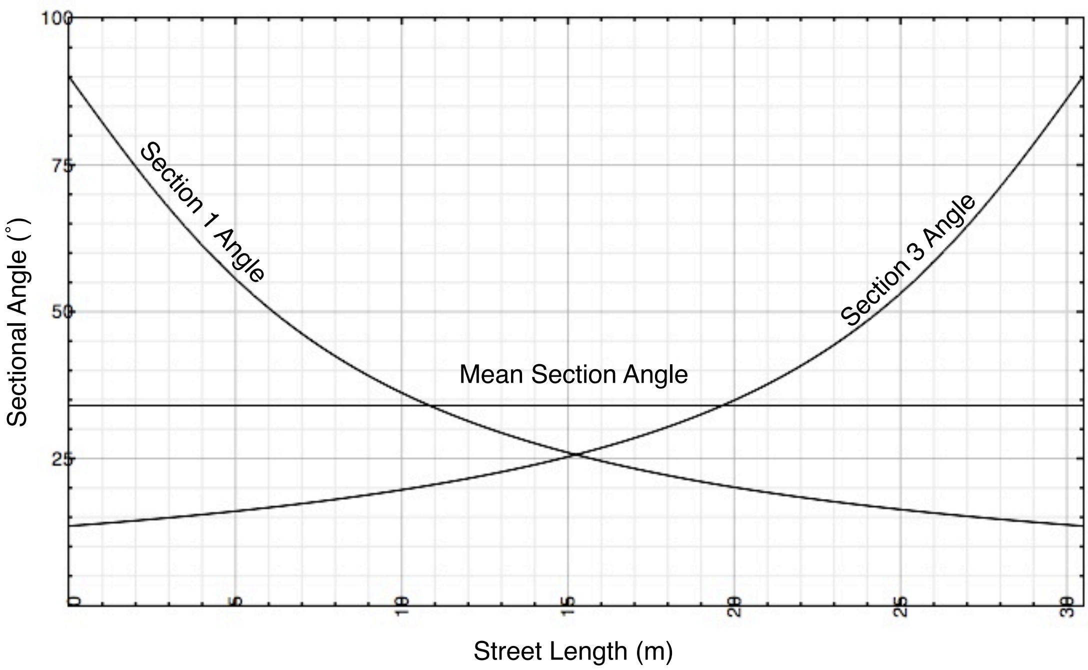


Figure 6.12: Frequency Distribution of expected angle associated with section 1 and section 3 of horizontal plane segmentation - Street 30.48m (100') in length and 7.32m (24') in width. Mean Angle = 34°, Median Angle = 26° (to nearest degree).

Horizontal View Plane Sectioning: 1947-1992

The daylight indicators in [15, 157] identify potential sectioning of the horizontal view plane. In [15] a maximum 50° view plane is considered for achieving the required daylighting requirements about the wall surface normal (see figure 6.14). In [157] daylight indicators are not considered in the 25° at the extremes of the 180° view plane. Combining these points has resulted in the sectioning given in figure 6.14.

This angular distribution is also applied for the period between 1972 and 1992.

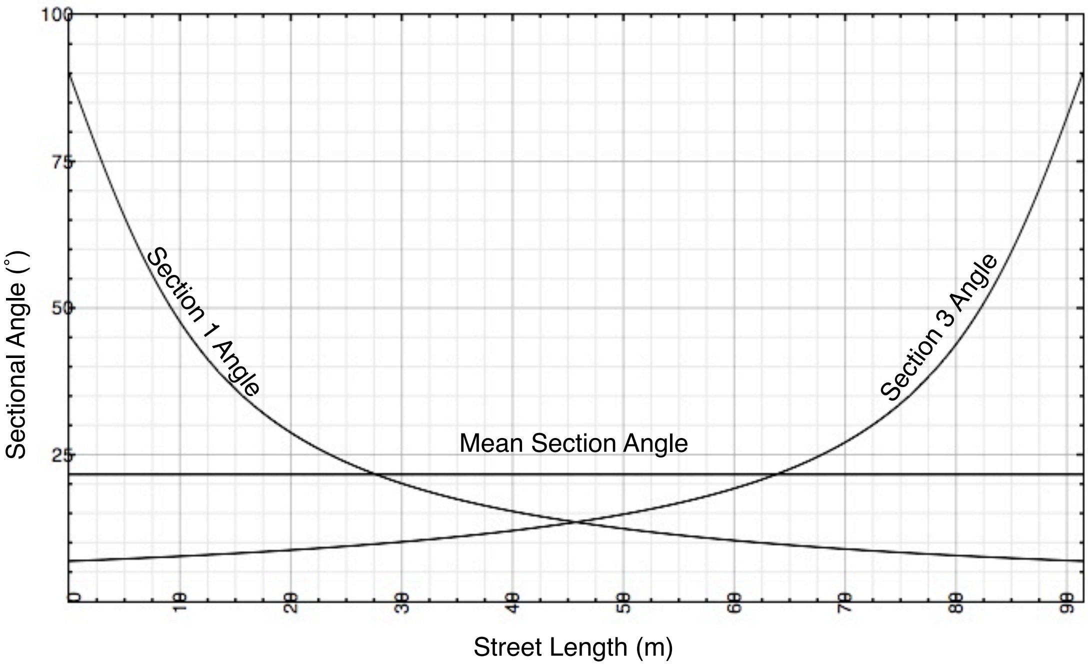


Figure 6.13: Frequency Distribution of expected angle associated with section 1 and section 3 of horizontal plane segmentation - Street 91.44m (300') in length and 10.97m (36') in width. Mean Angle = 22°, Median Angle = 13° (to nearest degree).

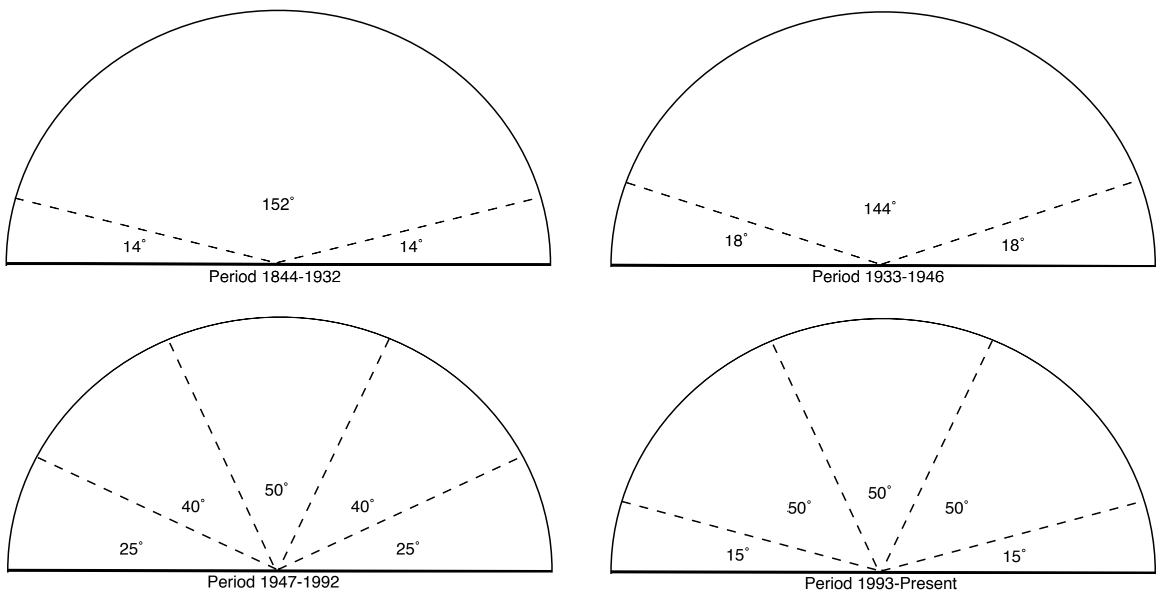


Figure 6.14: Sectional split of the horizontal view plane for determining the parameter of Sν for different periods of urban development.

Horizontal View Plane Sectioning: 1992-2008

Following the controls for sunlight from 1992 onwards, the angle of elevation at a latitude of 51.5° is restricted to 32° for a south facing façade. At this elevation angle the required winter sunlight falls approximately between ±60° either side of the normal to the wall. A horizontal angular view plane +75° or -75° from the normal is required for east and west facing façades, respectively.

To account for all orientations the larger angular displacement of ±75° is used for sectioning the horizontal view plane for this period of urban control. To account for greater diversity in urban form the middle section is split into three equal sections of 50°. The 50° sectioning is used based on reasoning used for the previous daylight control periods.

It is recognised that the theoretical deduction of view plane sectioning is limited by the assumptions applied to interpret the design guide and building controls. What is evident, however, is that latter design guides offer greater variability in urban form. The intention of view plane sectioning was to capture (in some way) this increased potential for variation in urban form and its influence on Sν.

The urban form variability could also be directly accounted for from associating a variable street length and width to the given angle of elevation. A probability applied to street length and width, with a consideration of what is beyond the end of the street, would give statistical variability to the horizontal view plane. This alternative approach is mentioned for completeness and is considered as possible future work in the model development.

6.7 Solar Obstruction

Surrounding obstructions not only influence Sν, but also affect direct solar gains. A different urban topography could result in the same Sν but with potentially different influences on solar gains.

To investigate this a model was developed to set a random geometry of sky dome obstruction. The obstructions were related to a spherical polar co-ordinate description of the sky dome, with an obstruction elevation angle (ϕ, from figure 6.4) set for each horizontal angular position (θ) of the sky dome.

The Sν was calculated from these angular values using the spherical polar coordinate relationship of:

$$dS = r^2 \sin\theta d\theta d\phi \tag{6.5}$$

where dS is the element of surface area of the dome.

A solar loading model for a 1m^2 area of glazing was developed using Bird's Model of Clear Sky Radiation [161]. The sky dome obstructing model was incorporated to calculate the shading impact of the obstructing objects on solar loading.

Combining the CIBSE Guide A method (taken from [162, 163]) for determining the direct and diffuse solar radiation transmitted through a window with the solar loading model, the annual clear sky solar load transmitted by a south facing double glazed window was determined for randomly generated patterns of sky dome obstruction.

Figure 6.15 shows the results for 60 iterations of the model, displaying a trend of increasing solar load with increased Sν. The non-linear relationship, however, is not exact as similar values of Sν, display very different levels of solar loading.

Correlating Sν to a random pattern of solar obstructions on the sky dome was considered beyond the capability of the building energy model used for probability modelling. As a significant trend between Sν and solar loading was demonstrated some basic relationship between solar load and Sν was considered necessary within the building energy modelling process.

By considering each façade of the building to be in a uniform infinite street canyon an obstruction elevation angle (at normal incidence to the façade) could be related to Sν (see equation 6.6). Solar obstructing objects were set in the template building energy models (see chapter 7) at a constant distance from each external wall. The elevation angle was, therefore, used to set the height of the solar obstructing objects.

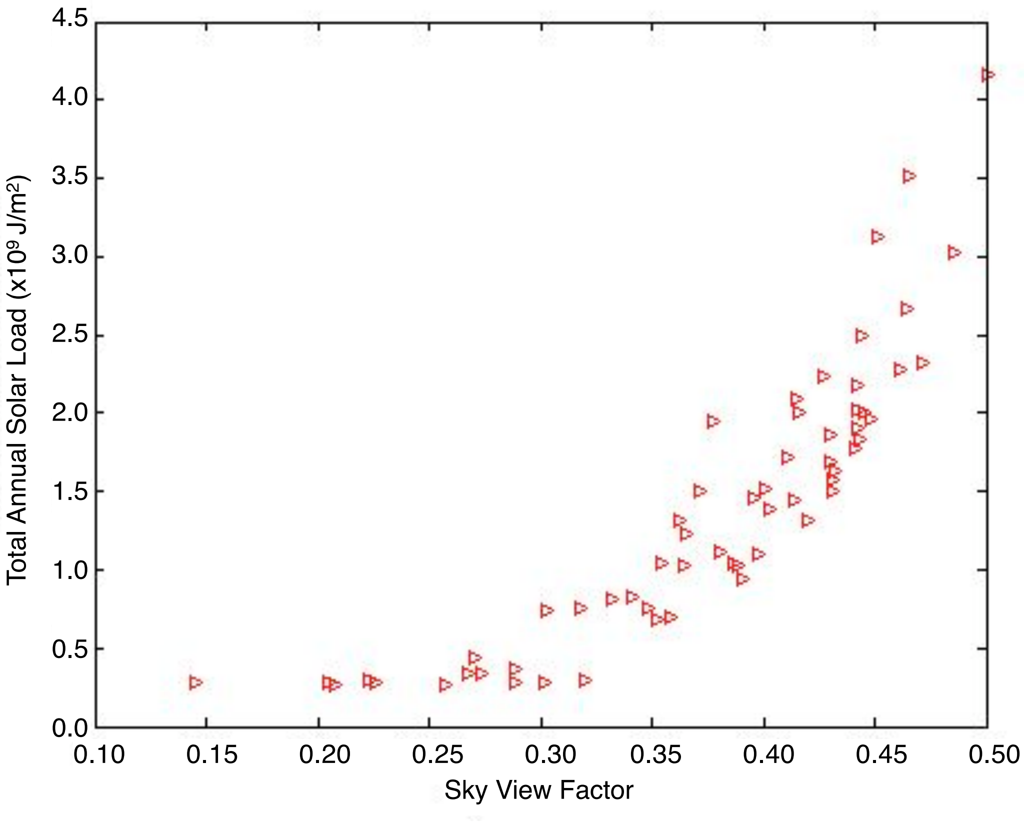


Figure 6.15: Transmitted annual solar radiation through 1m^2 of South facing double glazed window against Sν for randomly set sky dome obstructions.

6.8 Model Design for Calculating the Probable Distribution of Building Stock Sky View Factors

A study of building regulations, by-laws and town planning laws has resulted in determining the most likely angle of elevation from the base of a building to the unobstructed sky. These period dependent values have been calculated making the assumption that the most likely urban form is a street canyon.

Urban redevelopment and expansion, growth of trees, later laws encouraging more open urban development and undulating land are some of the factors that will contribute to a variation in the expected elevation angles. Though the identified building control documents provide expected values for angles of obstruction, they do not reflect the potential variation due to the factors listed above.

It can be said in all cases of vertical walls that the angle of obstruction will vary between $0°$ and $90°$. With no geometric description of the surrounding urban environment the elevation angle should be randomly selected. The building control laws and town planning laws have, however, offered prediction of stock tendency towards certain obstruction angles at normal incidence to a building façade.

A period dependent random selector for providing an obstruction angle at normal incidence to a building's façade (combined with varying urban layout) was used to determine a probable stock distribution in Sν. The most likely elevation angle in each horizontal section was determined by applying equation 6.4 to the modal elevation angle at the surface normal.

By looping N times, the theoretical probability distribution associated with obstruction angle predicts a probable distribution in Sν for a building stock associated with a given control period.

6.8.1 Urban Layout and Probability Distribution applied to elevation angle

The urban layout is determined by period of control and refers to the sectional division of the horizontal view plane (see section 6.6.3 and figure 6.14). For each section in the horizontal view plane an elevation angle of sky obstruction is randomly selected. The random selection is based on a triangular PDF (see chapter 3) that uses the elevation angle determined by control laws (see section 6.6.2) to represent the modal elevation angle at the surface normal of the considered wall.

Assuming equal height of obstructions within the considered horizontal section, equation 6.4 determines the resulting elevation angle at each angle of deviation from the surface normal (θ in figure 6.4). The process is repeated for each section in the horizontal view plane.

The triangular PDF used to describe the probable distribution in the elevation angle (Φ) at surface normal is physically limited to a range from $0°$ to $90°$. The modal value within this range is determined by the considered building/town planning controls. In all cases post-1894 the expected elevation angle is given as a range rather than a single value. Before utilising the triangular distribution to determine the surface normal elevation angle, a modal elevation angle must be determined.

Where ranges in expected elevation angle have been identified by the building/planning controls a value is randomly selected from this range (using a rectangular distribution). The randomly selected value is applied as the modal elevation angle in the considered triangular PDF. Figure 6.17 provides a graphical representation of the PDF applied to the random selection of elevation angle of obstruction[4].

[4] Used to calculate Sν according to period of urban development.

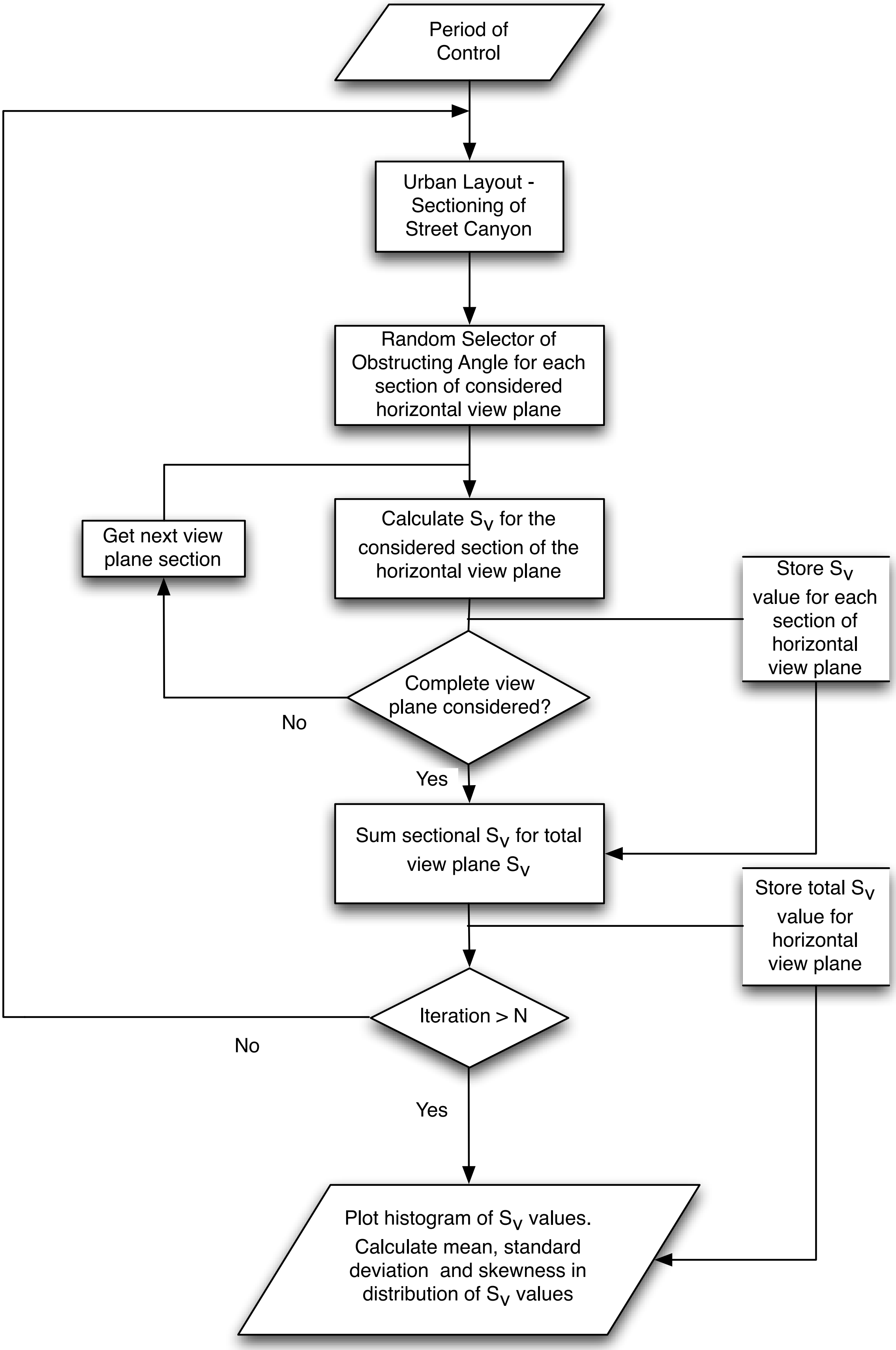


Figure 6.16: Flow Diagram of model procedure in determining Probable Stock Distribution of $S\nu$.

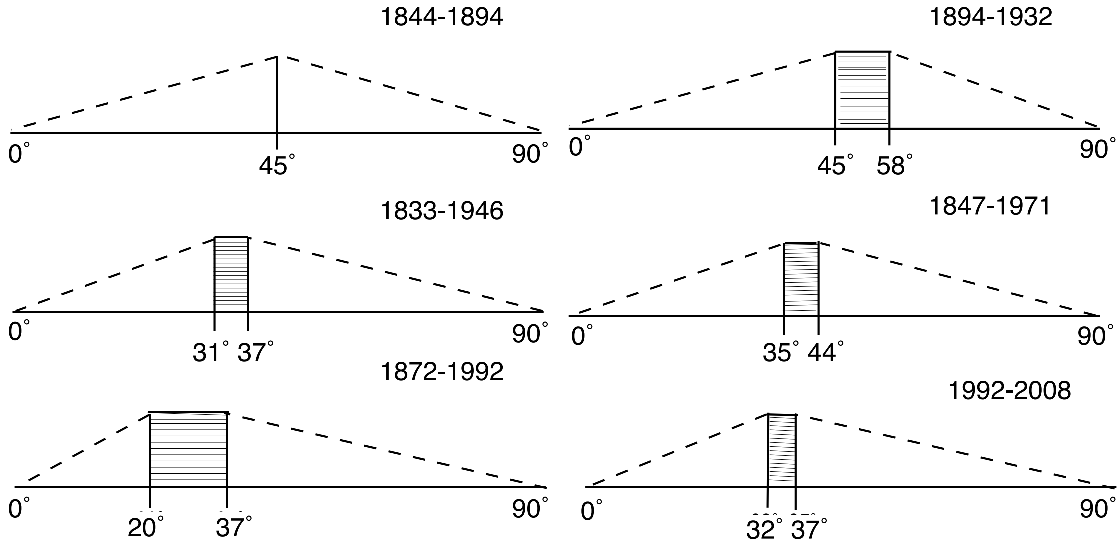


Figure 6.17: Graphical Representation of process to determine modal elevation angle and subsequent triangular distribution.

6.8.2 Calculating Sky View Factor from Obstruction Angle of Elevation

Sν is calculated from the elevation angle of obstruction (Φ) by:

$$S\nu = \frac{2*\pi}{360} \frac{\int_{-\Theta}^{\Theta} \sin(\frac{\pi}{2} - \phi_i) d\theta}{2\pi \sin(\frac{\pi}{2})} \tag{6.6}$$

where Φ_i is related to angle of horizontal displacement from the surface normal (θ) by equation 6.4. Θ represents the limits of horizontal displacement from the surface normal of the considered horizontal section. The total Sν is then given as the sum of the Sν for each section in the horizontal view plane.

6.9 Resulting Urban Distributions of Sky View Factor

A program was developed using the logic presented in the previous sections to provide a probable distribution in Sν for urban regions built under different periods of controls.

Figures 6.18 to 6.23 show the discrete distribution of the Sν for 5000 iterations of the model for each period of urban development. For each period the results are accumulated into 30 bins representing a range of ~0.01 of Sν.

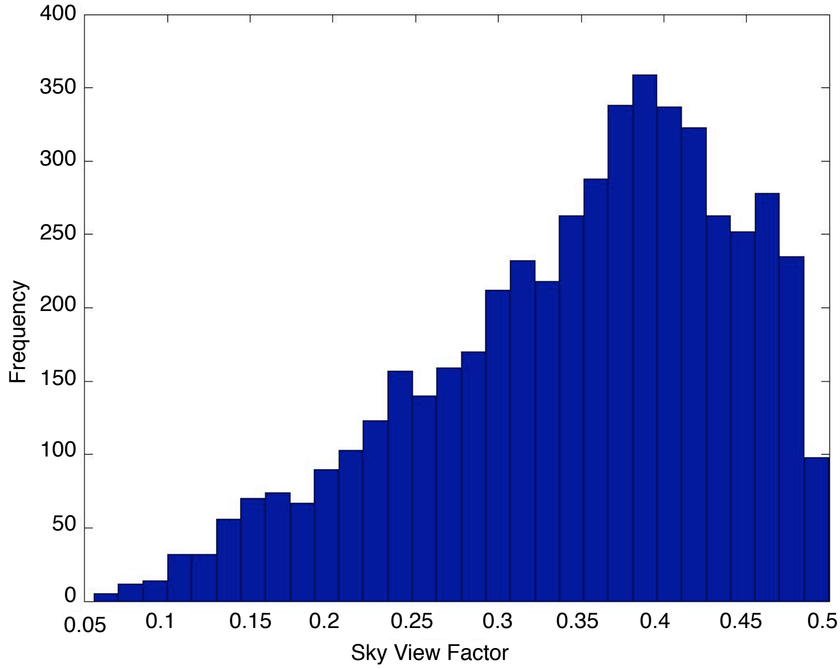


Figure 6.18: Discrete Distribution of Sν expected for the ground storey wall of a building in an urban area built between 1840-1894 (5000 samples).

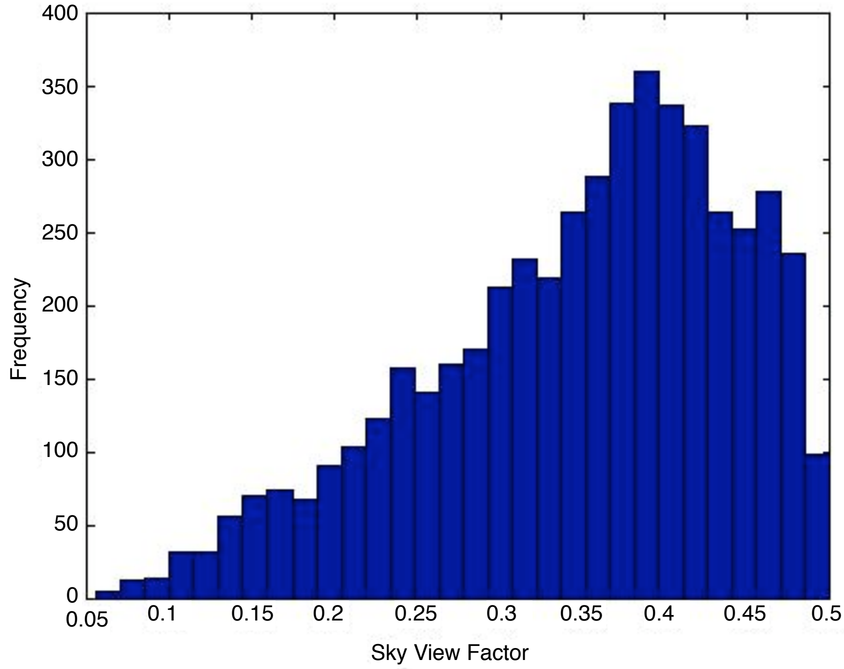


Figure 6.19: Discrete Distribution of Sν expected for the ground storey wall of a building in an urban area built between 1894-1932 (5000 samples).

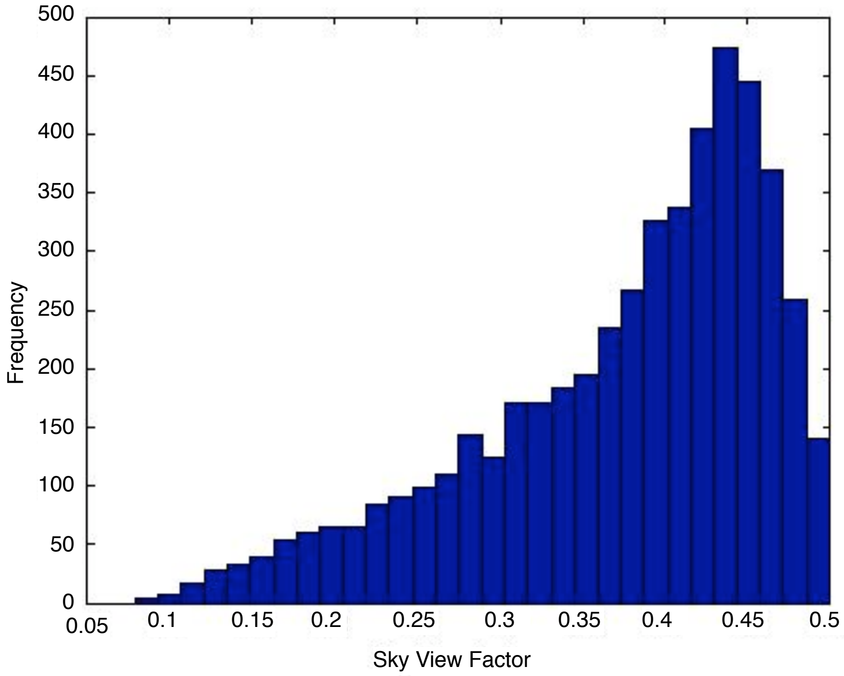


Figure 6.20: Discrete Distribution of Sν expected for the ground storey wall of a building in an urban area built between 1932-1947 (5000 samples).

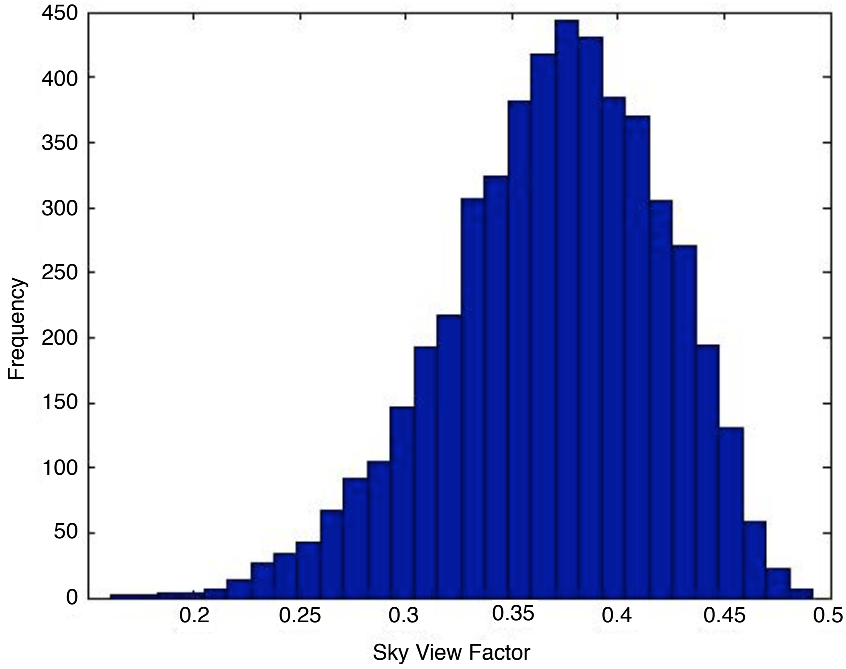


Figure 6.21: Discrete Distribution of Sν expected for the ground storey wall of a building in an urban area built between 1947-1972 (5000 samples).

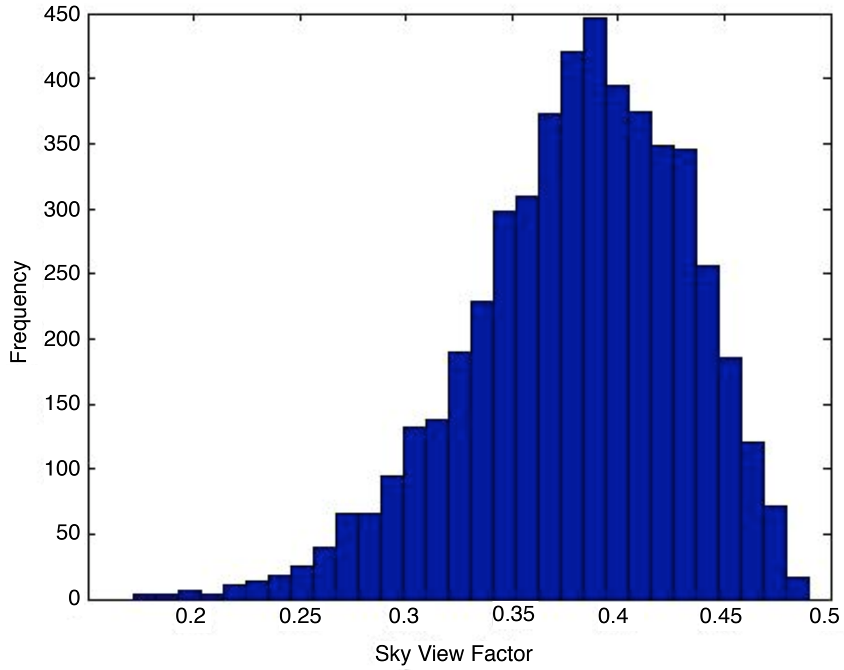


Figure 6.22: Discrete Distribution of Sν expected for the ground storey wall of a building in an urban area built between 1972-1992 (5000 samples).

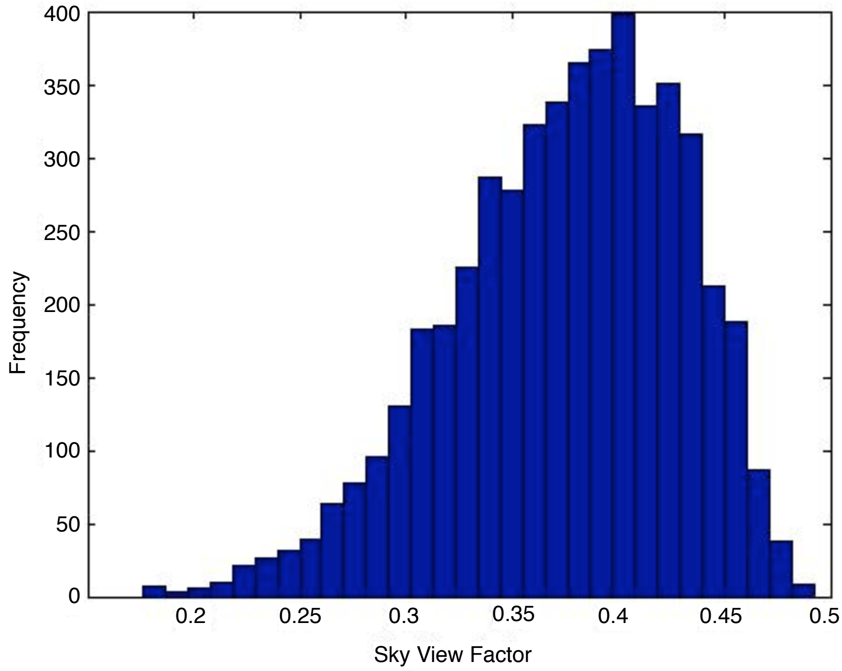


Figure 6.23: Discrete Distribution of Sν expected for the ground storey wall of a building in an urban area built between 1992-Present (5000 samples).

In each period a negative skew to the Sν is present. The skewness is greater for earlier periods of control where urban layout is most likely to conform to the urban canyon. For later control periods the greater flexibility in urban form (represented by sectioning the horizontal view plane - see figure 6.14) reduces the skew in distribution.

The mean Sν are similar for each control period; a small increase in mean Sν for more recent periods of control resulted from the developed model. Table 6.3 shows a maximum difference in mean Sν of 0.0473 for the modelled control periods.

The mean Sν associated with each period of control (table 6.3) are in general agreement with ESP-r representative values for areas with urban structures of uniform height (table 6.4). This is potentially a reflection on the assumption of uniform urban street canyons being the most likely urban form.

ESP-r's representative Sν value for general urban regions is 0.41 and for small buildings relative to their surroundings is 0.15 (table 6.4). As the distributions are negatively skewed modal values of Sν tend to higher than mean values. From inspection of figures 6.18 to 6.23 the modal values show greater agreement with the urban site value of 0.41 used by ESP-r.

Table 6.3: Mean Sν for building vertical surface in commercial urban districts of different age.

Period of Development	Mean Sv	Sv Standard Deviation
1840-1894	0.3334	0.0953
1894-1932	0.3479	0.0938
1932-1947	0.3742	0.0882
1947-1972	0.3693	0.0508
1972-1992	0.3807	0.0512
1992-Present	0.3752	0.0543

Table 6.4: ESP-r representative values of Sν [17].

Location	Sv
City Centre: surrounded by buildings at same height, vertical surface	0.36
City Centre: surrounded by higher buildings, vertical surface	0.15
Urban Site: vertical surface	0.41
Rural Site: vertical surface	0.45

6.10 Conclusions

The external influences of weather and the influencing factors of urban environment on building thermal performance modelling have been considered with regards to distribution in the ND building stock of England and Wales.

A probability distribution has been associated with weather files, according to a geographical ND stock distribution as identified by the NDBS project. In doing so a bias is placed on the South East weather region. Using this distribution within the model will give a distribution relevant to England and Wales as a whole. It is recognised that this distribution can be omitted to assess stock on a regional (by weather) basis.

The distributions of Sν (as calculated by the method presented in this chapter) are limited to a ground level value. Using current practical measurement techniques would, however, also only capture a ground level Sν.

In building energy modelling, only one value for Sν is used for the entire building where in reality the Sν potentially could vary across each façade's plane. The extent of the variation being dependent on the size of the façade in relation to the sky obstructing objects. The simplification of Sν consideration in the building energy model means calculating a single point Sν is adequate for modelling purposes.

The calculated distributions in Sν resulting from this study do not account for variation over a building's façade, rather a distribution in a single point value resulting from potential variation in the surrounding urban topography. The uncertainty of a representative Sν, when considering a notional building, can be accounted for by the probability distributions.

The influence of urban regeneration and development cannot be fully understood by the theoretical assessment method. Capturing this influence would help develop a stronger distribution. The flexibility and complexity of the controls considered to impact Sν for the latter two periods raises concern over the assumptions of basic urban form applied in developing this theoretical approach.

The relationship between Sν and solar shading chosen to be modelled in the stock probability model assumed an infinite street canyon form. This simplification was used to aid model development, but is recognised as a limitation as it doesn't account for the variability in solar shading for a given Sν.

Chapter 7

Building Stock Probability Assessment of Base Thermal Loads

Chapters 4 to 6 have reported on methods used to associate a priori probability to attributes of a building structure and the surrounding environment within a Non-Domestic (ND) building stock. These characteristics have been considered in the context of whole building energy modelling.

This chapter describes the application of the identified attribute values and associated probability distributions to a BEM tool. The results of this modelling method associate a statistical confidence in predicting the influence of period of construction on base level thermal performance of ND buildings in England and Wales.

The method of attribute setting and probability model design are presented in this chapter. A sensitivity analysis of the considered building characteristics is considered before the probability model results are analysed.

The study focused on commercial office buildings within the ND building stock of England and Wales. Thermal loads have, therefore, been calculated under a constant pattern of internal casual gains and within the CIBSE standard comfortable temperature range associated with office buildings. Appendix D describes the patterns of internal casual thermal gains and controlling temperature ranges applied to the model.

Construction control laws and building regulations were used to identify typical ranges in attribute values. The data presented in this chapter has, therefore, been considered within categories of identified periods of building control.

7.1 Model Design

Using an existing BEM tool a scripting process was developed to randomly set the parameters of a building model. The parameters are determined according to values and ranges in values identified from building controls and existing stock survey data. Of the identified categories of building attributes (see chapter 3 and figure 3.2) ranges in probable values in the English and Welsh ND building stock have been identified (chapters 4 to 6).

The initial process in parameter setting was to set the building control period to be assessed. The ten control periods associated with wall construction (presented in chapter 4) were applied for model assessment.

On setting the control period a predetermined sequence of setting up a representative ND building model was required. Interdependencies of building form and construction were identified in building control laws and stock distributions identified in the NDBS Project. Figure 7.1 provides a sequenced diagram of the resulting parameter setting processes used in probable modelling of the ND building stock's base thermal loads.

The central column of figure 7.1 describes the order of processes to define building model parameters with a given stock distribution. These distributions are either determined by construction period or as identified from published data from the NDBS project.

The right-hand column describes the processes defining other building structural and form features that have not been considered in terms of stock distribution. These parameters are set to constant values or are randomly set within ranges. The ranges are determined by model sensitivity and size limitations of the BEM tool (in this instance esp-r).

The left-hand column highlights the data resulting from building control laws as well as attributes resulting from the parameter setting processes that influence further parameter setting.

Of the 'unconsidered parameters' (with respect to stock variation), shape, size, internal layout and attachment were restricted to simplify the modelling process. For each shape, size (in terms of number of storeys), internal layout, roof type (flat or pitched) and level of building attachment a basic model in esp-r was created. A database of these basic models were then used in the Monte Carlo modelling process.

The internal layout was limited to either open plan or cellular, as identified in the basic building forms of the NDBS project [91]. For the open plan model each storey was considered as one zone, with no account of service rooms or stairwells. For cellular models a basic division of each storey into four equally sized cells was developed. No air flow connection between the model zones was given.

For the cellular models internal wall construction influences thermal behaviour by increasing building thermal mass, creating smaller zones of thermal control and introducing different solar load distribution to each storey. In all cellular model instances a high thermal mass internal wall construction was used, representing structurally significant internal walling.

The uncertainties of internal thermal loading and the impact on base thermal loads were not considered. A constant behaviour of internal loading was applied to the model - normalised to unit area of floor. This was done as the study is intended to consider the influence of varying building structure on base level thermal performance.

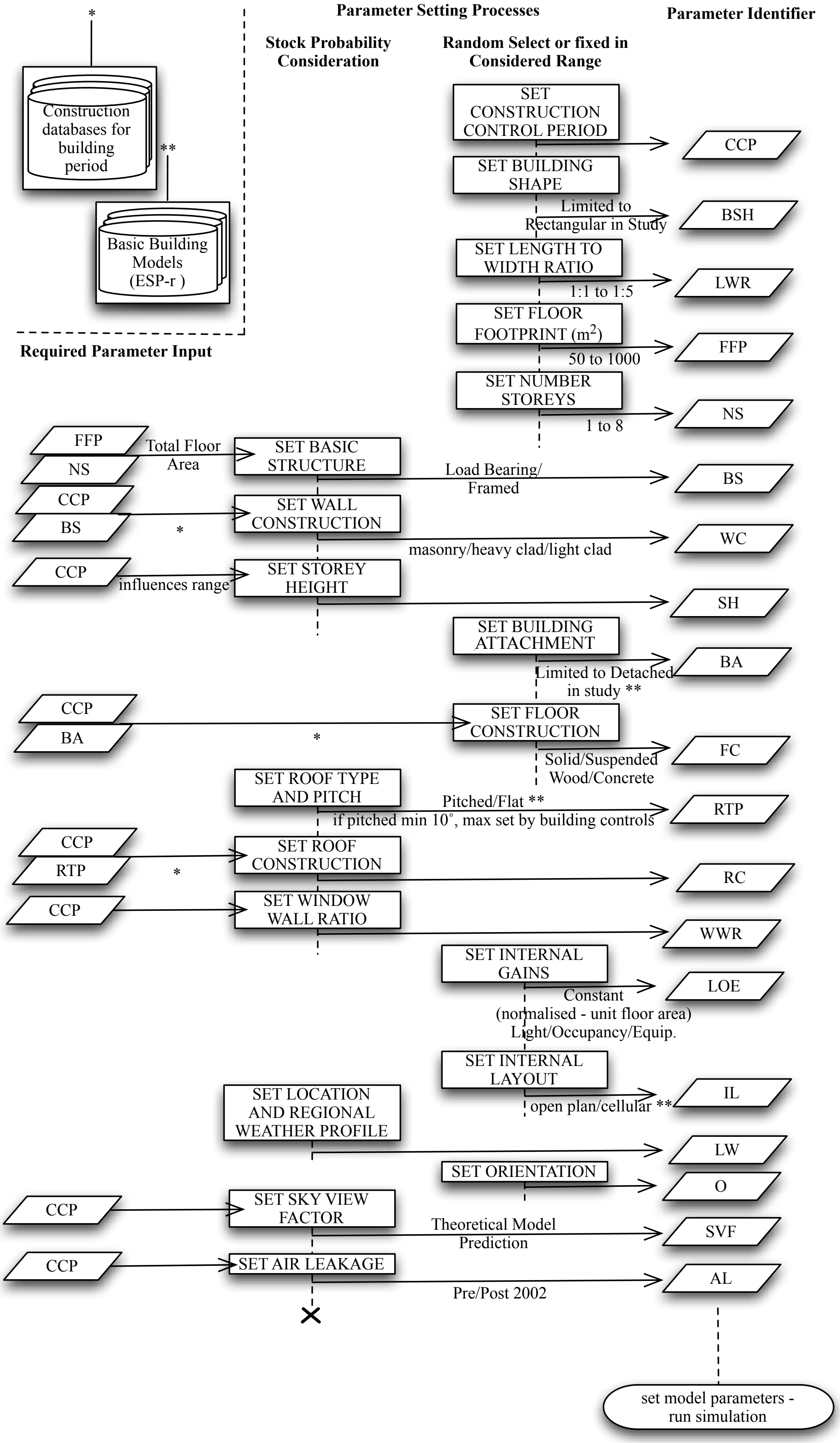


Figure 7.1: Sequenced Flow Diagram of Building Parameter setting for BEM.

7.2 Period Typical Case Behaviour

For each control period, typical component construction and component proportions have been identified (see chapters 4 to 6). Using these identified values a period-typical model was used to assess the expected variation in base level thermal performance of ND buildings according to period of construction.

Variations in building form within the building stock (such as floor footprint area, number of storeys and window distribution) have not been surveyed in this study. A period-typical building form has, therefore, not been accounted for.

The current non-domestic building stock parameter setting tool was limited to open-plan and basic cellular, detached rectangular buildings.

Based on the model simplifications a base case building was constructed to represent median values of the considered parameter ranges that influence form. A 4 storey, detached building with equal distribution of window area, a flat roof, of equal length and width, open plan layout and of brick-cavity-block wall construction was used as a base case model. The period-typical model values applied to this basic model form are given in table 7.1.

7.2.1 Period Typical Models - Base Thermal Performance

Each period-typical base case building model was simulated for a full Typical Reference Year according to the UK IWEC weather files. Figure 7.2 shows the monthly heating and cooling base loads for each period.

The heating load reduces within modern construction periods, as expected from improved control laws on thermal behaviour. A higher base level cooling load, however, occurred in the modern construction periods. Figure 7.2 shows an increased cooling period for the latter two control periods (1996-2001 and 2002-2008+) and higher monthly cooling loads than associated with the earlier period-typical buildings. This is explained as reduced exposure to thermal mass, and for the latest control period also a reduction in the expected adventitious leakage rate.

From the earliest to latest building control period a decrease of 85.6% in the normalised annual base heating load was demonstrated. For cooling a 165.3% increase was found (see table 7.2). Combining heating and cooling base loads show improved thermal performance of the later control periods.

Examination of the thermal behaviour showed thermal load to be influenced by the construction as determined by building control, the indoor set temperature range and the internal loads. It must, therefore, be stated that the current model will produce probability distributions of base level thermal behaviour under the set conditions of occupancy (and associated internal heat gains) and the given control range for internal temperature.

The period-typical results show earlier buildings have greater potential benefit from reducing heating loads by passive retrofit measures, whilst modern buildings require greater focus on reducing cooling loads.

To determine the influence of building form and construction parameters on these heating loads a sensitivity analysis was carried out.

Table 7.1: Base case parameters of the model for sensitivity analysis within each building period.

Parameter Type	Control Period									
	1894-1938	1939-1952	1953-1965	1966-1971	1972-1976	1977-1984	1985-1990	1991-1995	1996-2001	2002-2008+
Outer Layer Thickness (m)	Load Bearing			** Framed						
Ground Floor	0.2159	0.2159	0.1143	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016
1st Floor	0.2159	0.2159	0.1143	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016
2nd Floor	0.2159	0.2159	0.1143	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016
3rd Floor	0.1143	0.2159	0.1143	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016
Cavity Size (m)	0.0508	0.0508	0.0508	0.0508	0.0508	0.0508	0.0350	0.0500	0.0500	0.0500
Insulation Thickness (m)	0	0	0	0	0	0	0.0250	0.0550	0.0550	0.0800
Inner Layer Thickness (m)	0.1143	0.1143	0.1143	0.1000	0.1000	0.2400	0.1000	0.1000	0.1000	0.1000
Window Wall Ratio	set to 10% of floor area			33%			35%		40%	
Glazing Level	Single						Single ≤ 35% 35% < Double ≤ 70%		Single < 27% < Double Double < 53% < Triple	
Storey Height (m)	2.6 (8'6")	2.44 (8')	2.3 (7'6")			2.3				
Sky View Factor*	0.5									
Solar Obstruction Height*	0									
Number of Storeys	4									
Length-Width Ratio	1:1									
Floor Footprint Area (m^2)	200									
Air Infiltration ($m^3.h^{-1}.m^{-2}$)***	15									7
Floor Type	Concrete Solid									

* All base level cases considered in isolation. Sky View factor is for each vertical wall. Obstruction height is related to sky view factor.

** The introduction of thermal energy concerns to construction in the building regulations.

*** The value is only regulated for the latest regulatory period. Air infiltration studies have shown no correlation to building age and not enough data is available (nationally or even internationally) to obtain a mean and probability distribution in this value. A value of 15 is set for earlier control periods to account for the expected improved air tightness of buildings, with its introduction to building standards.

Table 7.2: Annual Base Level thermal Loads for period typical, 4 storey open plan masonry cavity wall building.

Period	1894-1938	1939-1952	1953-1965	1966-1971	1972-1976	1977-1984	1985-1990	1991-1995	1996-2001	2002-2008+
Heating ($kWh/m^2/y$)	57479	54378	55541	50236	49431	39702	38313	33519	19459	8286
Cooling ($kWh/m^2/y$)	18766	19253	19278	21380	21680	23197	24438	25503	36188	49790
Total ($kWh/m^2/y$)	76245	73631	74819	71616	71111	62899	62751	59022	55647	58076

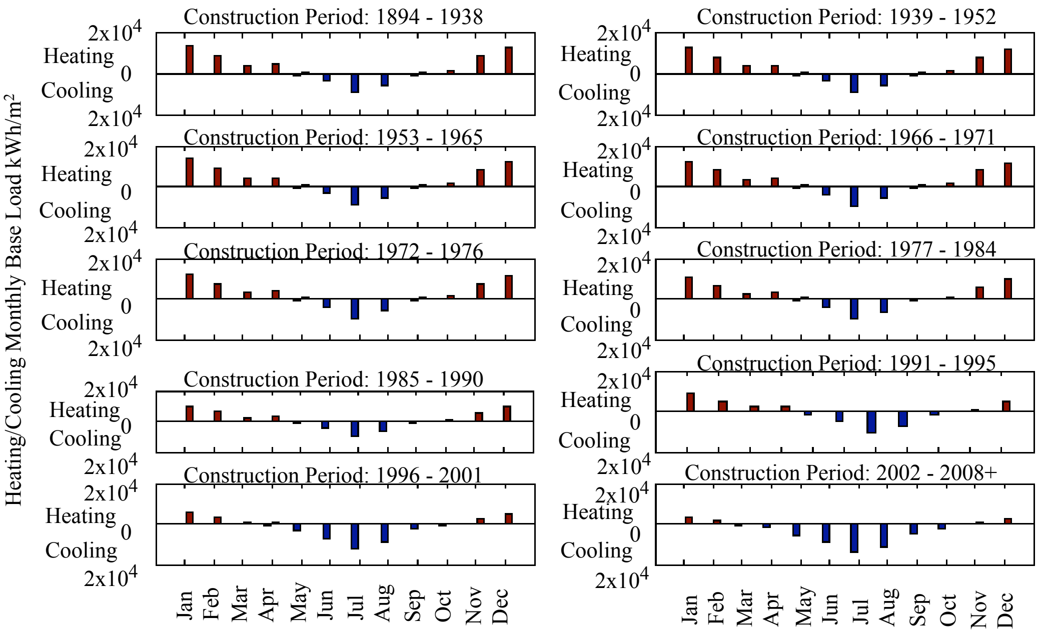


Figure 7.2: Monthly Base Heating/Cooling Loads for 'typical' building forms of identified construction periods.

7.3 One-at-a-time Sensitivity and Uncertainty Analysis

An evaluation of the individual parameter influences on thermal performance was carried out. The process was divided into sensitivity analysis for parameters with non-discrete distributions and uncertainty analysis for all parameters. Combined, the results offer an understanding of the most important parameters to the probability study, given the range in uncertainty within the considered ND building stock.

In each instance the analysis was carried out on the base case building identified for each period of control. For the sensitivity analysis, values were typically varied from the base case within a range of ± 20%. For the one-at-a-time uncertainty analysis the total potential range of each parameter was considered.

7.3.1 One-at-a-time Sensitivity Analysis

From the literature review (chapter 2) it is evident that sensitivity analysis is an important process to enhance understanding of modelled behaviour [164, 165, 91]. Hamby [91] highlights five potential reasons for carrying out sensitivity analysis that together provide a 'critical' step in validation of model behaviour. These reasons can be summarised as: identifying influential parameters to the uncertainty in model predictions.

Several techniques of sensitivity analysis exist [91], where the method required is dependent on the complexity of the model and the required interpretation of parameter sensitivity to model behaviour. A one-at-a-time sensitivity provides insight into the relationship of model behaviour to individual parameters. Applying this method to each period of building construction offered a simple approach to understand the causes for variation in thermal loads of a ND building stock.

Of the parameters identified as variable in the building stock (and likely to impact thermal loads) nine were investigated for sensitivity. These parameters were chosen for sensitivity analysis as are considered by continuous probability distributions within the modelling procedure. As they are not defined by discrete values that could be used to categorise model results, it is important to understand the models sensitivity.

Air Infiltration Sensitivity

Chapter 5 demonstrated a large uncertainty in associating air infiltration to buildings without detailed air leakage tests. Based on component leakage tests and the associated uncertainty in those tests a stochastic model was developed for prediction of air leakage rates. Figure 7.3 shows the heating and cooling load sensitivity for each building period's base case building to air infiltration.

For the heating loads, the latter two periods (1996-2001, 2002-2008+) show a much greater sensitivity than earlier construction periods. This is something that has been recognised with the introduction of regulations on building air leakage rates [166]; buildings with relatively low component U-value and less thermal mass are less affected by external conditions and the impact of thermal storage, so increasing sensitivity to air infiltration.

An inverse sensitivity is found for cooling rate, where increased air leakage has a beneficial impact on reducing cooling base loads. The sensitivity is still greatest for the period 2002-2008+, but the variation in sensitivity between this and earlier building periods is much less than the heating sensitivity.

Floor Footprint Sensitivity

Considering base thermal loads as normalised by unit floor area the sensitivity of these loads to varying footprint area (as seen in figure 7.4) can be explained by surface area to volume ratios. Increasing the footprint area increases the volume:surface area ratio, reducing the impact of external conditions on thermal loads. The ratio has a logarithmic growth against increasing footprint area, suggesting the sensitivity of thermal load diminishes for larger footprint areas. The non-linear sensitivity is evident in the results (figure 7.4).

Increased footprint reduces the normalised (kWh/m^2/year) heating load of the base case buildings. The latter control periods are less sensitive to footprint area for heating loads than earlier control periods.

Buildings built prior to the 1966 regulations have external walls with greater thermal mass than those post 1966. Whilst having a negative impact on heating loads, they offer a passive measure for controlling cooling loads. The sensitivity tests showed an increasing cooling requirement with increased floor footprint area for these earlier periods. As the footprint area increases the thermal mass to volume ratio reduces, so decreasing the influence of thermal mass on thermal control.

Post-1965 the cooling sensitivity is reversed, increasing footprint area reduces cooling loads. As with heating, the impact of external factors (external air temperature, solar loading) reduces as surface area to volume reduces. The thermal mass of buildings post-1965 is also reduced.

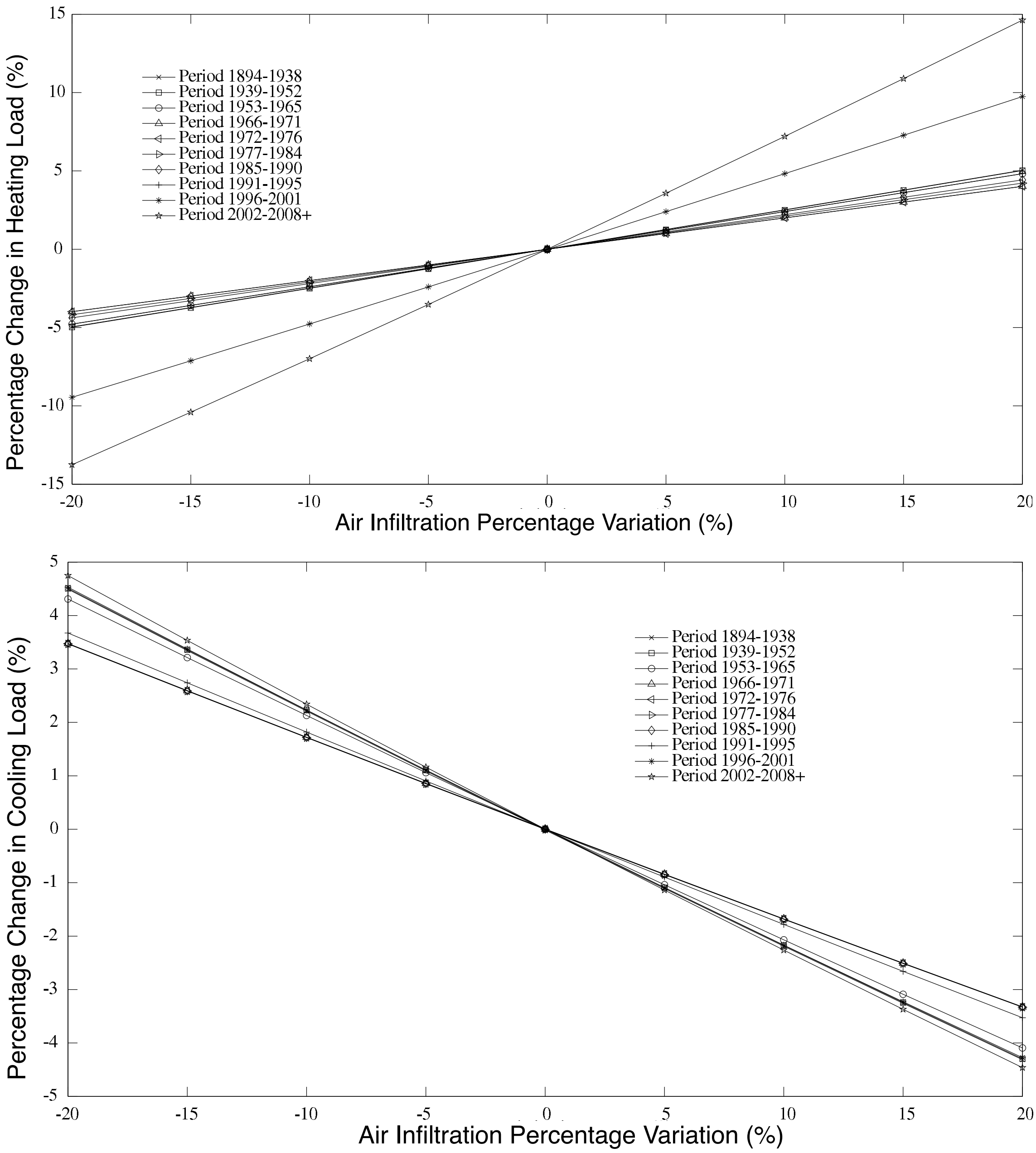


Figure 7.3: Air Infiltration - Heating and Cooling Base Thermal Load Sensitivity.

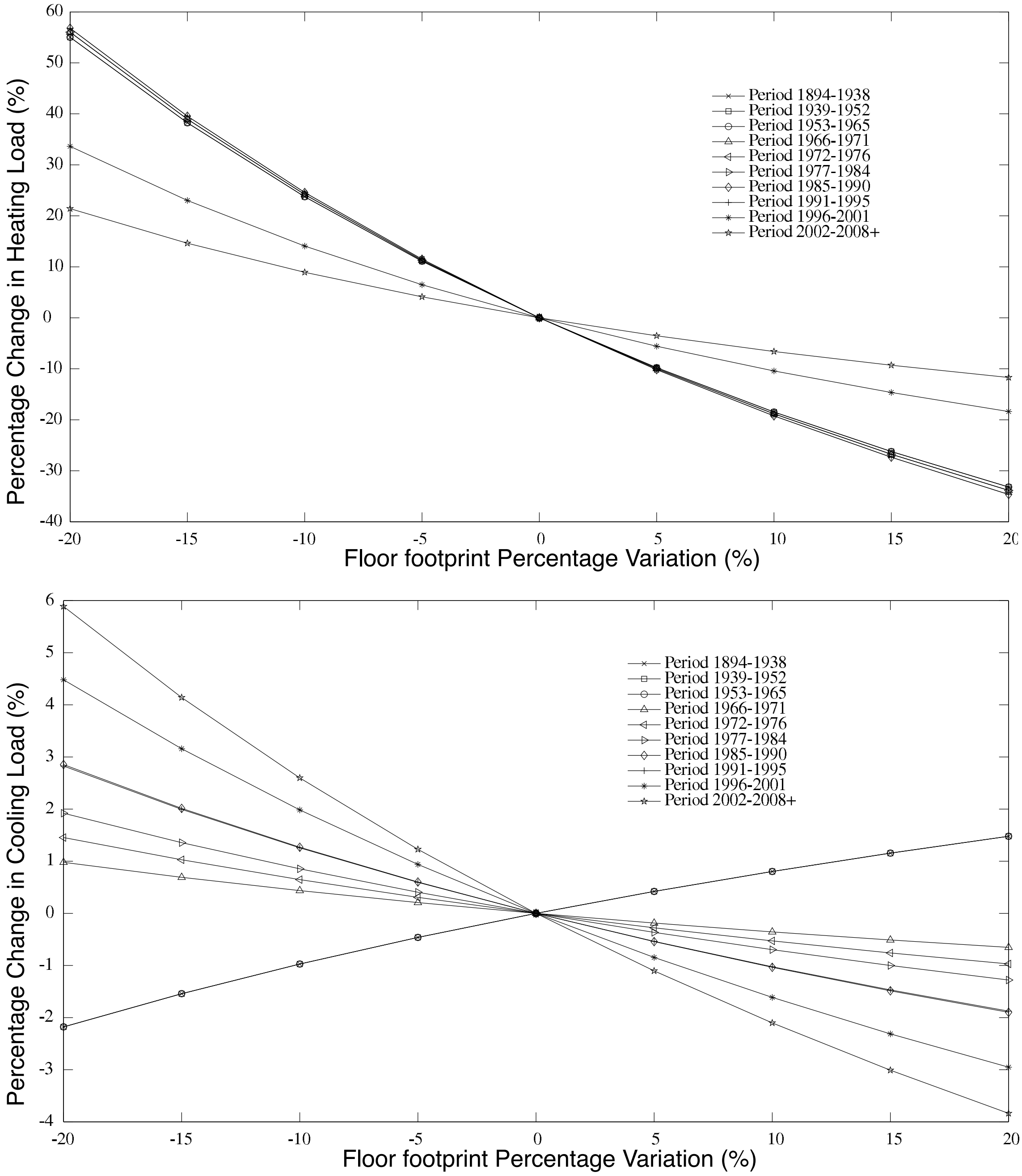


Figure 7.4: Floor Footprint - Heating and Cooling Base Thermal Load Sensitivity.

Wall Thickness Sensitivity

The sensitivity to wall thickness is dependent on the material of varying thickness and its location within a multilayered wall construction. The thickness of any insulating layer is dependent on the period of construction in which the building was built (especially post-1976) and so this sensitivity is not considered here. Depending on load factors the thickness of the structurally supportive element of walls can vary from building to building.

Two measures explaining the impact of wall thickness on heating and cooling loads are the wall heat transfer coefficient (U-value) and the admittance value (Y-value). As discussed in chapter 4 it is a combination of both factors that determine how the wall behaves, thermally, under dynamic consideration.

Generally for increasing wall thickness:

> U-value decreases, making the internal environment more sensitive to internal and solar gains
>
> Y-value increases, making the internal environment less sensitive to internal and solar gains.

For cavity walling the internal and external wall thickness have different impacts on these thermal control factors. Chapter 4 (in tables 4.2 - 4.4) showed that U-value is more sensitive to external wall thickness than Y-value. Increased internal wall thickness will, however, be influential to both thermal properties. An account of sensitivity for both internal and external wall thickness is given below.

<u>Outer Wall Thickness Sensitivity</u>

Earlier control periods displayed greatest sensitivity to outer wall thickness (figure 7.5 on page 129) as are more dependent on wall thickness influencing U-value than latter periods[1]. Reduced heating loads and increased cooling loads result from increased outer wall thickness for all construction periods. Heating loads are more sensitive to outer wall thickness than cooling loads.

As stated above, increasing outer wall thickness reduces U-value whilst Y-value can be said to stay relatively constant. This explains the reduced heating load with increased external wall thickness.

By increasing U-value with a fairly consistent admittance value, the internal building becomes more sensitive to internal and solar gains, explaining the increased cooling load with increased external wall thickness.

<u>Inner Wall Thickness Sensitivity</u>

Heating loads are seen to be more sensitive to inner wall thickness than cooling loads (figure 7.6, page 130). The heating loads showed a similar sensitivity to inner wall thickness as with outer wall thickness. This suggests the reduced U-value to be more influential to heating loads than the increased Y-value with increased inner wall thickness.

The cooling loads display little sensitivity to inner wall thickness for all periods of building control (in the case of brick-cavity-block wall construction of each construction period). Inter-period comparison of the cooling sensitivity to inner wall thickness, shows inconsistent sensitivities (figure 7.6, page 130). A wider range in percentage variation of base case value was considered to better understand this variable sensitivity. The cooling load sensitivity is, therefore, shown over a range of ±50%.

Figure 7.6 displays three basic sensitivity behaviours:

[1] As latter periods have insulation layers that most significantly determine U-value.

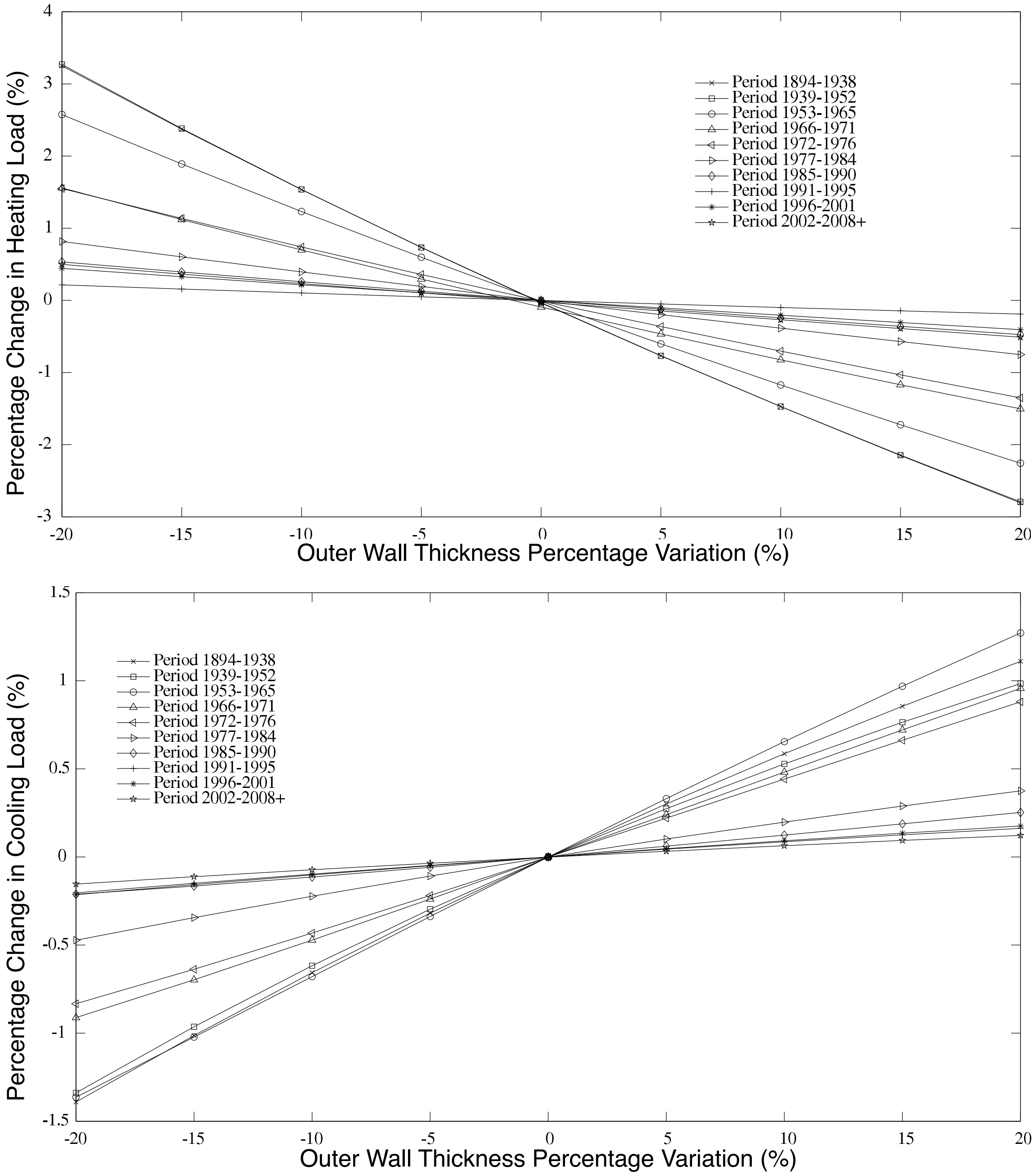
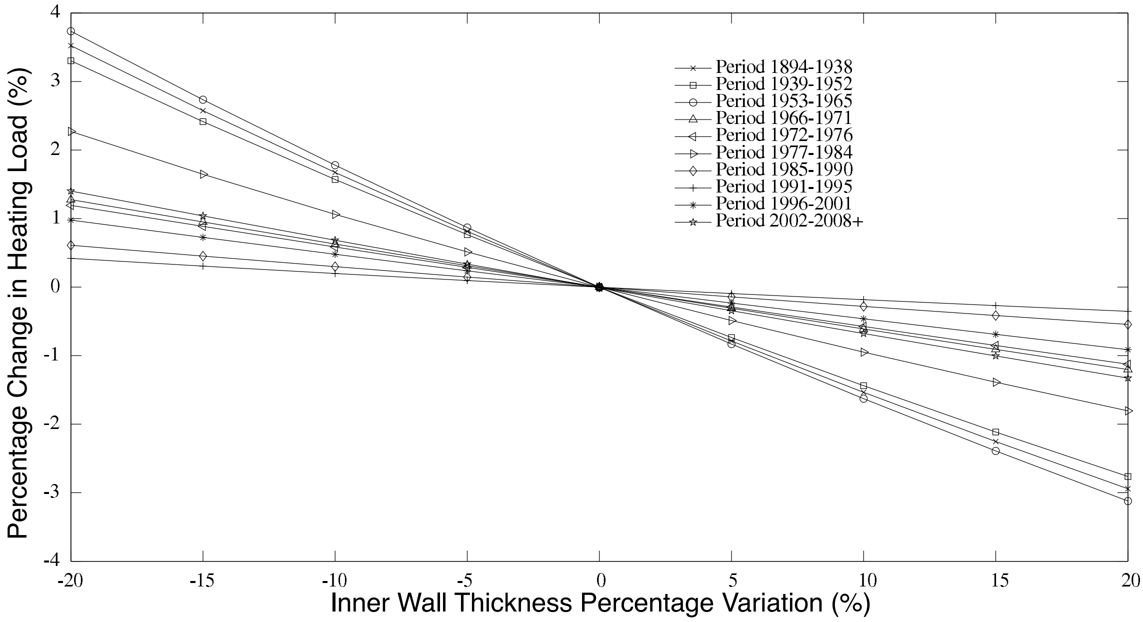


Figure 7.5: Outer Wall Thickness - Heating and Cooling Base Thermal Load Sensitivity.



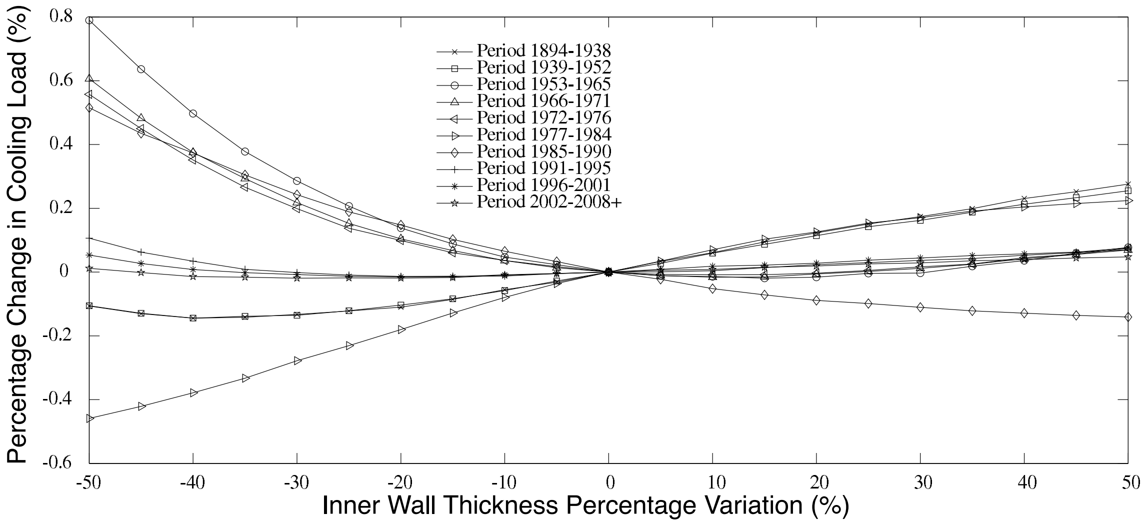


Figure 7.6: Inner Wall Thickness - Heating and Cooling Base Thermal Load Sensitivity.

1. A continually decreasing cooling load to increasing wall thickness
2. A continually increasing cooling load to increasing wall thickness
3. An initial reduced cooling load with increased thickness, followed by increasing cooling load

To explain the different observed sensitivities, both Y-values and U-values were studied in relation to inner wall thickness.

Using the Admittance calculation procedure (described in appendix A), the admittance can be shown to increase with increasing wall thickness to a maximum, before reducing to a steady-state at higher wall thickness (see figure 7.7). This behaviour is also recognised in [131].

U-value, decreases with increasing wall thickness by some exponential decay as demonstrated by figure 7.8.

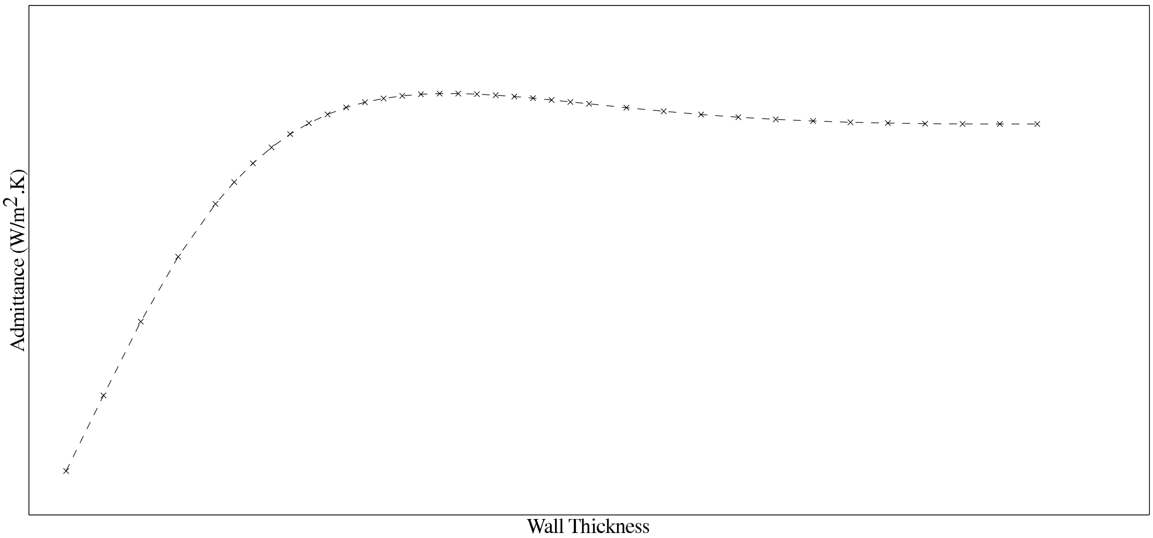


Figure 7.7: Admittance variation with inner wall thickness.

The cooling load sensitivity depends on the sensitivity of Y-value and U-value over the range of inner wall thickness considered in each construction period's sensitivity test. Figure 7.9 shows the varying sensitivities according to building control periods for both U-value and Y-value.

The first of the three sensitivity behaviours, listed above, Y-value dominates as the most sensitive property so as inner wall thickness increases, cooling load decreases. This applied to period (1985-1990).

The opposite behaviour (increased wall thickness - increased cooling load) results from U-value dominating. For the periods 1894-1938, 1938-1952 and 1977-1984, the inner wall is thick so Y-value is relatively stable.

The behaviour of reduced cooling followed by increased cooling load with increasing wall thickness, is consistent with the Y-value behaviour (figure 7.7). As Y-value reaches a maximum (near the periods' typical inner wall thickness) the cooling reaches a minimum before increasing as Y-value reduces with further increased thickness. This behaviour (seen in periods 1953 through to 1976 and 1990 onwards) implies Y-value dominates cooling load sensitivity to inner wall thickness.

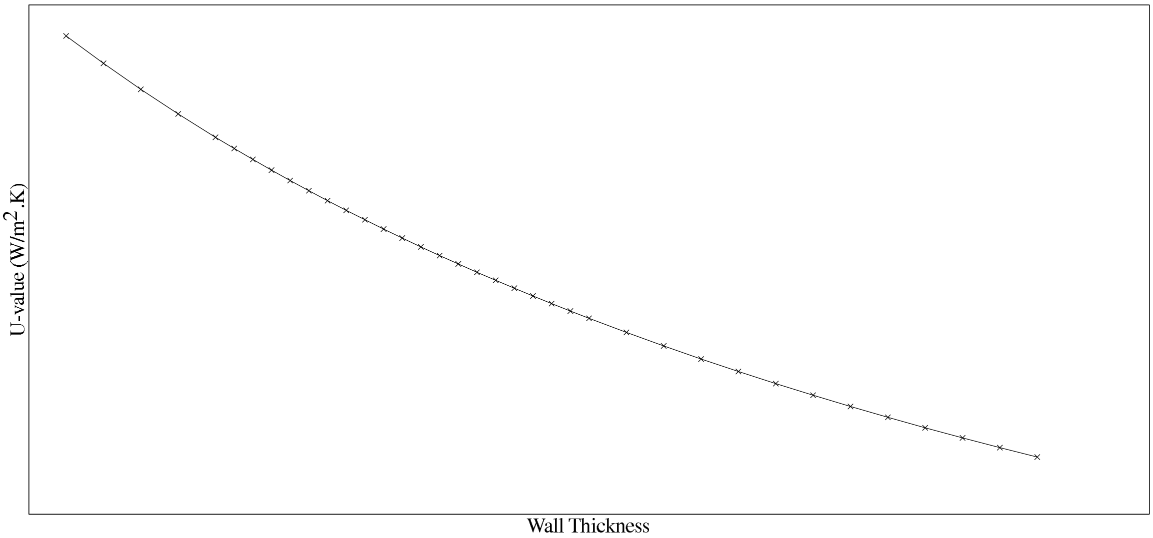


Figure 7.8: Thermal transmittance variation with inner wall thickness.

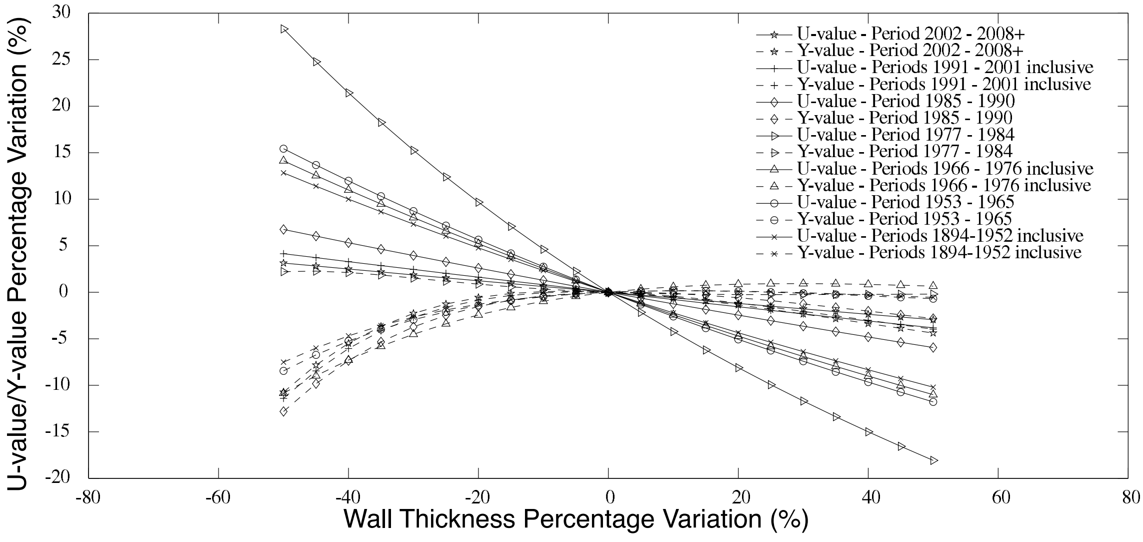


Figure 7.9: Thermal transmittance and Admittance Sensitivity to inner wall thickness.

Storey Height Sensitivity

The increase in storey height increases internal volume without increasing internal gains, so increasing heating requirements (figure 7.10, on page 134). The heating loads of base case buildings of latter control periods are more sensitive than earlier building periods as are more sensitive to internal gains from reduced thermal mass.

Except for the first three control periods, cooling loads increase with increasing storey height. Increased storey height results in larger window areas to floor area as the window-wall ratio was kept constant. Increased window area increases solar loading potential in the cooling season. For the earlier periods (with inverse sensitivity) smaller window-wall ratios mean window area is not as greatly increased by increased storey height and therefore solar gain is not as influential. In these circumstances the increased thermal mass and reduced internal gains per unit volume of space cause cooling load to reduce with increased storey height.

The latter control periods show greater sensitivity to increased storey height, as have greater sensitivity to internal gains and solar loading (lower U-value and lower Y-value).

Window Wall Ratio Sensitivity

Increasing the window-wall ratio, increases both cooling and heating loads (figure 7.11). The window has a lower U-value so increasing thermal transmittance whilst also increasing the level of solar loading (of greater significance during the cooling season).

The thermal loads of the latter building control periods are most sensitive to window-wall-ratio.

Roof Pitch Sensitivity

The dynamic simulation building models displayed little sensitivity to roof pitch (figure 7.12), as discussed in chapter 4.

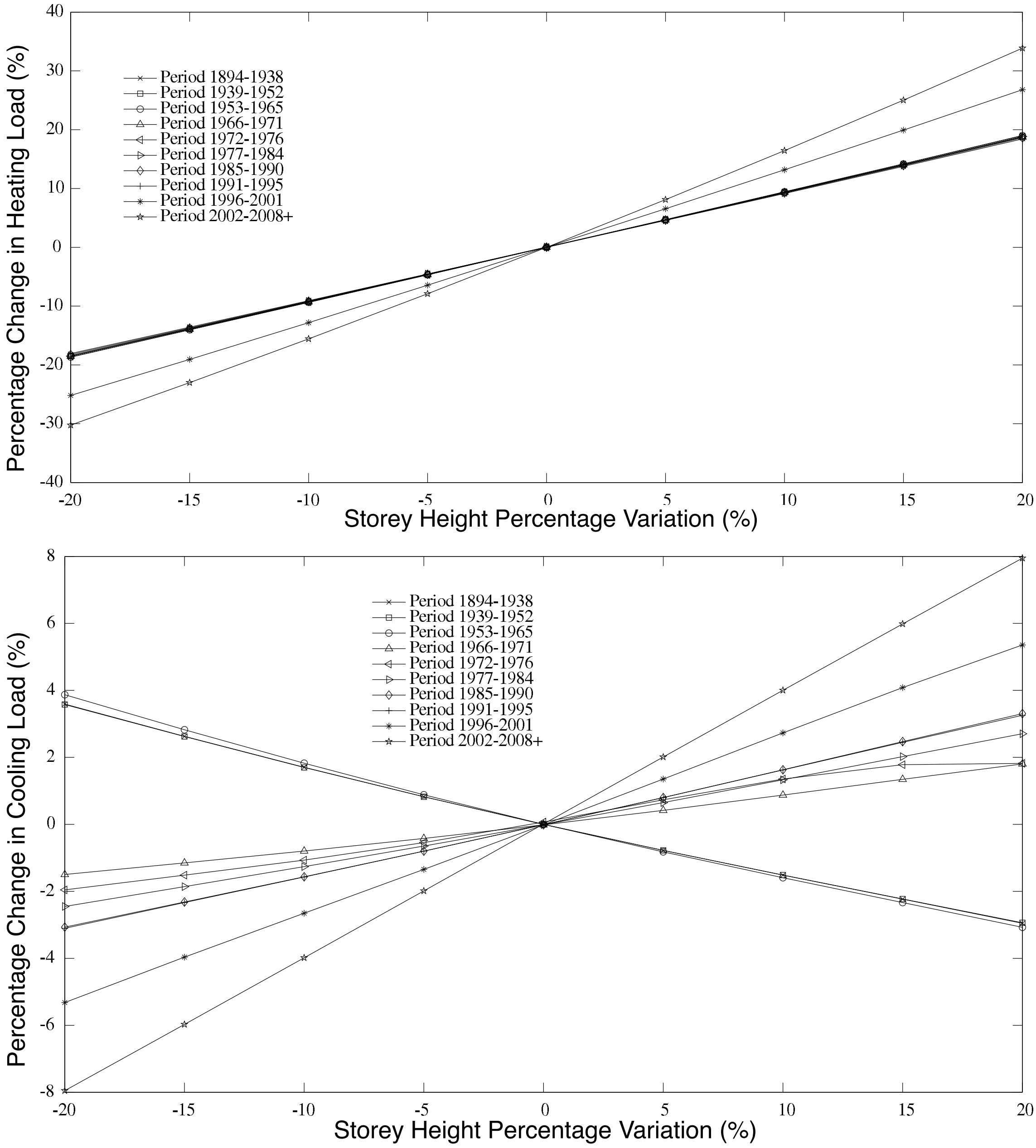


Figure 7.10: Storey Height - Heating and Cooling Base Thermal Load Sensitivity.

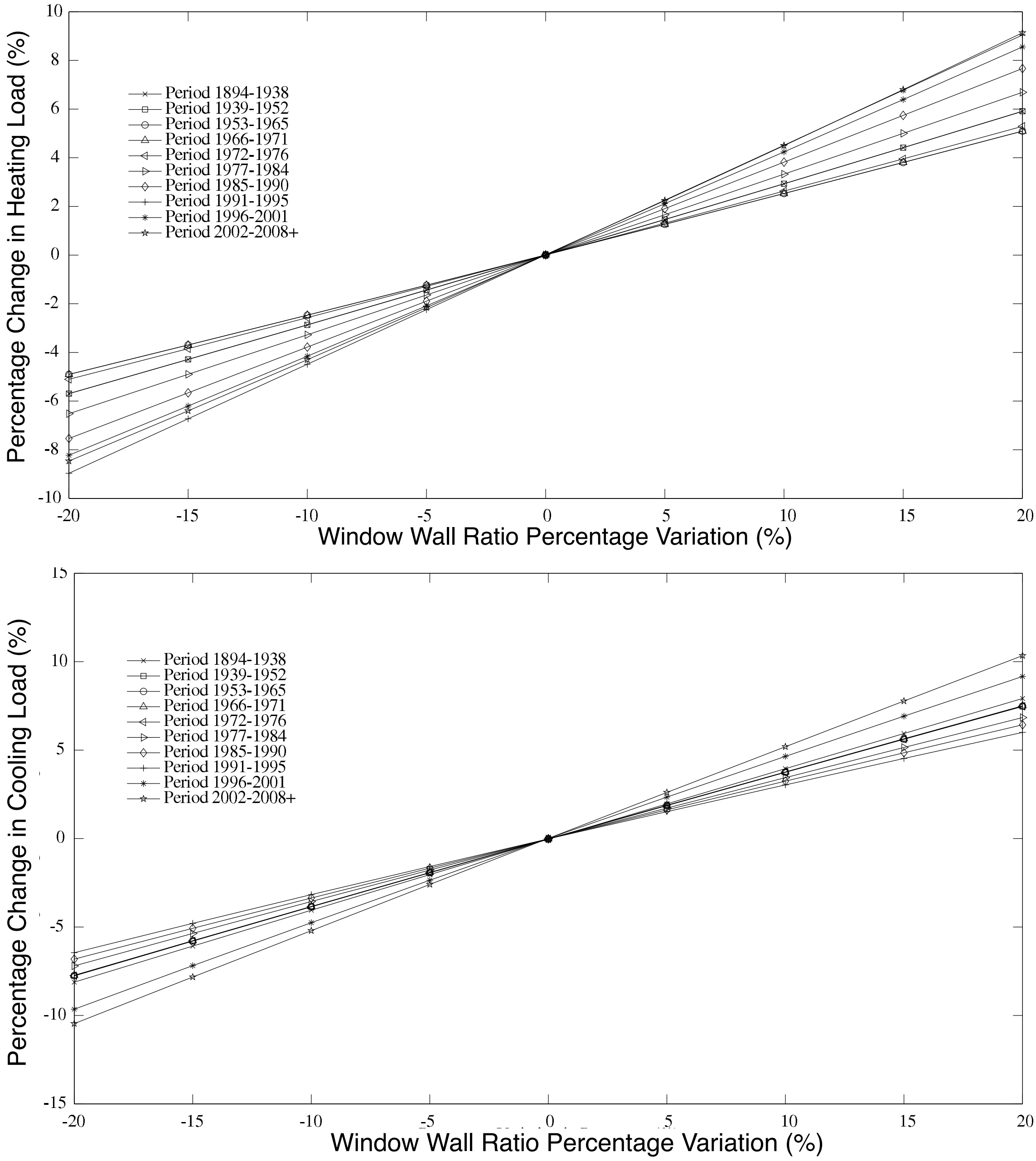


Figure 7.11: WWR - Heating and Cooling Base Thermal Load Sensitivity.

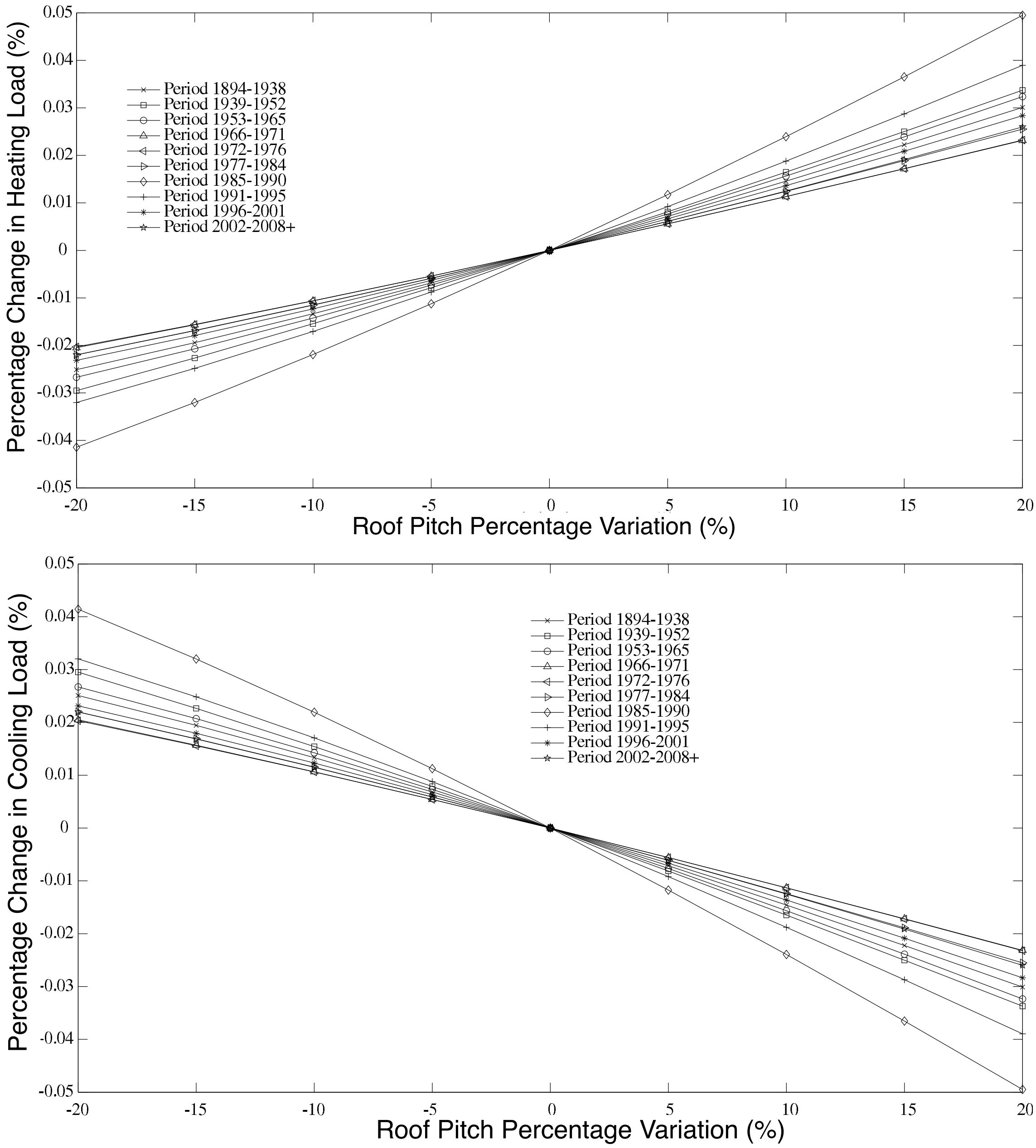


Figure 7.12: Roof Pitch - Heating/Cooling Sensitivity.

Built Environment Sensitivity

Surrounding structures, vegetation and land topography impact thermal loads by influencing longwave radiant heat exchange with the sky and causing solar shading. In the Dynamic Simulation Model used (ESP-r) each factor can be considered separately, though in reality some link between sky view and solar shading exists (as accounted for in the Monte Carlo modelling process). Sensitivity of sky view and elevation angle of sky (and therefore solar) obstruction were considered individually.

In both figure 7.13 and figure 7.14 the non-linear sensitivities are not fully captured by the limited number of tests.

Sky View Factor Sensitivity

The sky view factor (S_ν) was in all cases set to 0.3 to start, as a close approximation of the most probable S_ν according to the theoretical assessment carried out in chapter 6. Each model was considered in isolation, i.e. with no solar obstruction.

Increasing S_ν increased heating loads and reduced cooling loads due to increased night-time radiant losses (figure 7.13). More recent building periods showed less sensitivity to S_ν as increased insulation reduces the external surfaces thermal connection with the internal environment. The thermal sensitivity of the model representing the 2002-2008+ construction period is notably less than all other periods.

Obstruction Elevation Angle Sensitivity

The model relates solar obstructing objects for each face of the building with S_ν by assuming a street canyon to all exposed walls of the model building (see chapter 6). With elevation angle representing a S_ν of 0.3 for the base case, the elevation angle was varied over the entire physically feasible range (0 to 90).

Increased elevation angle reduces solar load, increasing heating requirements and reducing cooling requirements (figure 7.14). Greatest sensitivity occurs in the low-to-mid range of elevation angle (below the base case value). The base case models of the latter control periods show greater sensitivity to obstructing elevation angle and therefore solar loading.

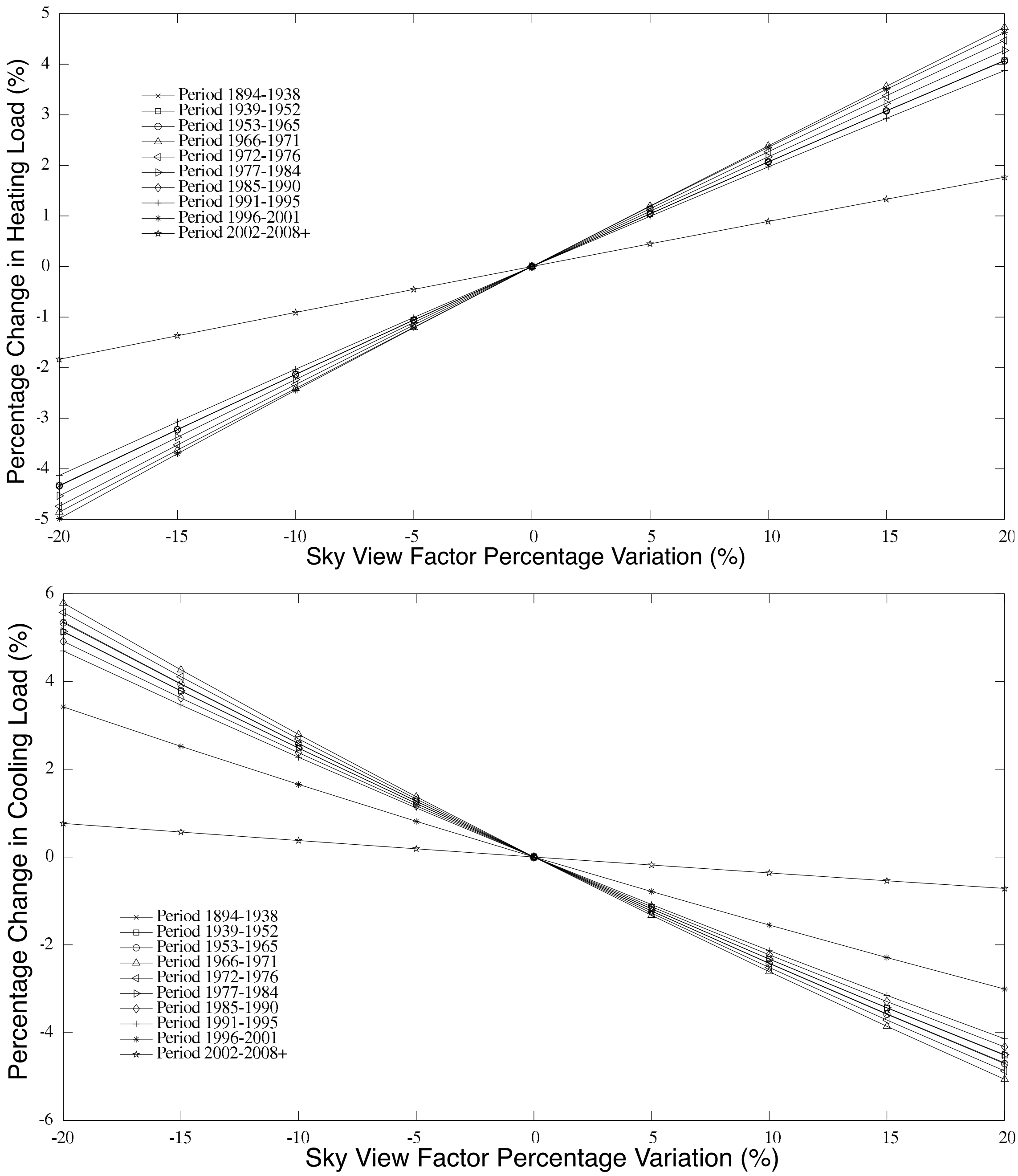


Figure 7.13: S_{ν} - Heating and Cooling Base Thermal Load Sensitivity.

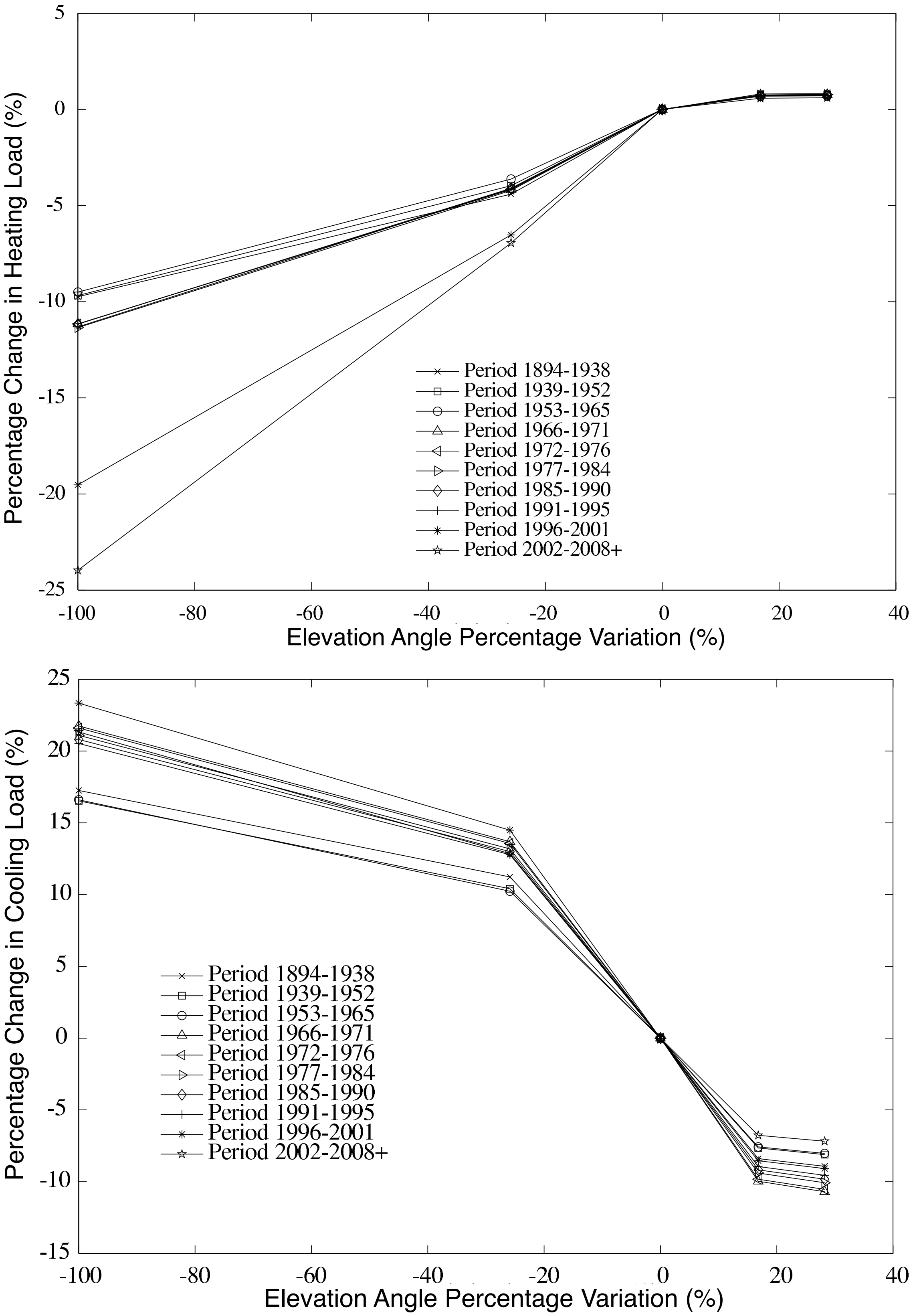


Figure 7.14: Obstruction Elevation Angle Heating and Cooling Base Thermal Load Sensitivity.

Orientation

Orientation influences solar loading patterns [167, 168] of a building. The total potential variation in orientation was considered to be ±180° from the original orientation (representing a ±100% variation for the sensitivity tests).

The period typical models used for sensitivity testing have a symmetrical, square structure that limits the range under which the building is likely to be sensitive to orientation. This limited the required sensitivity range to ±25% (i.e. ±45). The base case is aligned along the North-South axis.

Figure 7.15 shows the sensitivity of thermal loads to orientation. The sensitivity shows heating loads are reduced and cooling loads increased with varying orientation from the North-South axis. This suggests increased solar loading by varying orientation, even in a uniform, symmetrical square building. The thermal load sensitivity to orientation, however, is small relative to other considered parameters.

Earlier control periods are less sensitive than latter control periods.

7.3.2 One-at-time Uncertainty

In addition to the parameters considered for one-at-a-time sensitivity, there are other uncertain building characteristics that need to be considered for their impact on base thermal loads. These are discrete values that could provide further simple building categorisation in predicting probable thermal loads (see chapter 8). Seven different parameters were identified for analysis as:

i. Internal Layout

ii. Number of Storeys

iii. Length-Width Ratio

iv. Wall Construction

v. Floor Construction

vi. Location - Climate

vii. Location - Latitude

Internal Layout is a highly variable factor, when considering a building stock, that affects building air flow, solar distribution, internal gain distributions and increases internal thermal mass. All these factors influence the thermal performance of a building. For this study internal layout has been simplified into two forms: open plan and cellular.

The open plan form considers no sub-zoning of the building. The cellular layout provides a simplified account of the influence of internal walls, splitting each storey into four equally sized zones. Though not capturing the variable internal layout of a building stock, it accounts for increased thermal mass and varied solar distribution. No consideration of inter-zone airflow networks was given.

Table 7.3 below, shows the period typical model results for both open plan and cellular internal layout. The internal layout shows the same influence to base heating and cooling loads for all construction

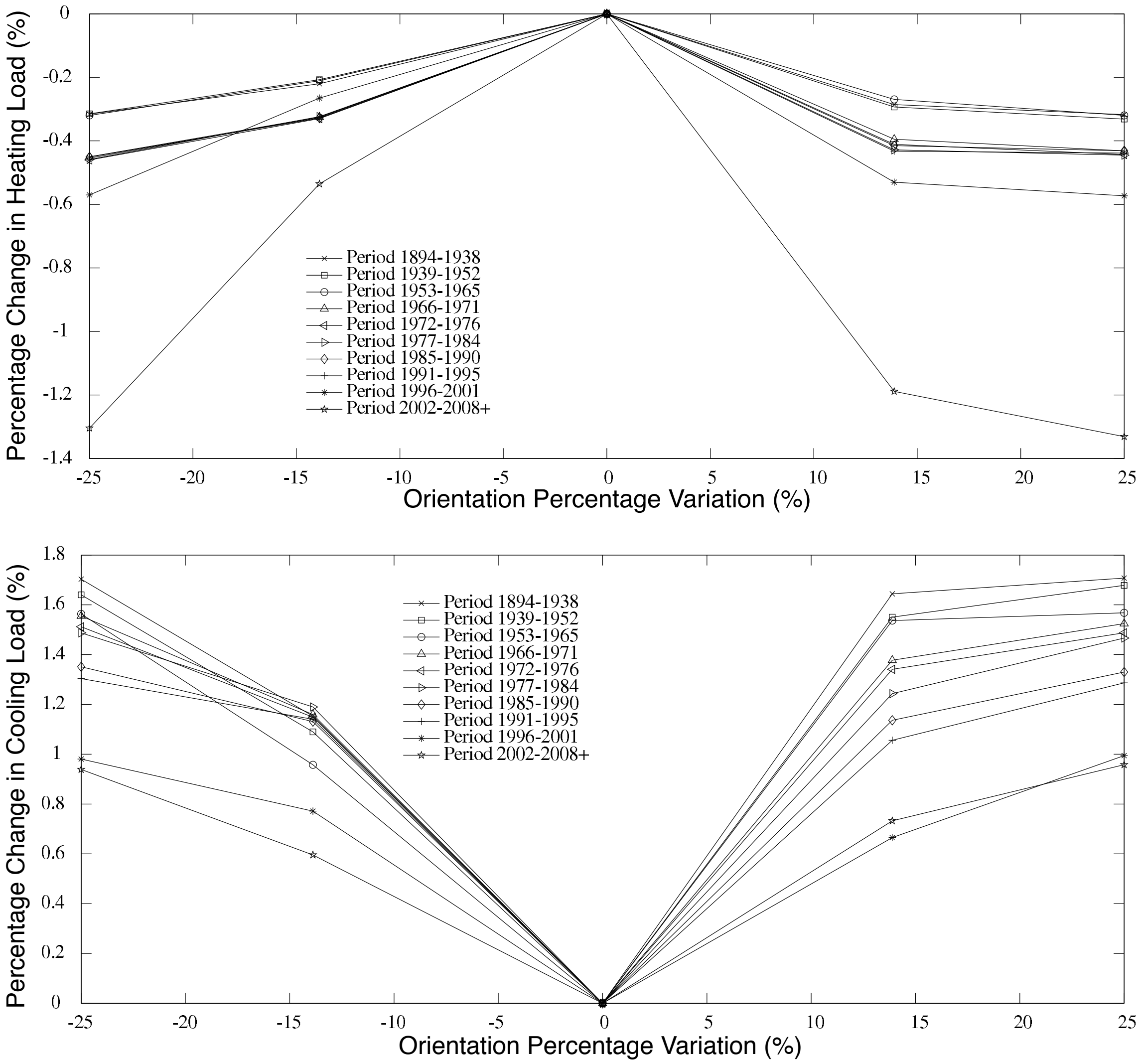


Figure 7.15: Orientation Heating and Cooling Base Thermal Load Sensitivity.

Table 7.3: Base Case Unit Thermal Loads for identified Periods of Building Control.

Base Case (kWh/m^2/year)	Control Period									
	1915-1938	1939-1952	1953-1965	1966-1971	1972-1976	1977-1984	1985-1990	1991-1995	1996-2001	2002-2008
Cellular Heating	79.7	74.03	75.55	84.36	83.21	76.86	73.58	68.64	28.83	10.69
Cellular Cooling	20.78	21.01	20.52	30.61	31.09	32.26	33.28	34.12	55.49	77.37
Open Plan Heating	67.35	62.58	64.2	74.77	73.71	67.67	64.97	60.22	22.14	7.45
Open Plan Cooling	28.28	28.67	28.11	36.51	37.24	38.6	39.86	40.67	64.96	92.22

periods. Heating load is higher for the cellular (more thermally massive) form but cooling load is less, compared to the open plan form.

For the remaining considered structural uncertainties of number of storeys, length-width ratio, wall and floor construction the influence on thermal performance varied according to period of construction. Appendix E provides a summary of these uncertainties, showing greatest uncertainty associated with number of storeys.

Location is also important in thermal loading, particularly with reference to the weather file used in modelling.

7.4 Modelled Probability Distribution of Base Thermal Loads

The parameter setting model (figure 7.1) randomly sets building attributes that are applied to a basic building model for thermal energy simulation. Ranges in attribute values (and probability distributions of these values within the ND building stock of England and Wales) have been identified from existing survey data and analysis of building control laws and regulations.

Associating probability of occurrence to the identified ranges in attribute values, and applying Monte Carlo modelling a probability distribution in base thermal loads was associated to ND office buildings (categorised by construction period).

The Monte Carlo method applies stochastic attribute setting. Based on the distributions identified for the considered building attributes, each attribute is pseudo-randomly set before carrying out a computer simulation. Figure 7.16 provides a schematic description of the Monte Carlo process.

Multiple simulations were carried out and the results collated to determine the range and probability distribution in base thermal loads for the ND building stock. The total number of combinations of parameter inputs is an exponential relationship to the number of variable parameters. By the Central Limit Theorem, the Monte Carlo method in energy simulation does not need to exhaust all possible combinations, as demonstrated by MacDonald [83].

7.4.1 Number of Required Runs

Furbringer et al. [169], showed for MCA only 60 to 80 simulations are necessary to obtain reasonable accuracy in the confidence interval associated with the distribution in results. This was also observed in MacDonald's research of uncertainty analysis in building energy modelling [83]. These applied the central limit theorem where equivalent distributions are applied to the input parameters and a normal distribution of the results occurs.

An investigation of the number of simulations to show convergence in the distribution of results by Monte Carlo simulation was carried out. Figures 7.17 and 7.18 show example plots of the distribution mean and dispersion for heating and cooling loads, respectively. The convergence plots shown are taken from Monte Carlo simulation for the building construction period (1894-1938) with only open-plan internal layout considered. In this instance the mean base heating load fluctuates within ±2 kWh/m^2/year of 70 kWh/m^2/year after approximately 200 simulations. After 200 simulation runs the mean base cooling load fluctuates within ±1 kWh/m^2/year of 43 kWh/m^2/year.

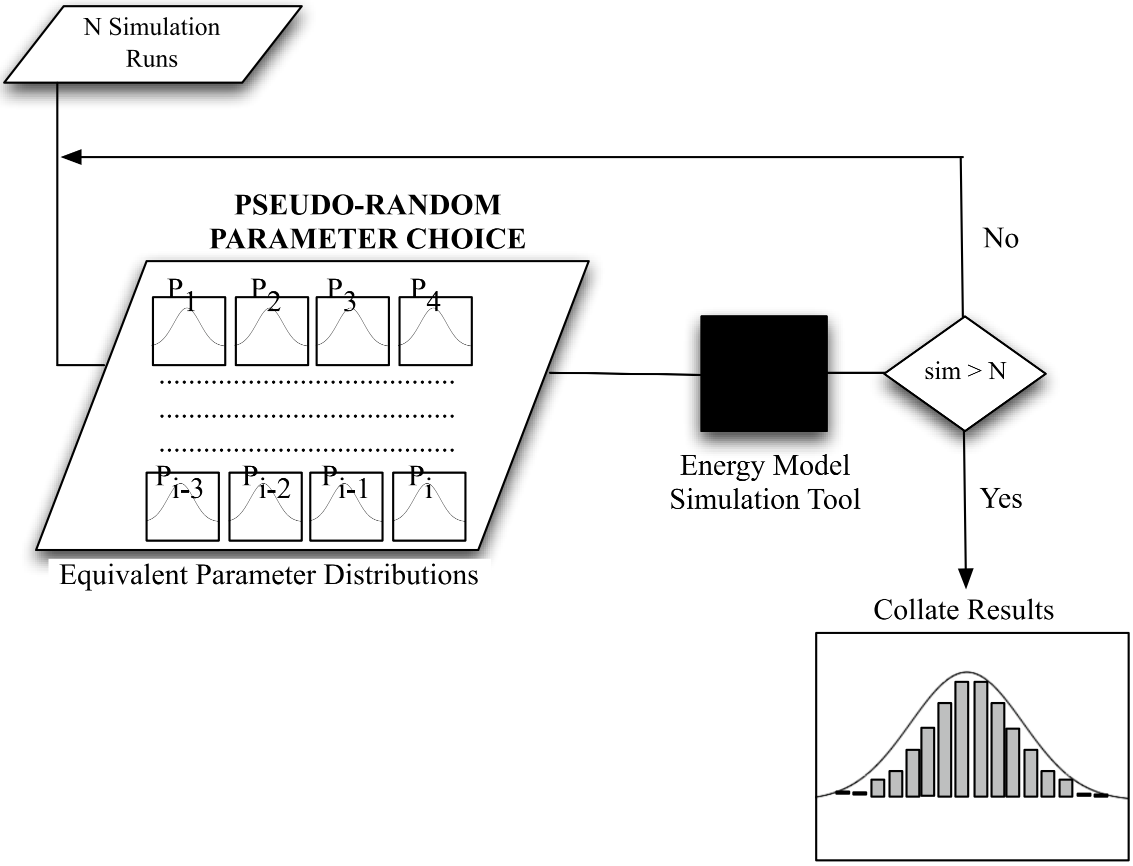


Figure 7.16: Schematic Representation of Monte Carlo Modelling Process.

Figures 7.17 and 7.18 also show the behaviour of dispersion in the modelled distributions of thermal load (measured as iqr). Beyond 300 simulation runs the variation in iqr stays within ±1% of the mean thermal load value. The iqr provides a measure that is less sensitive to outliers than a measure of σ, and makes no assumption of the distribution type.

The patterns of convergence in distribution demonstrated in figures 7.17 and 7.18 were present in all identified control periods. For the purpose of data analysis adequate convergence in the modelled distributions was considered to occur at 300 simulation runs.

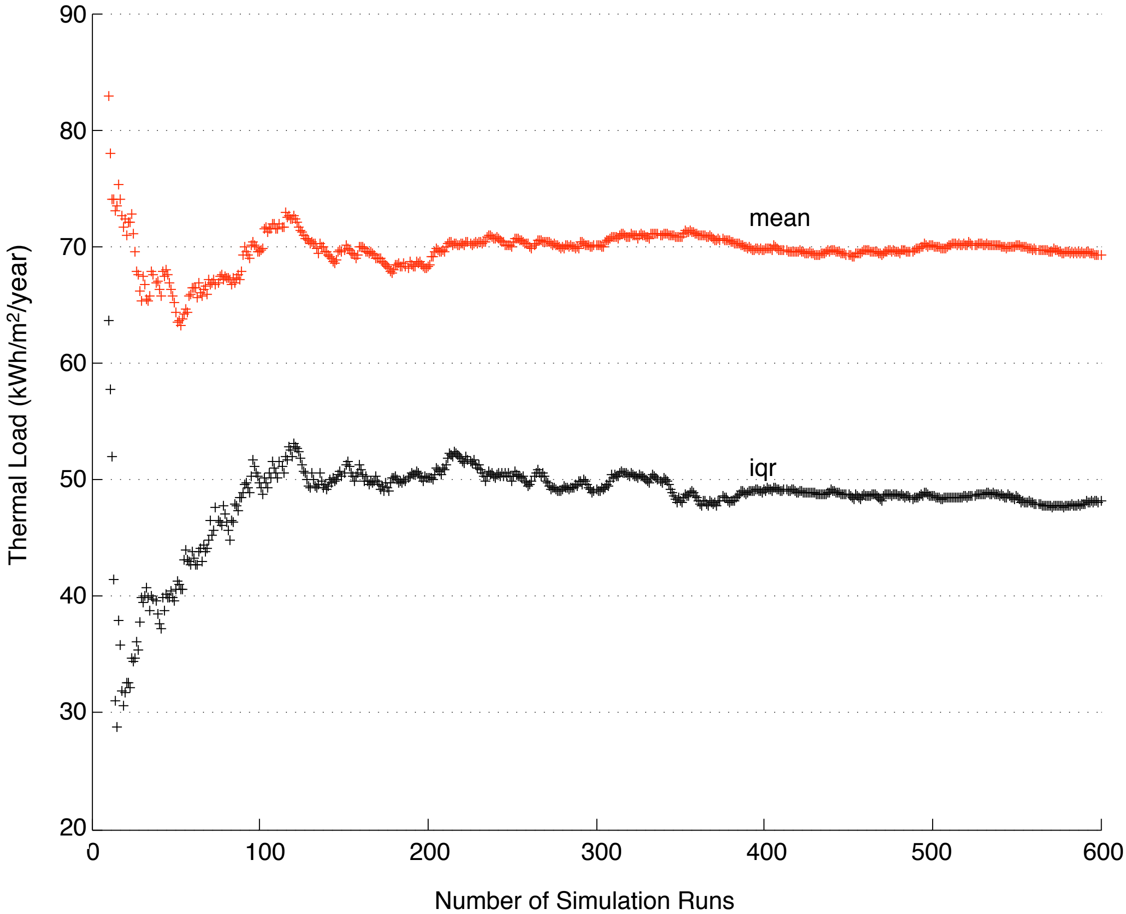


Figure 7.17: Convergence of mean base heating load and inter-quartile range in Monte Carlo simulation - Construction Period 1894-1938.

7.4.2 Base Level Thermal Distribution

Probability distributions associated with building characteristics within the ND building stock have been associated with periods of building control. Using the Monte Carlo method a probable distribution of base level thermal loads for each identified period of building control was calculated.

The base case models were shown to be sensitive to internal layout. No distribution was determined for internal and open plan internal layout within the considered ND building stock. MCA was therefore run separately for open plan and cellular building models.

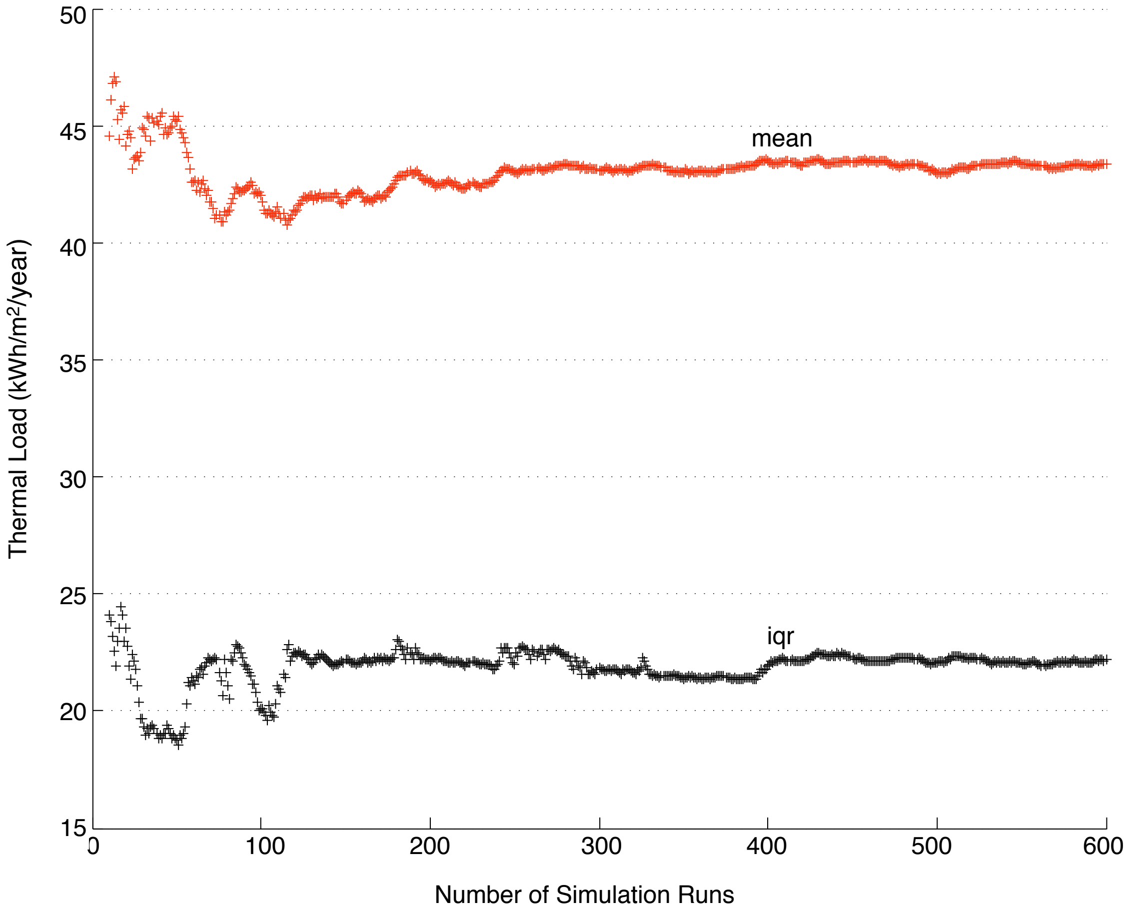


Figure 7.18: Convergence of mean base cooling load and inter-quartile range in Monte Carlo simulation - Construction Period 1894-1938.

The model results displayed asymmetry in the thermal load distributions. A tendency towards right-skewed distributions was noted, where the right-hand tail is stretched (see figure 7.19). The asymmetry in the distribution results in the mean, median and mode being different.

Tables 7.4 and 7.5 show the distribution results for each considered building period for open plan and cellular internal layouts, respectively. The cellular forms result in an increase in the average heating loads, whilst reducing the cooling loads. The impact is typically greater on the heating loads than cooling loads, though the level of change varies according to building period.

Table 7.4: Open Plan - Base Thermal Load Probability Distribution Results.

Period of Construction	Heating Load (kWh/m²/year)					Cooling Load (kWh/m²/year)				
	Mean	Median	Mode Range	Standard Deviation	Inter-Quartile Range	Mean	Median	Mode Range	Standard Deviation	Inter-Quartile Range
1894-1938	68.3	58	24.9 - 49.8	41.1	49.7	42.6	44.4	45.2 - 50.3	17.2	22.1
1939-1952	71.2	58.6	45.7 - 57.2	41.8	50	44.4	44.8	32.3 - 36.4	15.4	21.9
1953-1965	68.3	59.9	30.2 - 40.3	40	45.4	43.1	44.9	44.6 - 50.2	17.7	23.1
1966-1971	71.7	56.1	52.8 - 63.4	42.9	45.8	41.5	42.4	47.5 - 52.2	15.6	20.8
1972-1976	70.3	55.3	41.1 - 51.4	42	44.7	42.6	43.7	49.5 - 54.5	16	20.8
1977-1984	62	49.9	41.3 - 51.7	38.6	46.7	45.6	45.4	37.5 - 42.9	17.7	24
1985-1990	49.1	40.5	18.8 - 28.2	32.5	44.4	60.6	60	55.6 - 63.5	26.1	34.5
1991-1995	46.9	38.2	17.4 - 26.2	31.4	43.2	61	60.8	61.5 - 70.3	27.1	36.4
1996-2001	31.1	23.2	18.3 - 24.3	23.8	26.3	65.6	67.2	76.7 - 85.2	26.6	34.8
2002-2008	18.2	12.7	4.1 - 8.3	16	18.3	75.6	81.5	83.2 - 90.8	27.9	35

Table 7.5: Cellular - Base Thermal Load Probability Distribution Results.

Period of Construction	Heating Load (kWh/m²/year)					Cooling Load (kWh/m²/year)				
	Mean	Median	Mode Range	Standard Deviation	Inter-Quartile Range	Mean	Median	Mode Range	Standard Deviation	Inter-Quartile Range
1894-1938	146.3	118.6	66.1 - 99.1	97	122.2	31.6	29.9	26.7 - 32.0	16.8	22.9
1939-1952	175.6	142.7	47.2 - 94.3	134.1	134.9	26.4	22.7	14.3 - 19.0	16.4	23.5
1953-1965	142.4	119	66.5 - 92.4	95.5	118.3	32	30	26.3 - 31.4	16.9	22.9
1966-1971	226.7	173.8	86.1 - 130.1	171.9	206.9	19.2	16.8	11.5 - 15.2	13.2	19
1972-1976	231.3	176.1	90.4 - 135.6	173.6	207.9	19.7	16.6	11.9 - 15.8	13.9	18.8
1977-1984	209.7	156.7	83.1 - 124.6	161.1	198	18.4	13.5	5.0 - 10.0	15.4	19.7
1985-1990	209.7	156.7	83.1 - 124.6	161.1	198	24.9	17.7	7.9 - 15.8	23.1	26.3
1991-1995	209.7	156.7	83.1 - 124.6	161.1	198	25.6	21.4	6.1 - 12.2	21	25.3
1996-2001	160.8	111.3	74.2 - 111.3	145	150.5	26.5	19.2	6.4 - 19.3	22.3	26.7
2002-2008	31.1	21.3	6.8 - 20.5	26.3	29.5	60.1	62.8	61.6 - 68.4	26.5	37.1

Comparing the distribution data of the building construction periods, little variation is evident between the base thermal loads for the building periods between 1894 to 1965. For the two periods between 1966 to 1976, an increase in base heating load and reduction in base cooling load can be seen compared to the previous control periods. This variation is most significant in the cellular models.

From 1977 onward, the mean base heating loads reduce as the thermal regulations improve. The probable cooling loads, however, increase with each proceeding construction control period. The most significant reduction is between the last two control periods (1996-2001 and 2002-2008+), where mean heating load is almost halved for the open plan modelling and reduced to less than 20% of the previous period for the cellular modelling.

For the open plan models it can be stated that heating load reduction is expected from early to later construction periods. The reductions only become evident for post-1976 construction with highest mean

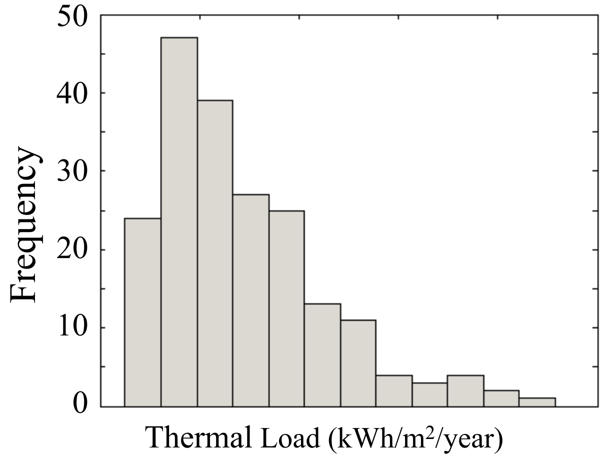


Figure 7.19: Typical Histogram of Construction Period Base Thermal Loads.

heating load occurring between 1966 and 1976.

The improved insulation of the building envelope for the latter control periods increases the sensitivity of the model to internal and solar loading. So, in the case of open plan layout, the latter control periods (post-1984) mean cooling loads increase.

Figures 7.20 and 7.21 provide a graphical representation of the modelled heating and cooling loads, respectively. The mean value in each construction periods modelled distribution is indicated by x for open plan and □ for cellular layout. The standard deviation is displayed, representing the variation associated with each period.

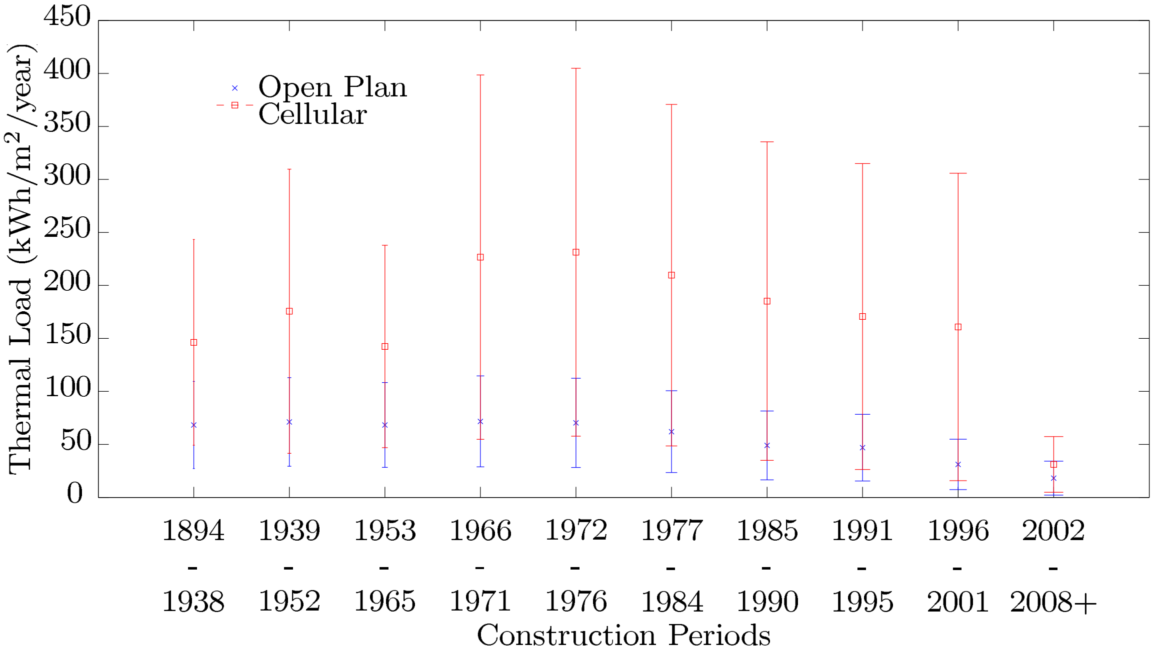


Figure 7.20: Base heating load distribution by Construction Period.

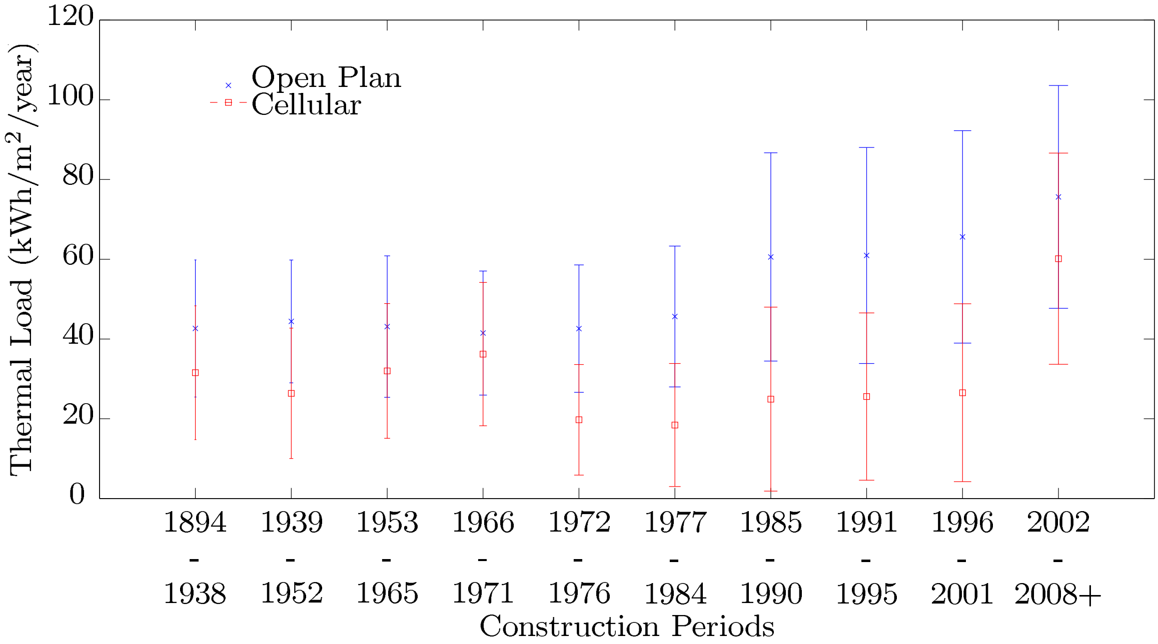


Figure 7.21: Base cooling load distribution by Construction Period.

7.4.3 Theoretical Distribution Description

The base thermal loads of a non specific building in a building stock are considered to be within a range from 0 to some arbitrary value - with a continuous PDF associated with the loads. The probability distribution is dependent on the probable distribution of the factors influencing thermal performance.

Using a Monte Carlo modelling method, the thermal load distribution of each considered construction period showed a tendency towards a right-skewed distribution. An attempt to associate theoretical distributions with the observed base thermal load distributions was carried out. This was done as an attempt to provide PDFs that could be applied more rapidly to assessing the probable thermal loads of a building stock, of mixed construction periods.

The Kolmogorov-Smirnov (KS) test was used to assess the relevance of typical right-skewed distributions as descriptions of the modelled probability distributions. The KS test provides a significance rating by measuring the maximum difference between the CDF of the theoretical and modelled distributions. The smaller the maximum difference is the more significant the theoretical distribution is as a description of the modelled distribution.

Figure 7.22 shows a comparison of a theoretical CDF plotted against that of a modelled distribution. For the KS test the frequency of the modelled distribution values is converted into a probability (total number of runs normalized to 1). The actual thermal load was also normalized according to the calculated standard deviation of the considered distribution.

Under the normalized conditions the modelled distributions of each construction period were tested for KS significance as a normal, weibull, gamma and log-normal distribution. The shape and scale parameters of each distribution were varied and the values recorded for the combination with the greatest significance (i.e. smallest maximum difference). Tables 7.6 and 7.7 show the most significant distributions for each construction period, with the given scale and shape factors of those distributions.

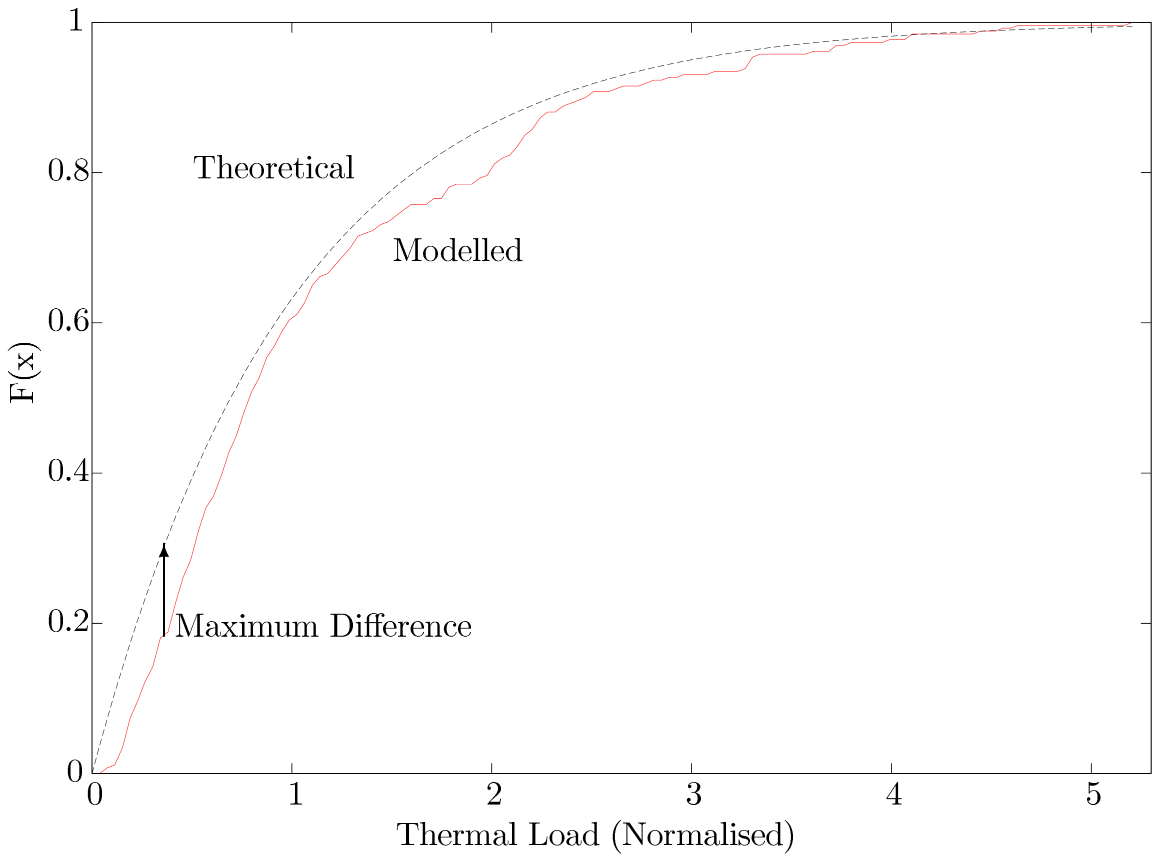


Figure 7.22: Theoretical distributions cumulative density function (CDF) and the modelled distributions CDF.

Table 7.6: Kolmogorov-Smirnov Test Results - most significant PDF by construction period (open plan).

Period of Construction	Heating Load (kWh/m²/year)				Cooling Load (kWh/m²/year)			
	Distribution	K-S Test Significance	Scale*	Shape*	Distribution	K-S Test Significance	Scale*	Shape*
1894-1938	Gamma	0.09	0.6	3	Gamma	0.12	0.3	8
1939-1952	Gamma	0.1	0.4	5	Weibull	0.08	3	3
1953-1965	Gamma - Log Normal	0.06 - 0.08	0.8 - 4.1	2 - 0.6	Gamma	0.1	0.4	6
1966-1971	Gamma	0.08	0.6	3	Weibull	0.08	3	3
1972-1976	Gamma	0.09	0.6	3	Gamma	0.09	0.4	6
1977-1984	Gamma	0.1	0.6	3	Gamma	0.07	0.4	6
1985-1990	Gamma	0.08	0.7	2	Weibull - Gamma	0.08 - 0.08	2.4 - 0.4	2 - 6
1991-1995	Weibull - Gamma	0.12 - 0.12	2.1 - 0.5	2 - 3	Gamma	0.1	0.6	3
1996-2001	Weibull - Gamma	0.1 - 0.09	1.1 - 0.7	1 - 2	Weibull - Gamma	0.1 - 0.1	2.4 - 0.4	2 - 6
2002-2008	Weibull - Gamma	0.06 - 0.06	1 - 1	1 - 1	Weibull	0.1	2.8	3

*These values result from the normalised thermal loads, using the distribution standard deviation = 1.
For normal and log normal distributions Scale is mean, Shape is standard deviation.

Table 7.7: Kolmogorov-Smirnov Test Results - most significant PDF by construction period (cellular).

Period of Construction	Heating Load (kWh/m²/year)				Cooling Load (kWh/m²/year)			
	Distribution	K-S Test Significance	Scale*	Shape*	Distribution	K-S Test Significance	Scale*	Shape*
1894-1938	Weibull - Gamma	0.15 - 0.15	1.1 - 1.1	1 - 1	Weibull - Gamma	0.13 - 0.11	2.4 - 0.5	2 - 4
1939-1952	Weibull - Gamma	0.12 - 0.12	1.2 - 1.2	1 - 1	Weibull - Gamma	0.15 - 0.16	2.1 - 0.4	2 - 5
1953-1965	Weibull - Gamma	0.11 - 0.1	1.1 - 1.1	1 - 1	Weibull - Gamma	0.12 - 0.1	2.4 - 0.5	2 - 4
1966-1971	Weibull - Gamma	0.14 - 0.14	1.1 - 1.1	1 - 1	Weibull - Gamma	0.08 - 0.1	2.1 - 0.4	2 - 5
1972-1976	Weibull - Gamma	0.13 - 0.09	1.1 - 0.5	2 - 3	Weibull - Gamma	0.12 - 0.12	1 - 0.7	1 - 2
1977-1984	Weibull - Gamma	0.13 - 0.12	1.9 - 0.5	2 - 3	Weibull - Gamma	0.16 - 0.16	1 - 0.7	1 - 2
1985-1990	Weibull - Gamma	0.13 - 0.12	1.9 - 0.5	2 - 3	Weibull - Gamma	0.14 - 0.14	1.1 - 1.1	1 - 1
1991-1995	Weibull - Gamma	0.13 - 0.12	1.9 - 0.5	2 - 3	Weibull - Gamma	0.11 - 0.11	1.1 - 1.1	1 - 1
1996-2001	Weibull - Gamma	0.1 - 0.1	1 - 0.7	1 - 2	Weibull - Gamma	0.14 - 0.13	0.9 - 0.7	1 - 2
2002-2008	Weibull - Gamma	0.12 - 0.12	1 - 0.7	1 - 2	Weibull - Gamma	0.1 - 0.11	2.3 - 0.4	2 - 5

*These values result from the normalised thermal loads, using the distribution standard deviation = 1.
For normal and log normal distributions Scale is mean, Shape is standard deviation.

In all instances, either the gamma or weibull distribution were shown to provide the most accurate description of the modelled distributions. Typically a distribution is said to be significant (i.e. an accurate representation) if the maximum difference is ≤0.05. None of the distributions, however, showed such levels of accuracy, ranging in significance from 0.06 to 0.16.

The open plan modelled distributions showed greater goodness-of-fit to the considered theoretical distributions than in the case of the cellular models.

7.5 Conclusions

The probability modelling in this study showed a statistically significant variation in base thermal loads of non-domestic buildings according to period of construction. The modelling was based on a combination of theoretically derived distributions, surveyed distribution according to the NDBS Project and simplified building forms developed for modelling.

The Kolmogorov-Smirnov test was used to relate the model distributions to theoretical, continuous probability density functions. Of the distributions considered, the right-skewed weibull and gamma distributions provided the best fit to the normalised model results. No accurate representation (within the 0.05 limit) of the modelled distributions was demonstrated by the considered theoretical distributions.

Little difference in the mean base level heating is predicted by the model for construction periods pre-1977. For the construction periods post-1976, each period represents a notable reduction in base level heating loads. This correlates to the improved thermal performance considerations in building controls/regulations from the 1970's onwards. The base cooling loads, however, showed an opposite trend, with increased loads correlating to a reduced level of exposure to the thermal mass in wall construction of the latter control periods.

The increased internal thermal mass of the cellular models reduced the base cooling loads and increased heating loads, relative to the open plan models. The internal wall structure was consistent through all building periods. The effect of the cellular internal layout had least detrimental impact on thermal loads for the most recent period of building control.

Period of construction has been demonstrated to influence building thermal performance. The variation in basic form and structural characteristics within the non-domestic stock of England and Wales means that period of construction does not identify unique thermal loading. As a result it cannot be said that a building built in a given construction period will necessarily be more or less thermally demanding than a building built in any other construction period. Rather a statistical measure of a building built in period A having more or less thermal loading than a building built in period B can be given[2].

Introducing different levels of attachment (detached/semi/terraced), variation in internal layout and variation in internal heat gains would further enhance the stock modelling complexity.

The one-at-a-time sensitivity and uncertainty analysis suggested that further categorisation of the building stock by number of storeys, weather-file location and floor footprint would be beneficial to reducing the range in base thermal loading for ND buildings.

Further categorisation by these basic form characteristics (within each identified period of building control) would allow for a more 'form specific' probabilistic thermal load assessment.

This process did not account for the bivariate nature of thermal loads; the cooling and heating loads being considered separately. A bivariate probability density function would be required if used as a tool in assessing probable base level thermal loads of buildings.

[2]Period A and Period B represent any two of the construction periods identified in the study.

Chapter 8

Validation

The modelling methodology developed and carried out in this thesis attempts to provide a probabilistic distribution of base thermal load of non-domestic office buildings in the building stock of England and Wales. These thermal performance distributions are related to periods of building construction, identified by changing building and planning regulations/laws/codes of practice/british standards. It was necessary for input data to be calculated by theoretical assessment of historical building documentation in combination with empirical data; theoretical measures were applied in response to limited stock levvel empirical data required for building energy modelling.

The modelling process developed in this thesis allows for a statistical analysis of building thermal performance by period of construction, without precise prediction. This accounts for the uncertainty and variability of factors influencing building thermal performance at stock level. As a model, however, its validity at answering the question of period related energy concerns must be substantiated in order for confidence to be given to the results.

The following chapter investigates the methods available for validation at stock level and within a downscaled context.

8.1 Validation Methods

From [170, 171], validation is defined as:

> "determining a simulation model to be an acceptable representation of the *real system* - given the purpose of the simulation model"

and by Schlesinger et al. [172] (as quoted in [18]) in the context of computer modelling as:

> "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model"

.

For the model in this thesis, validation depends on capturing the *real system's* values associated with model input parameters or the model results (or both). Two complications, however, must be addressed when determining the method of validation. These are:

(i) The probabilistic nature of the model and

(ii) The lack of empirical data that has encourage the modelling approach taken.

Addressing the second issue first, Kleijnen [170] discusses the use of statistical techniques for validating simulation models in relation to *real system* data availability. Splitting data availability into three possible situations of:

1. No data,
2. Only real data corresponding to the model output and
3. Both input and output data allowing for 'trace-driven'/correlated inspection.

The model developed in this thesis was motivated by the limited stock level data on ND building energy performance[1] and limited data on the distributions in building form and component structure that influence thermal performance. As a result theoretical input values to the model were developed where adequate empirical data could not be found or realistically collected in the given project time scales.

In the light of no adequate real-life data for validation Kleijnen states [170]:

> "there is still expert knowledge"

The statistical method for validating by expert (qualitative judgement) is considered later on.

A summary of validation techniques for simulation models is given in table 8.1 - used to identify appropriate techniques of validation for the stochastic modelling carried out in this thesis. From this, five validation methods were considered not only to be applicable to the modelling carried out, but also capable within the current state of knowledge and data availability of non-domestic building energy performance.

Degenerate tests and sensitivity analysis are considered of a similar nature and as such this form of model inspection/validation was considered in chapter 7. The results of sensitivity analysis showed varying sensitivity of the base case models according to the periods of construction. The varying sensitivities between building periods were explained by the varying impacts of thermal mass, u-values and initial base-case values.

Face validity and rationalism can only be used to give an indication of the model's validity. Both require expert knowledge to assess the results and underlying model assumptions to provide a qualitative confidence in the results. Identifying experts is a key factor to the credibility of this validation, especially within a field where the real system's data is not fully (or even adequately) appreciated.

Internal validity is associated with capturing the uncertainty in a system and seeing its influence on the model results. This, however, is the premise of the work undertaken in this thesis. This validation

[1] Specifically in reference to base thermal loading.

Table 8.1: Summary of Validation techniques for simulation based modelling, from [18].

Validation Techniques	Description	Applicable to Model	Currently Possible
Animation	Display dynamic model behaviour graphically through time.	☐	☐
Comparison of Models	Compare results against existing (valid) models	☑	☐
Degenerate Tests	Model's behaviour is tested by behaviour inspection when varying a given input parameter with known influence. This is in part covered by sensitivity analysis (see chapter 7).	☑	☑
Event Validity	Compare the events of the model against the events in the real system. This could be used to compare the distributions in thermal performance of the model, against distributions of empirically based thermal models.	☑	☐
Extreme Condition	Model output at extreme values is feasible. This is more appropriate to validate the dynamic simulation model used by the probability modelling method. These models undergo a strict set of validation tests and is not relevant here.	☐	☐
Face Validity	Ask 'experts' whether the behaviour is a reasonable reflection of their understanding of the real system. This is a qualitative measure only.	☑	☑
Historical Data	Use data already collected on the real system as input to the model as well as relevant output. Kleijenen terms this as trace-driven where regression analysis can be used to determine whether theoretical input data can be statistically compared to real input data. This is only possible if adequate input and output data of the real system are known.	☑	☐
Historical Methods	**Rationalism** - assumes that model assumptions are true and that logic can be used from the assumptions to derive the valid model. If the assumptions in the model are considered true then in this instance the model is a valid representation. This, however, requires wide spread agreement from expert opinion that the assumptions made are valid.	☑	☑
	Empiricism - every assumption and outcome to be validated by empirical means. Again not enough data exists for this to be carried out.	☑	☐
	Positive Economics - the model is only required to predict the future/ real system, regardless of the model assumptions and structure. This is not relevant to the probability modelling.	☐	☐
Internal Validity	Assess the stochastic nature of the model to capture the variability in light of system uncertainty. This is the premise of the model - to capture the variability in the non-domestic stock. Inspection of results can be used to offer some validation of the modelling method.	☑	☑
Multistage	Combining the three historical methods at different stages within the model	☑	☐
Operational Graphics	Show model behaviour as it is running. this is of no consequence to validating the probabilistic results.	☐	☐
Sensitivity Analysis	Assess the influence of input parameters on model behaviour. As sensitivity is dependent on the base case model to which it is applied the behaviour will vary for different building periods. this was covered in chapter 7.	☑	☑
Predictive	Compare model predictions to real system data. This requires a large scale field study to be carried out that standardises the influence of varying occupant and HVAC system behaviour on the thermal performance in order to measure the base case thermal behaviour.	☑	☐
Traces	Trace individual model components to determine if the logic is correct. This is not appropriate here.	☐	☐
Turing Tests	Ask knowledgeable 'experts' to discriminate between the real system and model results. This requires adequate real system data.	☑	☐

approach can be used to determine the appropriateness of building period as a category for investigating building thermal performance. This was used by results inspection in relation to a building case study.

The methods of validation summarised in table 8.1 are clearly presented for deterministic model validation in [18]. Validation for probability models is more complex, [170, 173], as the model is accounting for the uncertainty of the real system. According to Lind [174], probability statements cannot themselves be verified as the real system uncertainties are what force the probability statement. It is the model or method of producing the probability statement that can be validated by comparing real or simulated data.

Real system data is considered inadequate for validation and therefore any approach must use simulated data (either from other existing models or from expert judgement).

8.1.1 Validation for Probability Models by Expert Judgement

Expert judgement is required in the light of inadequate data on the real system being simulated. Kleijnen states in [170],

> "If no data on the real system are available, then strong validation claims are impossible."

Kleijnen's statement can be expanded for uncertainty modelling to say: without a statistically significant amount of data strong validation claims are impossible. This is acknowledged as a limitation in validating the modelling method within this thesis.

Kleijnen describes a sensitivity analysis approach to be taken when no real system data is available - using expert judgement to determine if the sign of the sensitivity in relation to parameters agrees with qualitative knowledge. This, however, is not fully applicable to uncertainty modelling.

Lind, [174], discusses the use of likelihood (L) and Shannon information (I) for use in relative validation. The likelihood of the model is the probability on the observations when considering the probability of the model as true. Comparing the likelihood of two models gives a relative measure known as the likelihood ratio. This requires real system observation to which a true/false statement can be applied to each outcome of the model.

The Shannon Information is the negative natural log of the likelihood (see equations 8.1 and 8.2),

$$L = p_1 p_2 p_3 \cdots p_n \tag{8.1}$$

$$I = -\log L = -\log p_1 - \log p_2 - \log p_3 ..... - \log p_n \tag{8.2}$$

where p_i is the probability of an independent prediction of the observed value being true, for n predictions.

The third validation measure presented by Lind is that of relative entropy (or Kullback-Leibler divergence) [175]. This measures the difference of two distributions, P_r (the real system distribution) and P_m (the modelled distribution). The measure is given as:

$$S(P_r \| P_m) = \sum_i P_r(i) \log \frac{P_r(i)}{P_m(i)} \tag{8.3}$$

for discrete random variables, and as:

$$S(P_r \| P_m) = \int_i^\infty p_r(x) \log \frac{p_r(x)}{p_m(x)} dx \tag{8.4}$$

for continuous distributions.

8.1.2 Validation Design

The Kullback-Leibler measure can be used to show the variation in the model's parameter distributions (derived from historical building regulations and other theoretical measures taken) against the current best understanding of the non-domestic (office) stock's distribution of building characteristics (resulting from large scale empirical and modelling studies). The real system being represented by expert knowledge.

The expert knowledge can also be used to identify typical component constructions according to building period. Those constructions presented by the experts can be compared to the construction databases developed for this modelling study. Depending on the similarity of construction a level of credibility in the construction databases can also be given.

Another method identified for validating was to downscale the probability model by physical characteristics. The downscaled model can be compared to detailed models of real buildings that are within a given construction period and of similar form to the downscaled probability model (with the same occupancy and internal load patterns as applied in the probability model). If the thermal loads calculated in the real models are comparable with the downscaled probability model then (if only partially) some confidence can be applied to the probability models ability at representing true thermal loads.

Figure 8.1 represents the two methods used to provide credibility to the probability model used in assessing a stock level influence of building construction period on thermal loading. The figure highlights the limitation in that no direct path for comparing the real system with the modelled system is available.

8.2 Model Inspection - downscaling for case study comparison

This section does not provide validation, but rather presents a method for potential validation, given a statistically significant sample of office buildings.

Within the project, a non-domestic office building was presented as a building with poor thermal comfort. Monitoring and modelling work was carried out in an attempt to highlight the main factors causing the reported comfort issues, see [176, 177].

The light-weight office building was used to demonstrate the method of downscaling and model comparison as in figure 8.1.

8.2.1 Building Description

The office building investigated was built in 1989 as a 3 storey light-weight, steel framed structure. A composite metal-insulation-metal panelling system and plasterboard interior finish was used for the top

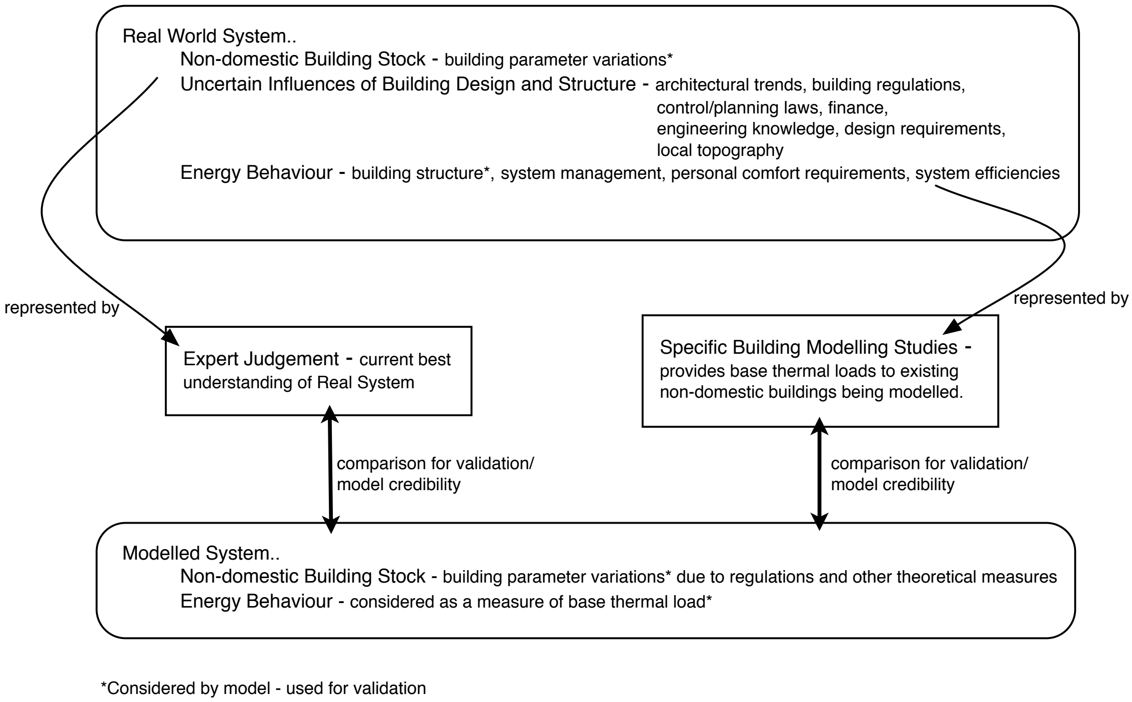


Figure 8.1: Schematic explanation of the validation methods applied.

two storeys with a brick-cavity-block wall cladding for the ground floor. The hip-pitched roof utilised a similar panelling system as the external walls of the top two floors.

The building is a uniform design - square in floor footprint (25m x 25m) and detached. It has no means of natural ventilation: relying on an air handling unit to supply the required fresh air and ceiling mounted fan-coil units for cooling and heating.

Floors are of concrete slab construction: hidden by a false ceiling and raised floor, so concealing thermal mass from the occupied zones. The ceiling voids are used as mixing plenum for ceiling mounted fan-coil units supplying heating and cooling to the building. All service pipes and wires are also contained within the floor and ceiling voids.

A central core containing the stairs, elevator and toilets utilised a combination of concrete block work with concrete slabs. Much of this central heavy mass was hidden by stud-walling and shelving. Within the roof void the central core provided the plant room for the air handling units.

The windows were aluminium framed double glazed units (6mm glass and 12mm cavity). The glass on the ground floor utilised a low emissivity coating (not spectrally selective) - reducing solar heat gain and daylight transmission. The windows were distributed uniformly on all sides of the building with a window-to-wall ratio of 47%.

The building site is within South Nottinghamshire on a business/industrial park. Figure 8.2 shows the building form as modelled in esp-r.

The surrounding buildings were included in the model as solar obstructions (see figure 8.3). Using the known geometry of the building site (i.e building and surrounding obstructing objects) a sky view factor at the mid point along the ground floor of each façade was calculated (see [154]). The averaged sky view factor of all façades was used in the model - a value of 0.38 was calculated.

No air leakage information was available on the building and early investigation of possible testing methods was considered too expensive and disruptive to be carried out. As such the model was run four times at different air infiltration rates between 0.14 and 1.0 ACH[2]. These were chosen to represent the potential range in adventitious leakage (as demonstrated in chapter 5).

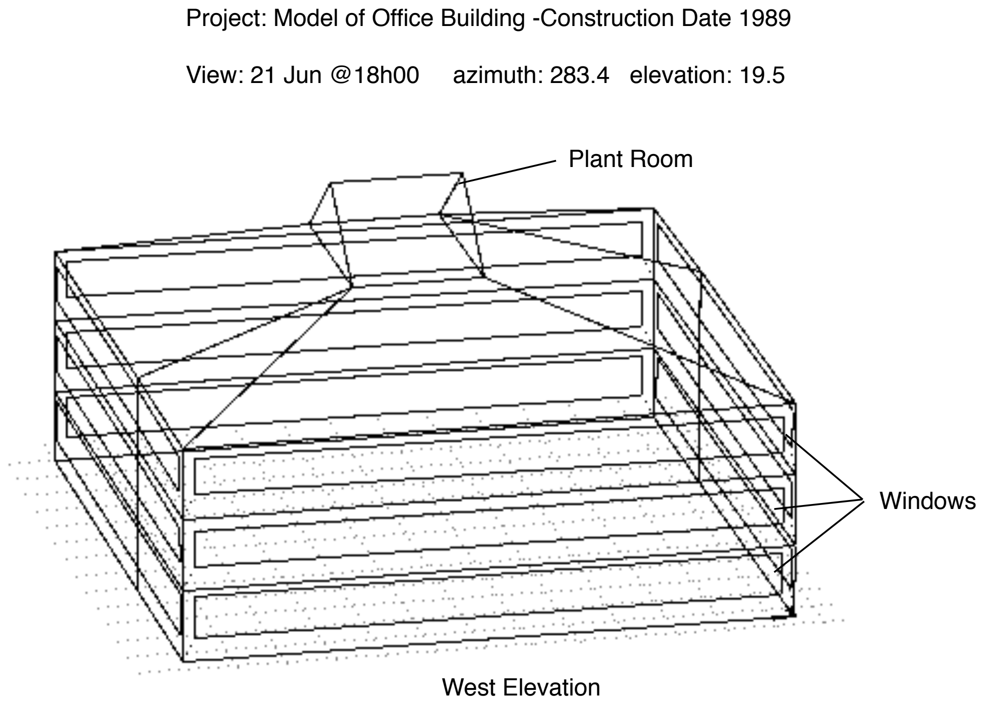


Figure 8.2: Office building - specific building model used to demonstrate validation technique in esp-r.

8.2.2 Downscaled Model Comparison

It is not the intention for the downscaled probability model to represent exact building structure and form characteristics of a specific building. Rather further categorisation of the building type is given to reduce uncertainty in parameters that were not identified as being influenced by period of construction. In this case, floor footprint, number of storeys, floor construction, roof type and site location were all fixed (within the Monte Carlo modelling procedure) at values representative of the case study building described above.

Probable distributions in roof pitch, wall construction, window construction and window-to-wall ratio, storey height, sky view factor and air leakage remained. The distributions applied were those derived from studying building laws and regulations for the regulatory period 1985-1990.

[2]For the considered building this range is $10m^3.h^{-1}.m^{-2}$ to $74m^3.h^{-1}.m^{-2}$.

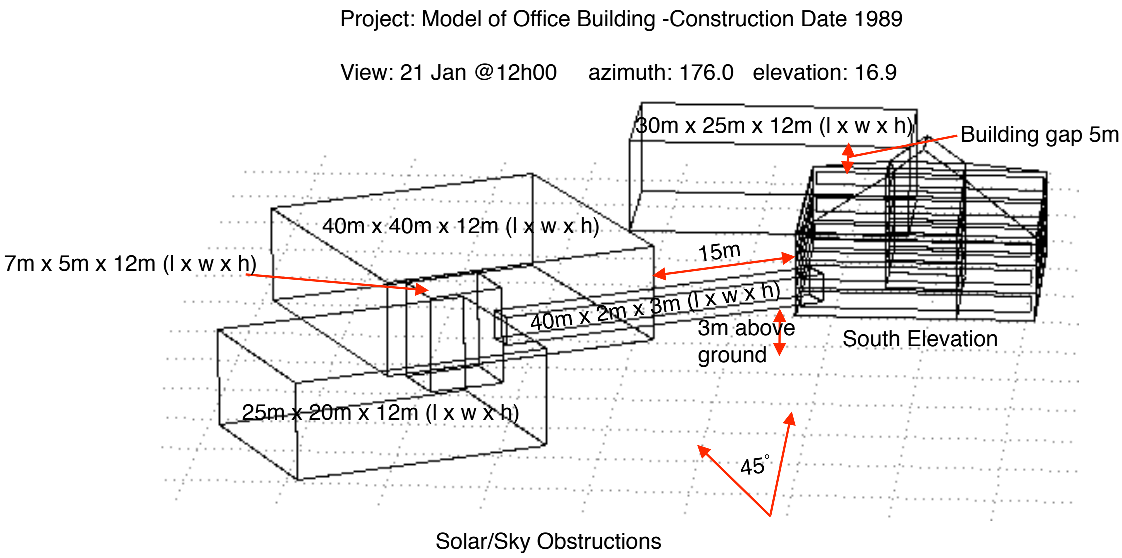


Figure 8.3: Office building - specific building model with solar obstructions in esp-r.

8.2.3 Results

Table 8.2 shows the simulated results of the case study building at four different air infiltration rates. It is clear that this significantly impacts both heating and cooling loads. No attempt has been made to determine which infiltration rate is more accurate for the building[3].

The same internal loads and loading patterns were applied to the building as applied in the Monte Carlo simulation. The high cooling loads are attributed to the building being of lightweight construction that make it sensitive to internal gains and solar loading.

Table 8.2: Case Study Building - Simulated Base Thermal Loads.

Air Infiltration (ACH)	Base Level Heating Load (kWh/m^2/year)	Base Level Cooling Load (kWh/m^2/year)
1	23.07	32.34
0.5	12.48	42.43
0.25	8.53	49.3
0.14	7.03	52.89

Comparing this building simulated value with the probability results requires a bivariate representation of the probability results. This is required as each model run returns a base level heating and cooling load applied to that specific model configuration. The two values must, therefore, be considered together.

The downscaled model was simulated 320 times. Figure 8.4 shows the bivariate histogram representation of the Monte Carlo simulation results. The lower colour grid highlights the frequency distribution of the results: showing two regions of more probable thermal performance. The lighter the colour the greater frequency of occurrence.

[3]As this would require use of considered methods in the probability model being verified.

Of the four case study runs: one falls within the bounds of the probability model results, two are within the cooling load bounds but the heating loads are lower than the probability modelled minimum heating load[4], and one exceeds the maximum probability modelled cooling load and is less than the minimum modelled heating load[5].

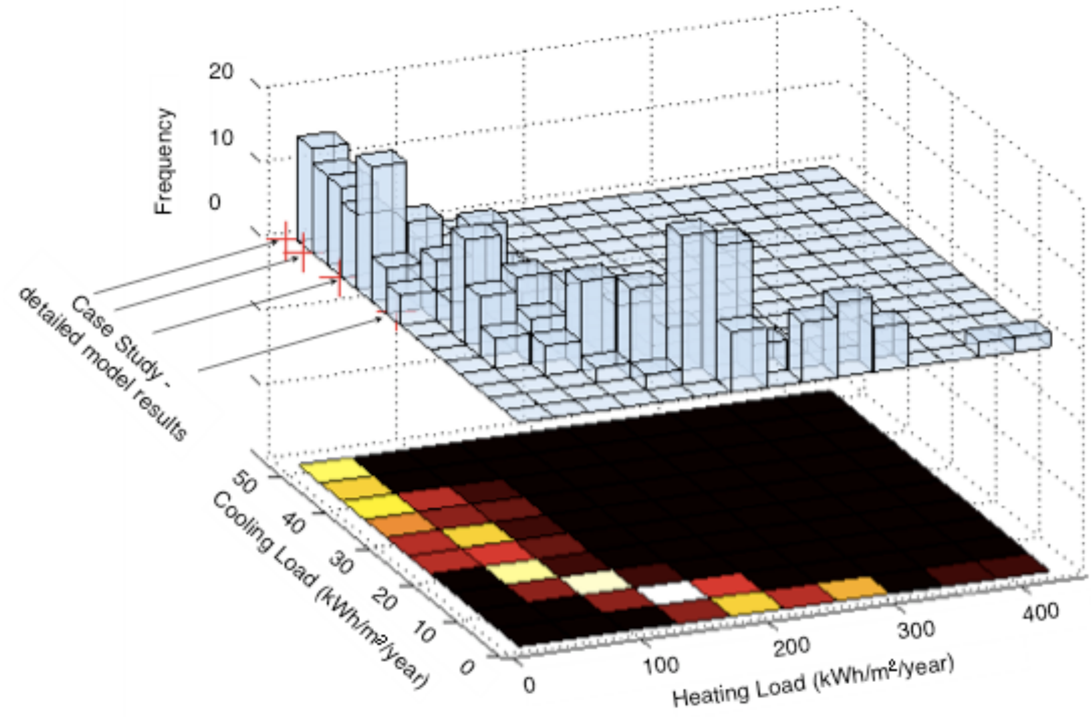


Figure 8.4: Bivariate histogram of downscaled Monte Carlo simulation results.

8.2.4 Discussion

The case study results are on the boundary of the probability model results. Though the case study results fall close to, or outside the bounds of the Monte Carlo simulation results, it shows that they are not adversely different to one of the more probable regions of thermal load (as resulting from the Monte Carlo simulation). This cannot validate the probability distribution, but does suggest the model captures real building base thermal loads.

There are some known limitations in the probability model, such as:

- multiple wall construction methods within one building are not considered
- exclusion of stair and service areas
- simplified internal layout
- uniformity of façades (i.e. equal window wall distributions)

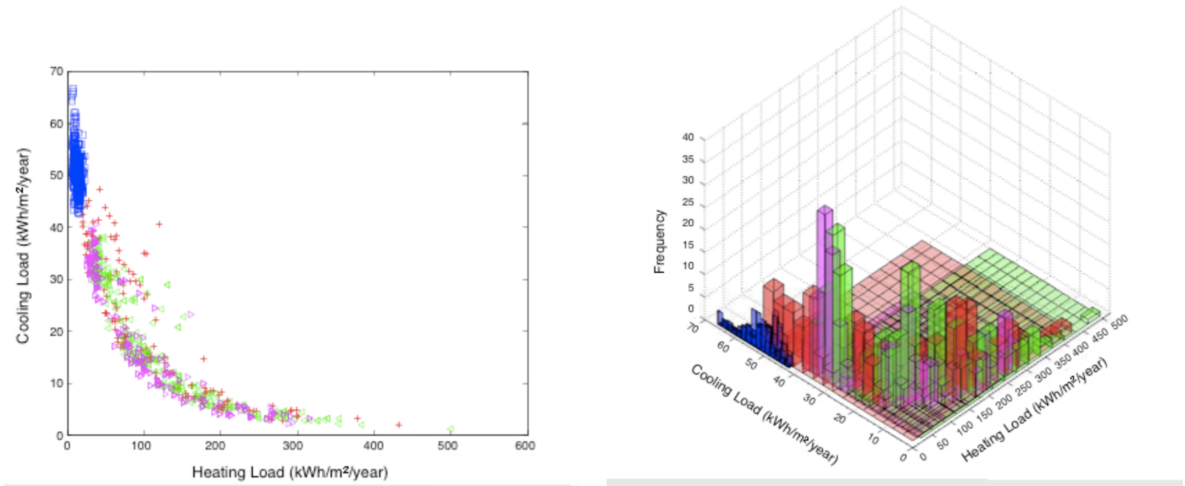
[4]By 1.37 kWh/m^2/year and 5.32 kWh/m^2/year.
[5]By 0.75 kWh/m^2/year and 6.82 kWh/m^2/year, respectively.

- buildings are all standalone with 4 exposed wall areas
- simplified building shape (rectangular only)

Though the case study building is standalone, square, and is uniform in window-wall distribution on each façade; stairs/service areas and multiple wall construction methods exist within the building. As the case study building has form and construction factors that cannot be represented by the probability model, the probability model cannot represent the true case study building. The probability model is (in this case) able to provide a basic representation of the real building and so predicts base thermal loads within close proximity of the more detailed building simulation.

From 320 runs the bivariate histogram (of figure 8.4) shows two regions of more probable base level thermal loading: a low heating load with a relatively high cooling load and a mid range heating and cooling load.

For this more detailed building type Monte Carlo simulations were carried out for three of the other nine identified periods of control. These are the 1900-1938, 1966-1971 and 2002-2008 periods[6]. Figure 8.5 shows the earlier periods display a similar trend in the spread of base thermal loading. The latest control period shows much less spread, with a general high cooling load and low heating load - relative to the modelled range in thermal loads.



(a) Scatter plot of cooling-heating load pairs for periods 1894-1938 ▷, 1966-1971 ◁, 1985-1990 +, 2002-2008+ □

(b) Bivariate histogram of thermal loading for downscaled model for periods 1894-1938 ▪, 1966-1971 ▪, 1985-1990 ▪, 2002-2008+ ▪

Figure 8.5: Thermal Loading of downscaled model for four of the ten identified construction periods.

Though the distributions of thermal load for different construction period in some instances follow similar trends, these distributions are not the same. The overlap and pattern similarity of these distributions highlight the complexity of labelling thermal efficiency according to period of construction.

[6]Chosen as thought to be significantly different in base thermal loading as identified from the simulations as of chapter 7.

8.3 Validation of Parameter Distributions

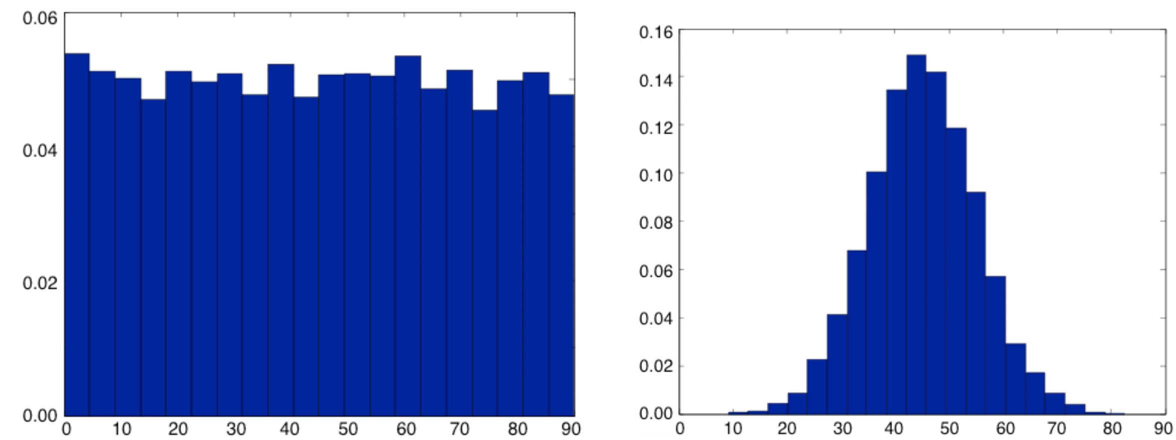
To aid the consideration of building stock form characteristics, distributions are considered in discrete bands in the questionnaires filled out by the considered expert bodies (see Appendix F). Using these discrete bands means the Kullback-Leibler function of equation 8.3, is used in qualifying the theoretically derived distributions.

Using this method, a measure of zero represents an exact match of the two distributions under comparison. To provide a scale for understanding the results, two clearly different distributions are compared by the Kullback-Leibler method.

Within an arbitrary value range of 0 to 90 two psuedo-random number generators provide sets of 5000 numbers each. One is a random number generator where all numbers between 0 and 90 have equal probability of occurrence (i.e. rectangular distribution). The other random number generator provides a normal distribution within the physical limits of 0 to 90, with a mean of 45 and a standard deviation of 10. A histogram plot of the resulting data sets are shown in figure 8.6.

Comparing the two distributions with the values divided into 10 discrete bins of equal width a value of 0.5603 is given when the normal distribution is considered the 'real' distribution and the rectangular distribution the 'modelled' distribution. Halving the number of bins reduces the sensitivity of the test: reducing the measured divergence in the two distributions. It must, therefore, be noted that the size of the discrete ranges which the experts use will be a limiting factor in qualifying the theoretically derived distributions.

The method is non-commutative.



(a) Rectangular Distribution of Randomly generated values 0 to 90

(b) Distribution of Randomly generated values 0 to 90 with normal distribution - mean 45 and standard deviation 10

Figure 8.6: Histograms of randomly generated data sets - distributions compared by equation 8.3.

The two expert bodies chosen for assessing the validity of the model input were chosen as the Bartlett School of the Built Environment, University College London (contact: Harry Bruhns) and the Institute of Energy and Sustainable Development, De Montfort University (contact: Andrew Wright). These two institutes were chosen for the work carried out on the Non-Domestic Building Stock (NDBS) Project and the Carbon Reductions in Buildings (CaRB) Project. Both projects represent the most extensive research to date on stock level building form and energy use (specifically for non-domestic buildings).

Communication with both expert bodies, showed agreement in that current best knowledge is still limited. With the best current source of data being the Valuation Office Agency (VOA) database on commercial premises. This data source is difficult to use for energy assessment[7] as was designed for taxation purposes only.

Within the time constraints of this project only one expert body was able to answer the questionnaire. In responding, it was frequently commented that this task was *very difficult* and that confidence in the results was low. It was noted that greatest confidence was attributed to the construction periods of pre-1930 (due to standard forms of construction) and post-2002 (due to tighter regulation constraining design). The comments and results are presented in Appendix G.

8.3.1 Results and Discussion

The first step in comparing the modelled parameter distributions with the expert body's distributions is to consider the difference in identified periods of construction. The guide in this thesis has come from identifying different building controls that resulted in ten periods from 1894 onwards. The responding expert identified five periods from 1900 onwards. The two sets of identified periods are represented in figure 8.7.

The considered expert body used typical wall construction methods for identifying construction periods. The reasoning used by the expert body are given below:

Pre 1900 - Many different construction methods in use (becoming more regular post 1900)

1900 - 1930 - Typified by cavity wall construction

1930 - 1950 - Introduction of concrete panel walling

1950 - 1980 - Increased variation in construction methods

1980 - 2002 - Energy regulated building construction

2002+ - Significant advance in energy regulation concerns of buildings

The reasoning of the expert body for defining construction periods are in general agreement with the knowledge obtained by investigation of building regulation and control documentation. The expert body's judgement is based on empirical investigation of building stock energy concerns.

Figure 8.7 shows an overlap of the two sets of identified construction periods. A greater number of differing construction periods were identified by the building control method. For the parameter distributions under investigation however, the change in distributions were not sensitive to all ten identified periods. Due to this reduced sensitivity and the overlap of construction periods, it was considered that enough similarity in the two sets of construction periods existed for data comparison.

Where one *expert defined* period encompasses multiple *modelled periods*, the multiple distributions from the modelled periods were combined to allow comparison of parameter distributions. The combined periods for comparison against the *expert defined* periods are represented in figure 8.7.

[7] Complicated by being considered by premises and with limited data pertaining to energy influencing characteristics.

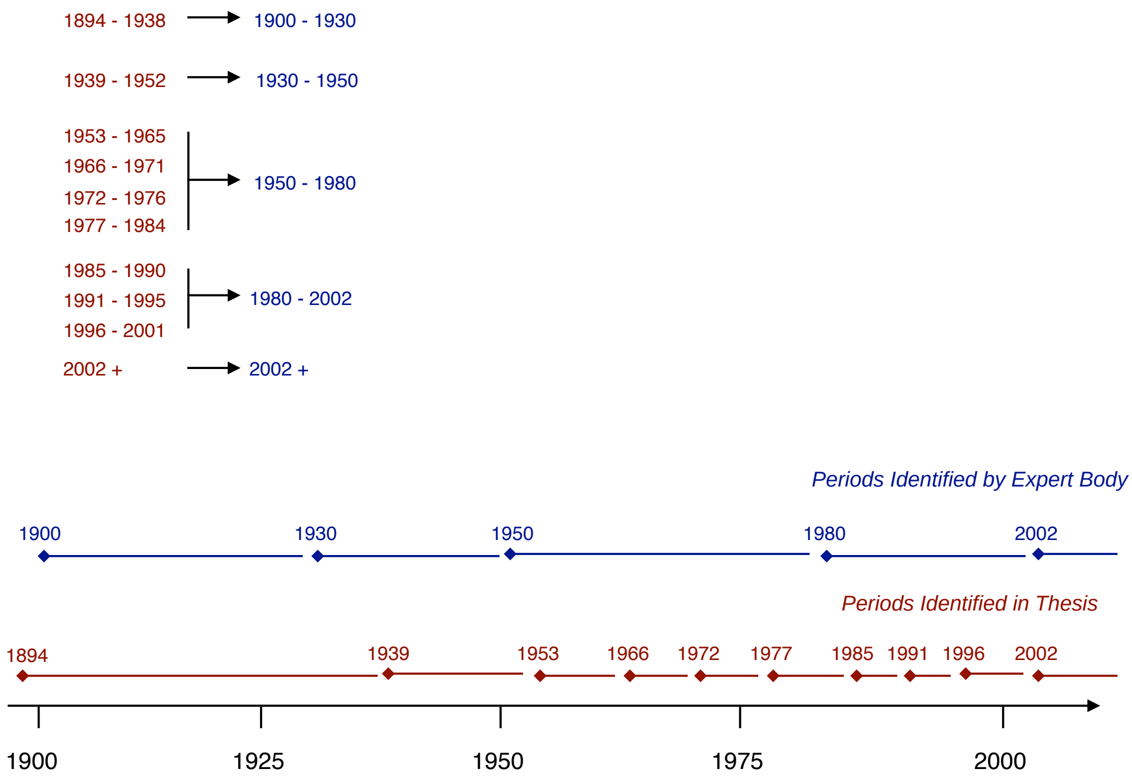


Figure 8.7: Construction Periods identified by building control documentation and by expert body.

The distributions associated with building characteristics as given by the expert body did not offer the same level of detail as presented by the model developed in this thesis. As mentioned above, this reduced detail reduces the sensitivity of the test that will influence the Kullback-Leibler entropy measure.

This limited detail is a reflection (as stated by the expert body) of the limited knowledge and data available to the expert for defining stock level building characteristics in this manner.

Table 8.3 shows the measure of divergence between the *expert defined* distributions and those used in the model. A range in divergence shows agreement for certain distributions and very high divergence (~38) for others.

In cases of no divergence the given characteristic is typically not represented by the given construction period. The instances of extreme divergence (38.1143 and 28.3735) occur for window-wall ratios (WWR) associated with glazing that are atypical of the considered period. The expert response noted very few instances within the non-domestic stock for the parameters with high divergence (see Appendix G for full questionnaire response).

A divergence of ~ 0.5 between a normal and rectangular distribution was demonstrated that suggested this measure to be a measure of high divergence. Eighteen of the forty-five (40%) measured distributions displayed divergence at or above 0.5. This shows a high level of divergence between the expert defined and thesis defined distributions in building form characteristics.

Similarity in basic component construction types was evident, though little detail of construction was offered by the expert body.

Table 8.3: Kullback-Leibler entropy discriminating between the modelled and expert defined (stock level) distributions in building form.

	Construction Types				WWR - Glazing				
Period	Wall	Ground Floor	Inter-Storey Floor	Roof Type	Single	Double	Triple	Storey Height	Air Leakage
1900 - 1930	0.4718	0.0823	0.1308	0.5105	0.1035	0	0	0.3218	0.5134
1930 - 1950	0.1126	0	0.0201	2.0325	0.3083	0	0	0.1405	0.5697
1950 - 1980	0.3956	0.3681	0.3681	0.5319	0.2935	38.1143	0	0.0051	0.9704
1980 - 2002	0.5599	0.6931	0.4946	5.2049	6.9338	3.6068	0	0.0247	1.2477
2002 +	0.9758	0.6931	0.4946	2.692	0	3.2846	28.3735	0.0304	0.1445

8.4 Conclusions

Full validation of the probability modelling assessment (as associated with period of construction) is currently not considered to be possible. This is a result of limited stock level building energy modelling and limited data for inspection of variation in structural and form characteristics by date of construction.

Expert knowledge and downscaled modelling were considered to present the best available methods for providing credibility to the model. The methods available could only provide a qualitative judgement on the modelling method.

The thermal behaviour of the chosen building energy modelling tool has itself been validated as part of its development [178]. The sensitivity tests (see section on One-at-a-time Sensitivity, Chapter 7) provide further evidence of correct thermal behaviour.

A case study building was simulated in detail as part of an energy and thermal comfort investigation (reported in part in [176, 177]) and was used to show a method by which to validate the model by downscaling. Though recognised as not validating - with just one case study - agreement was found between the detailed energy model results and a region of higher probability from the Monte Carlo results.

A discussion of varying period in the downscaled modelling context, highlighted similar trends in the relationship of heating to cooling loads. Bivariate plots (heating and cooling load) demonstrated a difference in probable distribution of thermal loads between building construction periods within the downscaled model.

The use of the Kullback-Leibler divergence measure showed a large variation between expert knowledge of the building stock and that defined by analysis of building regulations and published data such as [3]. The expert body provided the data with notes stating little confidence for identifying parameter distributions for the periods between 1930 to 2002. As a result little confidence could be given in the resulting measures of divergence.

Validation of stock level modelling is an area requiring significant further work. Further development of the model to encompass different building forms and survey of building component form (by period of construction) are required to validate - or replace - theoretically derived distributions in input parameters.

Chapter 9

Conclusions and Further Work

This thesis introduces an approach to building thermal energy assessment at stock level by utilising a dynamic simulation tool within a Monte Carlo simulation process. This process provided a method of capturing the variability of physical characteristics of buildings (that influence thermal loading) at stock level; utilising building control laws and regulations as guides to establish probable distributions in these thermally important physical characteristics.

The modelling approach taken was developed as stock level assessment by empirical survey was considered to be restricted by large stock size, limited metering capability within buildings, uncontrolled occupancy behaviour and limited time scales to achieve statistically significant data sets.

The theoretical assessment provided by the modelling process offers a measure of the structural thermal performance of buildings. This is achieved by normalising or excluding currently unquantified uncertainties from occupancy behaviour to heating and cooling system inefficiencies and management. As a result the measures of the modelling process offer a metric by which suitable strategy for improved passive thermal performance of an existing building stock can be measured.

According to the studied literature, economics have significantly influenced building construction and form - steered by regulations, by-laws, engineering standards and town planning laws. As such the theoretical distributions are considered to offer a good, yet basic, guide to approximating statistical variation in building component form. Only an extensive survey of a significant proportion of the building stock can offer a more detailed understanding of distribution in building form and construction. Doing so, raises questions such as:

- What defines a significant proportion of the stock?
- Should a significant proportion mean a significant proportion of each period of construction control?
- Do the limits of the survey identify the true limits experienced in the building stock?
- Can surveys be realistically carried out to determine detailed structural information due to invasive and destructive testing techniques?

These questions, or indeed the answers to these questions present barriers to effective research of the building stock by empirical means alone. Many of these barriers are surmounted by theoretical modelling.

Though limitations in the theoretical approach exist, and robust validation of this method is currently lacking, it is an approach that compliments the field of stock level energy research that should be developed to form part of future research projects.

9.1 Modelling Method

The process of developing a dynamic building energy model was used as a framework for investigating thermally influential building characteristics at stock level. Three areas of significant[1] thermal influence were investigated for stock level variation within a framework of identified periods of differing construction controls. These three areas were presented as building component form, adventitious leakage and radiative concerns (both long and short wave).

The influence of varying factors such as building shape, internal layout and occupancy behaviour were either partially considered or held constant throughout the modelling. This was a result of limitations in time and understanding of automating the process as well as limitation of the interface of the modelling tool (esp-r).

Heating and cooling systems have a much shorter life expectancy than the basic building structure. It was, therefore, not considered reasonable to associate these systems with different construction periods. The period of construction was considered only with regard to its influence on base thermal loading.

9.1.1 Parameter Values

Theoretically derived parameter distributions were used in light of little stock level information regarding building characteristics and structural properties associated with period of construction. The theoretical assessment resulted in a stochastic modelling process by use of Monte Carlo method. It does not allow the results to be considered as a precise description of reality, but rather a statistical measure. The approach, therefore, provides a statistical measure of how period of construction influences thermal loading.

The confidence of the model results is dependent on the confidence applied to the theoretical parameter distributions. A measure of confidence would result from comparison to real stock distributions, but as stated such real data is currently not available.

The ranges in parameter values were kept within physically reasonable limits, either set by control laws or set by the parameter definition (i.e. sky view factor of a vertical wall has limits of 0 to 0.5).

Building Component Form

It was demonstrated that dynamic thermal properties of composite building components are dependent on construction order and material used. This raised a concern of using steady-state properties (i.e. U-value) in regulating a building's thermal efficiency.

Building regulations and model by-laws were used to develop databases of building component constructions. The databases covered use of different materials and varied order of material layers for composite constructions. By capturing potential variation in component construction the model considers varying

[1] Significant to passive thermal performance.

dynamic thermal properties, for otherwise constant steady-state properties. Each constructions database represented a different period of construction control for buildings built specifically for commercial office use.

These databases are not a comprehensive description of all feasible constructions, but rather a range of constructions that represent the potential variation in dynamic thermal behaviour. It is, therefore, not considered necessary (though desirable) to expand each constructions database to cover all potential and known component construction forms.

Beyond identifying glazing types the ratio of windows to wall area is important in terms of solar loading, daylight and heat transfer and storage. The impact of daylight on artificial light requirements was not represented in the model.

Regulations, model by-laws and daylight standards were examined to determine modal values and physical limitations in window-wall ratios. A triangular distribution was used in all cases from which a random window-wall ratio would be applied. As the building models were all free standing with four external walls, each wall was given the same ratio. This was recognised as a limitation in the model as, for example, if the building adjoins two others the exposed façade will necessarily have a higher window-wall ratio. This would particularly effect the lower window-wall limit of the considered distributions; regulations stipulate a minimum window area of 10% of floor area.

The method taken in randomly determining window-wall ratio is limited by the limited database of building models.

In all instances of a pitched roof the resulting roof void was considered as an unoccupied zone with free floating temperature. The variation in roofing types were limited in the modelling to flat and pitched-gable-ended roof types. A sensitivity study showed that for an uncontrolled roof void these two roof types were an adequate representation of roof types in the building stock[2].

In all, the model captures variation in building component form that is significant to the varying thermal behaviour[3] of buildings in the non-domestic office stock of England and Wales. The application of probability distributions to the occurrence of these different forms in the stock have been limited to theoretical prediction. These predictions being governed by application of economic reasoning to physical and regulated limitations in building form.

Adventitious Leakage

Uncontrolled air leakage in a building is highly variable; a result of building design, maintenance, build quality and construction methods. Literature review highlighted insufficient data is available to associate expected leakage rates with different building types. The types being categorised by use, construction method and region, for example.

A new modelling approach was taken to associate adventitious leakage rates with a building. By applying a probable component leakage to a building described by its component parts, a statistical evaluation of expected leakage could be given. This method relied on existing experimental data on component leakage rates to which a normal distribution was assumed.

[2]As applied to the dynamic thermal modelling tool of esp-r.

[3]The thermal behaviour as determined by the building structure and form - i.e. passive thermal behaviour.

This novel method allowed air leakage rates to be applied to the stochastic modelling process undertaken in the thesis. The method showed a high degree of variation, not only in average leakage rates for feasible building types but in variance of the probability distribution of buildings displaying similar average leakage rates. This provided supporting evidence to the difficulty (reported in the reviewed literature) of associating building types with air leakage.

The advantage of this component leakage model over other methods is that it not only accounts for the variation in component form of a building stock, but it also provides a statistical evaluation of adventitious leakage for every considered building form. There is no requirement for categorising buildings to offer a statistical prediction according to some predefined building type.

The value of this method is limited by:

(i) the level of component leakage data

(ii) the data is not specific to one country

(iii) much of the data result from laboratory based testing and

(iv) the sample size of tested components are (in some instances) very small.

The model would become more comprehensive with further leakage testing of the considered building components along with incorporating other component types.

Weather Data

The weather data was limited in value as was:

(i) geographically limited - limited number of weather files used

(ii) does not offer an account of statistical variability in weather

(iii) the TRYs are based on 1961-1990 recorded data - does not represent future (changing) climate

No account was made for determining the geographical distribution of building stock in relation to period of construction; an equal distribution by construction period was assumed. With a higher resolution of weather locations a better approach would be to consider the proportion of stock (in each weather region) belonging to each period of construction control. By this downscaling the model could be used to provide regional policy. The use of future climate scenarios would also be more beneficial to understanding future energy demands of the existing building stock.

Radiative Factors

A theoretical approach to determining sky view factor (Sν) was examined to offer the probable variation associated with buildings constructed in different control periods. This method, in the first instance, was more applicable to earlier control periods than later periods as a 'closed' (i.e. a street canyon) urban form was assumed. For later control periods the building controls[4] encouraged more 'open' form; so

[4] As considered to influence urban form and Sν.

contradicting the assumption of a street canyon in determining modal elevation angle and resulting Sν. By sectioning of the 180° horizontal view plane some account of varying urban form was given.

Though no validation could be given for the model results (again a restriction of required scale of data for validation) the mean and modal Sν for each control period were similar to 'representative' values published in energy modelling literature.

This approach does not account for urban redevelopment that result in mixed control regions and is limited in consideration of variable urban forms. The method applies a singular Sν to a building façade with no consideration for variation in the vertical or horizontal plane of the façade. For building energy modelling, however, this is an accepted practice (as stated in the EnergyPlus engineering reference manual). For the purposes of energy modelling this approach is adequate.

9.1.2 Period of Construction

As building control by-laws, town planning laws, building regulations, standards and codes of practice were studied to understand probable values in building characteristics, the model inherently categorises probable thermal loads by periods of construction. In doing so the impact of period of construction on thermal loading was presented.

The sensitivity tests carried out on a set of base case building models showed varying thermal sensitivity to the influencing parameters, according to period of construction. Of the parameters tested, base heating loads were most sensitive to floor footprint and storey height. Studies within the Non-Domestic Building Stock project show large variation in thermal loads according to floor area of buildings and as such present data grouped by building/premise floor area. This sensitivity suggests greater model categorisation by floor footprint would benefit the modelling process undertaken. Further categorisation in the model (beyond construction period) was discussed in chapter 8 as part of downscaling for validation.

MCA was carried out for each construction period, with 300 simulation runs considered necessary to provide stability in the mean of the thermal load distributions. For both open plan and cellular models, little variation in mean thermal load were seen between the three control periods identified between 1894 to 1965.

For the following two periods to 1976, the mean heating load increases for both the open plan and cellular models. These two periods represent the highest mean heating loads of all considered construction periods and the largest inter-quartile range. This periods poor thermal control represents 20% of office floor area (as of 1994 - see table 2.3) - highlighting a significant period of building stock to reducing stock level thermal loads.

It is clear that part L building regulations have reduced heating loads and potential load variation in the modelled stock. The base cooling loads however, are increased post 1984. Whilst for a temperate climate (representing that measured in the UK between 1961-1990) much of the cooling loads can be met by a relatively cool ambient air temperature. Whether such thermally efficient buildings for the present day will become thermally expensive buildings in a warming climate should be considered as an important area of further research.

Normalising the results for each construction period showed (by the Kolmogorov-Smirnov test) that the gamma and weibull distributions were most representative of all the thermal load distributions - bounded by zero and right skewed. In this analysis the model was attempting to categorise the building stock by construction period only. The model, however, is limited in varying building form, size and location (specifically in relation to construction period) and so must acknowledge that the thermal load variation is representative of a stock that falls within these limitations.

The distributions presented in chapter 7 are limited in that they do not show the relationship of cooling and heating base loads. A bivariate distribution offers a better understanding of this relationship (as demonstrated in chapter 8) and should be considered in future model development. Applying bivariate analysis to a downscaled model in chapter 8 showed an exponential relationship between heating and cooling loads. This trend suggests that if an existing building is achieving a low heating load it is more likely to be experiencing a high cooling load, and vice versa.

9.2 Example Model Application

For organisations with a large building stock, informing a strategy relating to stock level thermal loading is limited by understanding of the considered stock. It has been shown within this thesis that heterogeneity of a non-domestic stock proves a significant barrier in providing useful information that can inform strategic thinking.

Using a simple identifier for categorising a large number of buildings that accounts for stock variability can guide strategy by statistical analysis. To better place the model for use in this context, a hypothetical situation is developed and discussed here.

Supposing a local council, responsible for a portfolio of several hundred commercial office buildings wishes to implement a district heating system to those buildings. It is intended that a biomass plant be used with N kWh/year of available biomass, so for a system efficiency of e the overall available heating energy is denoted as N_e kWh/year.

The data available on the building stock is limited and information is needed as to the ability of the biomass plant to meet overall heating demands (H) placed on the district heating system. With what confidence can it be stated that $N_e \geq H$?

From the limited data that is available to the council, the building stock can only be categorised by period of construction, floor footprint and number of storeys. In so doing a downscaled version of the model can be run such that the weather profile is set constant for the local area and each building can be represented by setting its construction control period, floor footprint and number of storeys. These values are set via a controlling script that is explained by the initial (sequenced) parameter setting processes of figure 7.1.

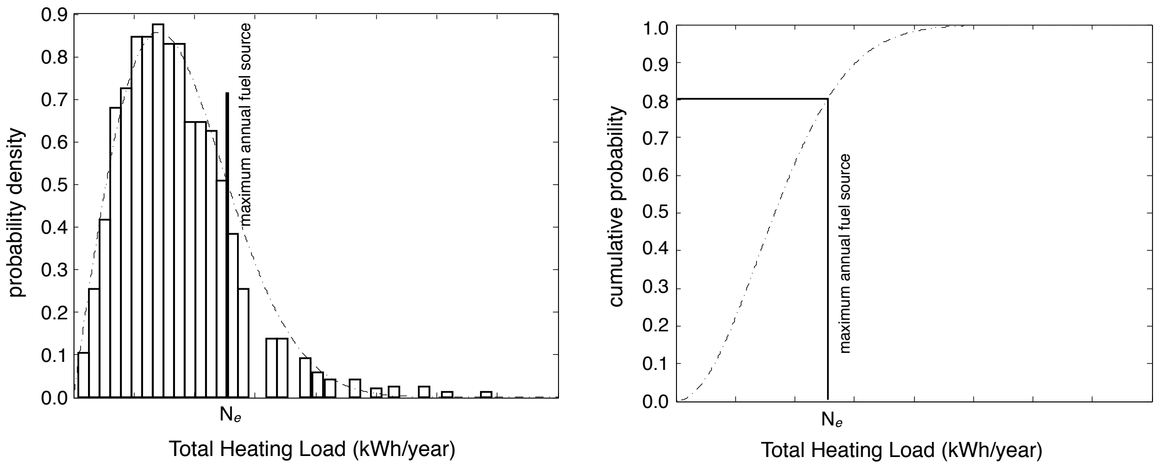
The model can be run for each building resulting in a probable thermal load for that building type, held in a *.grt* ascii file that is output by the DSM. To achieve a total yearly thermal load, normalised by floor area a further results analysis script is run, giving a value in kWh/m^2.year. It should be noted that this script can be modified to provide the total base thermal load as kWh/year or even on a monthly basis, depending on what level of information is required. It is seen in this example that a value of kWh/year is most appropriate.

A single value of thermal load for each building is meaningless due to very limited input data and the recognised uncertainty of building form and construction. It is, therefore, necessary to run the model using MCA, using the random selection of unknown parameters that are built into the model according to period of construction. For each downscaled instance of the model that is representative of a building in the local council's non-domestic stock, the model should be run to the order of 300 times[5].

With 300 simulations a stable distribution would start to emerge in the model results. Applying a goodness-of-fit test to the results (as demonstrated by the KS test in chapter 7) against theoretical continuous PDFs then provides a more complete sampling space for understanding the statistical variability in thermal load of the modelled buildings.

At this stage a further Monte-Carlo sampling procedure would be carried out[6] to understand the strategic question as to whether the proposed district heating system's fuel source will be capable of meeting demand.

Each PDF generated by the model represents a building in the given stock. A random value from each PDF should be taken and all values summed to determine a probable annual thermal load of the considered building stock. This process would be repeated multiple times (again until stability in the resulting distribution is observed).



(a) Histogram plot with a representative PDF overlay

(b) Plot of CDF relating to the representative PDF of the model results

Figure 9.1: Example of resulting model data informing strategic thinking. Total energy source marked on the PDF and CDF of the modelled thermal load of the building stock.

Figure 9.1 represents a hypothetical outcome of the model where the PDF and CDF demonstrate 80% confidence in the biomass plant being adequate for the thermal load of the considered building stock. With this information the council could carry out a risk analysis to determine whether back up fuel sources or heating systems should be considered within the strategy for district heating.

It is feasible to substitute the biomass example with other fuel source such as waste incinerators or even conventional gas boilers. The model could also be applied to other stock level considerations such as building refurbishment, retrofit of micro-generation technologies and the influence of a changing stock by percentage make-up of different construction periods.

[5]It is important to note at this point that whilst multiple simulations are computationally expensive, a greater amount of time, technical ability and knowledge are required for the more traditional deterministic approach of specific (detailed) building modelling.

[6]This time with the theoretical PDFs that have been deduced from the model of this thesis.

9.3 Validation

Validating the model was not feasible within the project time and funding scales. Different validation methods were, however, presented for completeness.

Sensitivity tests displayed physically reasonable behaviour, indicating correct model functionality in terms of thermal simulation and the parameter setting processes.

To validate the theoretically assessed parameter distributions extensive stock surveys, categorised by age of construction are necessary.

Part of the motivation for implementing a theoretical approach to thermal load assessment is that stock level surveys, providing detail of structural properties and form, are time consuming, invasive (to building occupants) and expensive. A stock level survey for validation was, therefore, beyond physical feasibility for this study.

Data sourced from existing surveys and publications from organisations/individuals considered as leading experts were used to partially validate parameter values where possible (see previous chapters).

Chapter 8 presents a case study building (modelled in detail as part of a thermal comfort study) for partial validation against a statistically downscaled version of the probability model.

9.4 Limitations

Many of the limitations have been discussed within the above sections in this chapter. A list of the main limitations in the study are provided for completeness.

- Validation - Theoretically derived (and simple - i.e. triangular) parameter distributions are currently not validated due to limited or no sample data
- Building model simplification -
    1. internal layout simplified to two representations only, cellular (four equally sized zones per storey) and open plan (one zone per storey)
    2. building shape limited to rectangular only
    3. level of attachment - the building model is in all instances detached with 4 external walls
    4. surrounding environment - uniform consideration of solar obstructions
    5. symmetry - equally distributed window wall ratio
    6. singular construction type - only one wall/window construction method applied to a building model; no consideration of combined construction types
    7. zone air connectivity - no internal air flow modelling considered
    8. no current ability to assess retrofit measures
- Model by-laws - no account for local government variation on these laws

9.5 Further Work

For earlier building periods, building controls were considered from model by-laws and associated standards. Model by-laws provide a guide by which local authorities can develop their own controlling laws. Investigating control laws by region may offer greater detail of structural components, further categorising buildings by location as well as date of construction.

To aid model development, the building models were limited in complexity as a result of the automated parameter setting requirement for Monte Carlo simulation. These simplifications restrict the ability of the model to capture the true diversity of the non-domestic building stock in England and Wales. Reducing these limitations depends on further development of:

- the database of basic building types - by level of attachment, shape, number of storeys
- increased complexity of form - both internal layout[7] and façade formation[8]
- dynamic simulation complexity (e.g. by considering internal air flow networks and potential operation of window openings within all models)

With a more complete database of building models and greater consideration of passive thermal behaviour (i.e. air flow) the model could be used to determine the stock level effectiveness of passive retrofit measures/technologies. This would require 'switches' that turn the considered technologies on and off within the model, so requiring two runs per randomly generated building model. This is currently considered beyond the capability of the chosen dynamic simulation tool (esp-r), but could potentially be used within the EP-Macro facility of EnergyPlus.

9.6 Summary

A fundamental aim of this research was to investigate the impact of construction period on thermal loading. By Monte Carlo modelling of building component form and construction[9], construction period was shown to influence the probable thermal loading of a non-domestic office building. In energy assessment of non-domestic buildings it is, therefore, beneficial to categorise buildings by construction period.

For each of the ten identified periods (1894 onwards), the modelling showed a variation in thermal load distributions. A trend of reducing mean heating load and increasing mean cooling load for latter control periods was modelled.

Some adjacent control periods displayed similar probable thermal loading. In these instances combining the periods in categorising the building stock would not adversely impact conclusions in stock level results. These similarities, however, are not consistent for all model types (i.e. variation for open plan and cellular models). As a result the ten control periods should be used in categorising the non-domestic building stock of England and Wales when researching stock level energy use and efficiency measures.

This thesis explored the potential of utilising dynamic simulation tools in stock level building energy assessment. With increased computing power, data storage facilities and continually improving dynamic

[7] Including component constructions as well as variation in zones.
[8] E.g. variable distribution of windows use of multiple walling constructions in one building.
[9] In relation to period of construction.

simulation models the approach will offer an efficient process by which a diverse building stock can be represented. This method also allows different realisations of future building stock, categorised by periods of construction, to be investigated for future trends in thermal loading. This can then be used to guide best regulation and retrofit policy for existing buildings. A stochastic modelling approach utilising dynamic thermal energy simulation tools, therefore, provides a useful process to aid policy making for a sustainable 'low carbon' building stock.

The applied modelling approach can only be analysed statistically, but at stock level statistical analysis is an appropriate form of inspection (i.e. applying confidence to impact of energy saving strategies). This, therefore, reduces the burden on capturing a fully detailed description of the non-domestic stock. By reducing building stock data requirements (or at least reducing the required detail of data inspection) the process can offer guidance to Government to ensure carbon reduction targets can be met.

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Appendices

In assessment of structural component variation in the building stock, building regulations were used as a method of identifying variation in component form. For later regulations components have been regulated by thermal transmittance. It was recognised that this did not account for thermal diffusivity, a dynamic thermal property accounting for thermal storage.

To investigate the influence of component form on dynamic thermal properties, cyclic dynamic response functions were applied. The theory of the steady-state thermal transmittance and the chosen response function method are provided in this appendix.

.1 Steady-state Thermal Property

The introduction of Building Energy Regulations in 1966 provide recommendations for thermal property requirements of a building's structural components. The main value used is the U-value - a measure of thermal transmittance (by conductive, convective and radiative processes) in a building component. Total thermal transmittance, U, of a wall is given by the inverse sum of thermal resistance, R , of each layer in the wall. For n layers, with each (i^{th}) layer of thermal conductivity κ_i and a thickness dx_i an overall U-value ($W/m^2.K$) is given by:

$$U = \frac{1}{\sum_{i=1}^{n} \frac{dx_i}{\kappa_i} + R_{si} + R_{se}} (W/m^2.K) \tag{1}$$

R_{si} and R_{se} are respectively, internal and external surface resistance due to convective and radiative properties.

.2 Dynamic Thermal Assessment - Admittance Method

From the Fourier Heat equation:

$$\frac{\partial^2 \theta}{\partial x^2} = \frac{1}{\alpha} \frac{\partial \theta}{\partial t} \tag{2}$$

α represents thermal diffusivity, a factor that accounts for thermal conductivity (k) and thermal flux.

$$\alpha = \frac{\kappa}{\rho C_p} (m^2/s) \tag{3}$$

Thermal diffusivity is considered a dynamic performance indicator, accounting for thermal storage potential as well as thermal conductivity.

Different methods can be applied to assess the dynamic thermal performance. Considering the walls in isolation a cyclic response function (admittance method [108, 179] - given in BS EN ISO 13786:1999) was used to assess dynamic thermal performance variation between external walls built under different control periods.

Using Laplace transformation to solve equation 2 for a given wall construction results in a relationship between internal and external temperature (θ) and flux (q) represented in matrix form as:

$$\begin{bmatrix} \theta_i \\ q_i \end{bmatrix} = \begin{bmatrix} 1 & -R_{si} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} m_1 & m_2 \\ m_3 & m_1 \end{bmatrix} \begin{bmatrix} n_1 & n_2 \\ n_3 & n_1 \end{bmatrix} \cdots \begin{bmatrix} 1 & -R_{se} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta_e \\ q_e \end{bmatrix} \tag{4}$$

where the matrices m, n $\cdots$ represent the properties of each layer in the considered wall that relate the internal and external temperature and heat flux. A matrix, M, represents the product of the matrices for each layer in the wall.

$$M = \begin{bmatrix} M_1 & M_2 \\ M_3 & M_4 \end{bmatrix} \tag{5}$$

The admittance method assumes a periodic cycle (usually 24 hours) for external temperature and heat flux variation. The response of the internal environment to the external cyclical conditions is dependent on the diffusivity (α) of each layer. This is described by a periodic penetration depth (δ) (equation 6) where the amplitude of the sinusoidal variation in external sol-air temperature is reduced by a factor of e (~2.781). The sol-air temperature is a hypothetical value that represents heat flux by at the external surface by convective and radiative processes.

$$\delta = \sqrt{\frac{Tk}{\pi \rho C_p}} (m) \tag{6}$$

where T is the period of one cycle in seconds.

For the admittance method,

$$m_1 = \cosh(p + ip) \tag{7}$$

$$m_2 = -\frac{dx \sinh(p + ip)}{k(p + ip)} \tag{8}$$

$$m_3 = -\frac{k(p + ip) sinh(p + ip)}{dx} \tag{9}$$

where,

$$p = (\frac{\pi \rho C_p dx^2}{Tk})^{0.5} \tag{10}$$

and i is the imaginary component of a complex number ($i^2 = -1$).

The admittance method is concerned with the internal building response to a cyclic variation in external conditions as a result of the considered component of the building envelope. The building component (i.e. external wall of building in this case) is considered in isolation to other components. The method provides three response factors used to describe this behaviour. Each response factor has an associated time lag/lead, where the construction causes a phase shift in the periodic variation in internal temperature to the external sol-air temperature.

The factors are: 1) **Decrement factor (f)** - ratio of external heat wave amplitude to the internal heat wave amplitude. It describes the dynamic internal-external temperature variation relating to thermal transmittance (U). This is calculated as:

$$f = |f_c| = |\frac{1}{-UM_2}|(-) \tag{11}$$

and decrement time lag

$$\phi_d = \frac{12}{\pi}\arctan(\frac{\Im(f_c)}{\Re(f_c)})(h) \tag{12}$$

2) **Admittance factor (Y)** - ratio of heat flux (environment node to internal surface) to the temperature deviation from the environmental node's mean temperature. This factor represents the thermal storage capability of the considered construction. It is calculated as:

$$Y = |Y_c| = |-\frac{M_4}{M_2}|(W/m^2.K) \tag{13}$$

and admittance time lead is

$$\phi_Y = \frac{12}{\pi}\arctan(\frac{\Im(Y_c)}{\Re(Y_c)})(h) \tag{14}$$

3) **Surface Response factor (s)** - ratio of re-admitted heat flux (to the internal environment node) to the total absorbed heat flux at constant temperature. This is calculated as:

$$s = |s_c| = |1 - R_{si}Y_c|(-) \tag{15}$$

and surface factor time lag is

$$\phi_s = \frac{12}{\pi}\arctan(\frac{\Im(s_c)}{\Re(s_c)})(h) \tag{16}$$

Appendix B

CONTROL PERIOD 1915-1938 Wall Thickness Charts for domestic (including commercial buildings not industrial or warehouse) [R. H. Harper. 1985. Victorian Building Regulations. Summary tables of the principal English Building Acts and Model By-laws 1840-1914.].

Table 1: SOLID BRICK WALL CONSTRUCTION

Minimum Wall Height (m)	30.48		27.432		24.384		21.336		18.288		15.24			12.192		7.62		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<8.82	<13.23	>13.23	<10.29	>10.29	<8.82	>8.82
Storey Wall Minimum Thickness (m)																			
1	0.7747	0.8763	0.6604	0.7747	0.6604	0.7747	0.5461	0.6604	0.5461	0.6604	0.4445	0.5461	0.4445	0.4445	0.5461	0.3302	0.4445	0.2159	0.3302
2	0.6604	0.7747	0.5461	0.6604	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.4445	0.3302	0.4445	0.4445	0.3302	0.3302	0.2159	0.2159
3	0.6604	0.7747	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0.3302	0	0
4	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0	0
5	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.2159	0.3302	0.3302	0	0	0	0
6	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0
7	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0
8	0.4445	0.5588	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0
9	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.3302	0.4445	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2: SOLID MASONRY STONE WALLING $\frac{4}{3}$ the thickness of equivalent brick wall.

Minimum Wall Height (m)	30.48		27.432		24.384		21.336		18.288		15.24		12.192			7.62		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<8.82	<13.23	>13.23	<10.29	>10.29	<8.82	>8.82
Storey Wall Minimum Thickness (m)																			
1	1.033	1.168	0.881	1.033	0.881	1.033	0.728	0.881	0.728	0.881	0.593	0.728	0.593	0.593	0.728	0.440	0.593	0.288	0.440
2	0.881	1.033	0.728	0.881	0.728	0.881	0.593	0.745	0.593	0.745	0.593	0.593	0.440	0.593	0.593	0.440	0.440	0.288	0.288
3	0.881	1.033	0.728	0.881	0.593	0.745	0.593	0.745	0.593	0.745	0.440	0.593	0.440	0.440	0.440	0.440	0.440	0.000	0.000
4	0.728	0.881	0.593	0.745	0.593	0.745	0.593	0.745	0.440	0.593	0.440	0.440	0.288	0.440	0.440	0.288	0.288	0.000	0.000
5	0.728	0.881	0.593	0.745	0.593	0.745	0.440	0.593	0.440	0.593	0.440	0.440	0.288	0.440	0.440	0.000	0.000	0.000	0.000
6	0.593	0.745	0.593	0.745	0.440	0.593	0.440	0.593	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.593	0.745	0.440	0.593	0.440	0.593	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.593	0.745	0.440	0.593	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.440	0.593	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.440	0.593	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3: BRICK CAVITY BRICK/BLOCK WALLING

Wall Minimum Height (m)	30.48		27.432		24.384		21.336		18.288		15.24		12.192			7.62		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<8.82	<13.23	>13.23	<10.29	>10.29	<8.82	>8.82
Storey	Wall Minimum Thickness (m)																		
1	0.6604	0.762	0.5461	0.6604	0.5461	0.6604	0.4318	0.5461	0.4318	0.5461	0.3302	0.4318	0.3302	0.3302	0.4318	0.2159	0.3302	0.1143	0.2159
2	0.5461	0.6604	0.4318	0.5461	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0.1143	0.1143
3	0.5461	0.6604	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0	0
4	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.2159	0.1016	0.2159	0.2159	0.1143	0.1143	0	0
5	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.1016	0.2159	0.2159	0	0	0	0
6	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0
7	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0
8	0.3302	0.4445	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0
9	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.2159	0.3302	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cavity Thickness (m)	0.0508	to	0.0762																
Thickness of inner Leaf (m)	0.1143																		

Table 4: MASONRY (BRICK/BLOCK) WALL CLADDING STEEL/CONCRETE FRAME STRUCTURE

Wall Minimum Height (m)	30.48		27.432		24.384		21.336		18.288		15.24		12.192			7.62		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<8.82	<13.23	>13.23	<10.29	>10.29	<8.82	>8.82
Storey	Wall Minimum Thickness (m)																		
1	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159
2	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159
3	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159	0	0
4	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0	0
5	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0
6	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0
7	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0
8	0.3302	0.3302	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0
9	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.3302	0.3302	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

CONTROL PERIOD 1939-1952 Wall Thickness Charts [G. E. Mitchell. 1939. Model Building Byelaws Illustrated.]

Table 5: REINFORCED CONCRETE SLAB WALLING

Wall Minimum Height (m)	30.48		27.432		24.384		21.336		18.288		15.24		12.192			7.62		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<8.82	<13.23	>13.23	<10.29	>10.29	<8.82	>8.82
Storey	Wall Minimum Thickness (m)																		
1	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016
2	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016
3	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0
4	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0
5	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0	0	0
6	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0	0	0	0	0	0
7	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0	0	0	0	0	0	0	0
8	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0	0	0	0	0	0	0	0	0	0
9	0.1016	0.1016	0.1016	0.1016	0.1016	0.1016	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.1016	0.1016	0.1016	0.1016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.1016	0.1016	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6: SOLID BRICK OR BLOCK WALL CONSTRUCTION

Wall Minimum Height (m)	27.432		24.384		21.336		18.288		15.24		12.192			9.144		7.62			4.572		0
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	<7.35	<7.35	>10.29	<8.82	>8.82	<8.82
Storey	Wall Minimum Thickness (m)																				
1	0.6604	0.762	0.6604	0.762	0.5588	0.6604	0.5588	0.6604	0.4445	0.5588	0.4445	0.4445	0.5588	0.3302	0.4445	0.2159	0.3302	0.3302	0.2159	0.3302	0.2159
2	0.5588	0.6604	0.5588	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.4445	0.3302	0.4445	0.4445	0.3302	0.3302	0.2159	0.2159	0.3302	0.2159	0.2159	0.2159
3	0.5588	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0
4	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4318	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0
5	0.4445	0.5588	0.4445	0.5588	0.3302	0.4318	0.3302	0.4318	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0	0	0	0	0	0
6	0.4445	0.5588	0.3302	0.4445	0.3302	0.4318	0.3302	0.4318	0.3302	0.3302	0.2159	0.3302	0.3302	0	0	0	0	0	0	0	0
7	0.3302	0.4445	0.3302	0.4445	0.3302	0.4318	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0
8	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7: NON-BRICK/BLOCK MASONRY WALLING (i.e. QUARRY STONE)

Wall Minimum Height (m)	27.432		24.384		21.336		18.288		15.24		12.192			9.144		7.62			4.572		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	<7.35	<7.35	>10.29	<8.82	>8.82	<8.82	>8.82
Storey	Wall Minimum Thickness (m)																					
1	0.881	1.016	0.881	1.016	0.745	0.881	0.745	0.881	0.593	0.745	0.593	0.593	0.745	0.440	0.593	0.288	0.440	0.440	0.288	0.440	0.288	0.587
2	0.745	0.881	0.745	0.881	0.593	0.745	0.593	0.745	0.593	0.593	0.440	0.593	0.593	0.440	0.440	0.288	0.288	0.440	0.288	0.288	0.288	0.406
3	0.745	0.881	0.593	0.745	0.593	0.745	0.593	0.745	0.440	0.593	0.440	0.440	0.440	0.288	0.440	0.288	0.288	0.288	0.288	0.288	0.000	0.000
4	0.593	0.745	0.593	0.745	0.593	0.745	0.440	0.576	0.440	0.440	0.288	0.440	0.440	0.288	0.288	0.288	0.288	0.288	0.000	0.000	0.000	0.000
5	0.593	0.745	0.593	0.745	0.440	0.576	0.440	0.576	0.440	0.440	0.288	0.440	0.440	0.288	0.288	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.593	0.745	0.440	0.593	0.440	0.576	0.440	0.576	0.440	0.440	0.288	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.440	0.593	0.440	0.593	0.440	0.576	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.440	0.593	0.440	0.440	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.440	0.440	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.440	0.440	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.440	0.440	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 8: BRICK-CAVITY-BRICK/BLOCK

Wall Minimum Height (m)	27.432		24.384		21.336		18.288		15.24		12.192			9.144		7.62			4.572		0	
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	<7.35	>7.35	>10.29	<8.82	>8.82	<8.82	>8.82
Storey	Wall Minimum Thickness (m)																					
1	0.6604	0.762	0.6604	0.762	0.5588	0.6604	0.5588	0.6604	0.4445	0.5588	0.4445	0.4445	0.5588	0.3302	0.4445	0.216	0.3302	0.3302	0.2159	0.3302	0.2159	0.2159
2	0.5588	0.6604	0.5588	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.4445	0.3302	0.4445	0.4445	0.3302	0.3302	0.216	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159
3	0.5588	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.3302	0.216	0.2159	0.2159	0.2159	0.2159	0	0
4	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4318	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0.216	0.2159	0.2159	0	0	0	0
5	0.4445	0.5588	0.4445	0.5588	0.3302	0.4318	0.3302	0.4318	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0	0	0	0	0	0	0
6	0.4445	0.5588	0.3302	0.4445	0.3302	0.4318	0.3302	0.4318	0.3302	0.3302	0.2159	0.3302	0.3302	0	0	0	0	0	0	0	0	0
7	0.3302	0.4445	0.3302	0.4445	0.3302	0.4318	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0
8	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.3302	0.3302	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Cavity thickness (m)	0.0508	to	0.0762
Thickness of Inner Leaf (m)	0.1143		

Table 9: MASONRY BRICK/BLOCK WALL CLADDING STEEL/CONCRETE FRAME

Wall Minimum Height (m)	27.432		24.384		21.336		18.288		15.24		12.192			9.144		7.62			4.572		0
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	<7.35	<7.35	>10.29	<8.82	>8.82	<8.82
Storey	Wall Minimum Thickness (m)																				
1	0.5461	0.6477	0.5461	0.6477	0.4445	0.5461	0.4445	0.5461	0.3302	0.4445	0.3302	0.3302	0.4445	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159
2	0.4445	0.5461	0.4445	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159
3	0.4445	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0
4	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.2159	0.3175	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0
5	0.3302	0.4445	0.3302	0.4445	0.2159	0.3175	0.2159	0.3175	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0
6	0.3302	0.4445	0.2159	0.3302	0.2159	0.3175	0.2159	0.3175	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0
7	0.2159	0.3302	0.2159	0.3302	0.2159	0.3175	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0
8	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10: REINFORCED CONCRETE SLAB WALLING

Wall Minimum Height (m)	27.432		24.384		21.336		18.288		15.24		12.192			9.144		7.62			4.572		0
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	<7.35	<7.35	>10.29	<8.82	>8.82	<8.82
Storey	Wall Minimum Thickness (m)																				
1	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159
2	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159
3	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0
4	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0
5	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0
6	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0
7	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0
8	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.2159	0.2159	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

CONTROL PERIOD 1953-1965 Wall thickness Charts [Ministry of Housing and Local Government. 1952. Model Byelaws: series iv: Buildings. 1952.]

Table 11: SOLID BRICK OR BLOCK WALL CONSTRUCTION

Wall Height (m)	30.48		27.432		24.384		21.336		18.288		15.24			12.192			9.144		3.6576		0
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	>13.23	<8.82	<8.82	<8.82	>8.82	>0
Storey	Wall Thickness (m)																				
1	0.762	0.8763	0.6604	0.762	0.6604	0.762	0.5461	0.6604	0.5461	0.6604	0.4445	0.4445	0.5461	0.4445	0.4445	0.4445	0.3302	0.3302	0.2159	0.3302	0.2159
2	0.6604	0.7747	0.5461	0.6604	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.4445	0.4445	0.3302	0.4445	0.4445	0.2159	0.3302	0.2159	0.2159	0
3	0.6604	0.7747	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0
4	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0.2159	0.2159	0
5	0.5461	0.6604	0.4445	0.5588	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.3302	0.3302	0.2159	0.2159	0	0	0
6	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.2159	0.3302	0	0	0	0	0
7	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0
8	0.4445	0.5588	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.2159	0.3302	0.3302	0	0	0	0	0	0	0	0
9	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0
10	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.3302	0.4445	0.3302	0.3302	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0.3302	0.4445	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0.3302	0.4445	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.3302	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12: BRICK/BLOCK CAVITY WALL CONSTRUCTION

Wall Minimum Height (m)	30.48		27.432		24.384		21.336		18.288		15.24			12.192			9.144		3.6576		0
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	>13.23	<8.82	<8.82	<8.82	>8.82	>0
Storey	Wall Minimum Thickness (m)																				
1	0.6604	0.7747	0.5588	0.6604	0.5588	0.6604	0.4445	0.5588	0.4445	0.5588	0.3429	0.3429	0.4445	0.3429	0.3429	0.3429	0.2286	0.2286	0.1143	0.2286	0.1143
2	0.5588	0.6731	0.4445	0.5588	0.4445	0.5588	0.3429	0.4572	0.3429	0.4572	0.3429	0.3429	0.3429	0.2286	0.3429	0.3429	0.1143	0.2286	0.1143	0.1143	0
3	0.5588	0.6731	0.3429	0.4572	0.3429	0.4572	0.3429	0.4572	0.3429	0.4572	0.2286	0.2286	0.3429	0.2286	0.2286	0.2286	0.1143	0.1143	0.1143	0.1143	0
4	0.4445	0.5588	0.3429	0.4572	0.3429	0.4572	0.3429	0.4572	0.2286	0.3429	0.2286	0.2286	0.2286	0.1143	0.2286	0.2286	0.1143	0.1143	0.1143	0.1143	0
5	0.4445	0.5588	0.3429	0.4572	0.3429	0.4572	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0.2286	0.1143	0.2286	0.2286	0.1143	0.1143	0	0	0
6	0.3429	0.4572	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0.2286	0.1143	0.1143	0.2286	0	0	0	0	0
7	0.3429	0.4572	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0.2286	0	0	0	0	0	0	0	0
8	0.3429	0.4572	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0.1143	0.2286	0.2286	0	0	0	0	0	0	0	0
9	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0
10	0.2286	0.3429	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.2286	0.3429	0.2286	0.3429	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.2286	0.3429	0.2286	0.2286	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0.2286	0.3429	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0.2286	0.3429	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.2286	0.2286	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Cavity Thickness (m)	0.0506	to	0.0762
Thickness of Inner Leaf (m)	0.1143		

Table 13: MASONRY BRICK/BLOCK CLAD FRAMED STRUCTURE - REINFORCED BRICK/CONCRETE BLOCK WALLING

Wall Minimum Height (m)	30.48		27.432		24.384		21.336		18.288		15.24			12.192			9.144		3.6576		0
Wall Length (m)	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<13.23	>13.23	<10.29	>10.29	>13.23	<10.29	>10.29	>13.23	<8.82	<8.82	<8.82	>8.82	>0
Storey	Wall Minimum Thickness (m)																				
1	0.6477	0.9906	0.5461	0.6477	0.5461	0.6477	0.4318	0.5461	0.4318	0.5461	0.3302	0.3302	0.4318	0.3302	0.3302	0.3302	0.2159	0.2159	0.1016	0.2159	0.1016
2	0.5461	0.6604	0.4318	0.5461	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.3302	0.3302	0.2159	0.3302	0.3302	0.1016	0.2159	0.1016	0.1016	0
3	0.5461	0.6604	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.2159	0.2159	0.3302	0.2159	0.2159	0.2159	0.1016	0.1016	0.1016	0.1016	0
4	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.2159	0.2159	0.1016	0.2159	0.2159	0.1016	0.1016	0.1016	0.1016	0
5	0.4318	0.5461	0.3302	0.4445	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0.1016	0.2159	0.2159	0.1016	0.1016	0	0	0
6	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0.1016	0.1016	0.2159	0	0	0	0	0
7	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0
8	0.3302	0.4445	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.1016	0.2159	0.2159	0	0	0	0	0	0	0	0
9	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0
10	0.2159	0.3302	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0.2159	0.3302	0.2159	0.3302	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0.2159	0.3302	0.2159	0.2159	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0.2159	0.3302	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0.2159	0.3302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.2159	0.2159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 14: MINIMUM THICKNESS TO MEET 1 HOUR FIRE RESISTANCE REQUIREMENT OF EXTERNAL WALL APPLICABLE TO FRAME CLAD WALLING

Material	Concrete Block	Crushed Stone Block	Gypsum Block	Reinforced Concrete	Bricks (clay)	Plaster Board	Glass Bricks	Clay Blocks (Hollow)	Concrete Hollow Block Plastered	Crushed Stone Hollow Block (plastered)	Gypsum Hollow Block
Thickness for 1 hour fire resistance (m)	0.1016	0.1016	0.1016	0.1016	0.2159	0.0508	0.1016	0.2159	0.1143	-	0.1016

APPENDIX 4A - BUILDING CONTROLS FOR WALL CONSTRUCTION OF COMMON CONSTRUCTION METHODS IN NON-DOMESTIC BUILDING STOCK

CONTROL PERIOD – 1966-1971 – Building Regulations 1965 - Statutory Instruments No. 1373
No use of Wall Thickness charts – Building Regulations stipulate minimum wall thickness by fire, sound and basic thermal insulation levels.

U-value (when surface resistances are taken as 0.18) ≤ 1.70 W/m².K
SMALL BUILDING – Not greater than 12.19m (40 feet) in height with a maximum bearing load 292.9kg/m² (60lbs/square foot). - **Schedule 7 of S.I No. 1373**
Solid Brick/Block Wall – Up to 3.66m (12 feet) in height, **minimum wall thickness of 0.2032m (8 inches)**

- Between 3.66m (12 feet) to 9.14m (30 feet) in height
  - Wall length <= 9.14m, **minimum wall thickness of 0.2032m (8 inches)**
  - Wall length > 9.14m, **minimum wall thickness of 0.3048m (12 inches)**
- Between 9.14m (30 feet) to 12.19m (40 feet) in height
  - Wall length <= 9.14m, **minimum wall thickness of 0.3048m (12 inches) for 1st storey, 0.2032m (8 inches) above**
  - Wall length > 9.14m, **minimum wall thickness of 0.3048m (12 inches) for first two storeys, 0.2032m (8 inches) above**

Thermal Insulation of External Walls controlled by **Schedule 11 of Statutory Instruments No. 1373 (values converted from Imperial to Metric):**

	PLASTER	INTERNAL WALL	CAVITY	EXTERNAL WALL	
A	**Y**	Brick work min thickness 0.1016m	min. 0.0508m max. 0.0762m	Brick work min. thickness 0.1016m	
B	**Y**	Aerated Concrete Block density ≤ 1922.22kg/m³ min thickness 0.1016m	min. 0.0508m max. 0.0762m	Aerated Concrete Block density ≤ 1922.22kg/m³ min. thickness 0.1016m	
C	**Y**	Aerated Concrete Block density > 1922.22kg/m³ min. thickness 0.1524m	min. 0.0508m max. 0.0762m	Aerated Concrete Block density > 1922.22kg/m³ min. thickness 0.1524m	
D	**Y**	Hollow Clay Block min. thickness 0.0762m	min. 0.0508m max. 0.0762m	Aerated Concrete Block density > 1922.22kg/m³ min. thickness 0.1524m **or** Brick work min. thickness 0.1016m **or** Aerated Concrete Block density ≤ 1922.22kg/m³ min. thickness 0.1016m	**(i)** **(ii)** **(iii)**
E	**Y**	Cellular/Aerated Concrete Block min. thickness 0.0762m density ≤ 1601.85kg/m³	min. 0.0508m max. 0.0762m	Aerated Concrete Block density > 1922.22kg/m³ min. thickness 0.1524m **or** Brick work min. thickness 0.1016m **or** Aerated Concrete Block density ≤ 1922.22kg/m³ min. thickness 0.1016m	**(i)** **(ii)** **(iii)**

F	**X**	Timber Stud Frame min. thickness 0.0762m	min. 0.0508m max. 0.0762m	Aerated Concrete Block density > 1922.22kg/m³ min. thickness 0.1524m **or** Brick work min. thickness 0.1016m **or** Aerated Concrete Block density ≤ 1922.22kg/m³ min. thickness 0.1016m	**(i)** **(ii)** **(iii)**
			STUD WALL LINING Fibreboard ≥ 0.0127m thick **or** Insulating Gypsum Plaster ≥ 0.0095m thick		
G	**Y**	Compressed Straw Slabs min. thickness 0.0762m	min. 0.0508m max. 0.0762m	Aerated Concrete Block density > 1922.22kg/m³ min. thickness 0.1524m **or** Brick work min. thickness 0.1016m **or** Aerated Concrete Block density ≤ 1922.22kg/m³ min. thickness 0.1016m	**(i)** **(ii)** **(iii)**
H	**Y**	Hollow Clay Blocks min. thickness 0.0762m	min. 0.0508m max. 0.0762m	Hollow Clay Blocks min. thickness 0.0762m	
I	**Y**	Cellular/Aerated Concrete Blocks density ≤ 1601.85kg/m³ min. thickness 0.0762m	min. 0.0508m max. 0.0762m	Cellular/Aerated Concrete Blocks density ≤ 1601.85kg/m³ min. thickness 0.0762m	

SOLID WALL CONSTRUCTION

	PLASTER	WALL MATERIAL	DENSITY	MINIMUM THICKNESS	
J	**Y**	Cellular/Aerated Concrete Block	ρ ≤ 1441.66kg/m³	0.2032m	**(i)**
			1441.66kg/m³ < ρ ≤ 1601.85kg/m³	0.2540m	**(ii)**
			1601.85kg/m³ < ρ ≤ 1762.03kg/m³	0.3048m	**(iii)**
K	**Y**	Stone/Conrete Wall		0.3556m	**(i)**
		with			
		Internal backing of C/A Concrete Block	ρ ≤ 1441.66kg/m³	0.1016m	**(ii)**

APPENDIX 4A - BUILDING CONTROLS FOR WALL CONSTRUCTION OF COMMON CONSTRUCTION METHODS IN NON-DOMESTIC BUILDING STOCK

CONTROL PERIOD – 1972-1976 – Building Regulations 1972 - Statutory Instruments No. 317
No use of Wall Thickness charts – Building Regulations stipulate minimum wall thickness by fire, sound and basic thermal insulation levels.

U-value (when surface resistances are taken as 0.18) ≤ 1.70 $W/m^2.K$
SMALL BUILDING – Not greater than 12m in height with a maximum bearing load of $3kN/m^2$. - **Schedule 7 of S.I No. 317 (values given in Metric units)**
Solid Brick/Block Wall – Up to 3.6m in height, **minimum wall thickness of 0.2000m**

- Between 3.6m to 9m in height
  - Wall length <= 9m, **minimum wall thickness of 0.2000m**
  - Wall length > 9m, **minimum wall thickness of 0.3000m**
- Between 9m to 12m in height
  - Wall length <= 9m, **minimum wall thickness of 0.3000m for 1^{st} storey, 0.2000m above**
  - Wall length > 9m, **minimum wall thickness of 0.3000m for first two storeys, 0.2000m above**

Thermal Insulation of External Walls controlled by **Schedule 11 of Statutory Instruments No. 317 (values given in Metric units):**

	PLASTER	INTERNAL WALL	CAVITY	EXTERNAL WALL	
A	**Y**	Brick work min thickness 0.1000m	min. 0.050m max. 0.075m	Brick work min. thickness 0.1000m	
B	**Y**	Aerated Concrete Block density ≤ 1920.00kg/m^3 min thickness 0.1000m	min. 0.050m max. 0.075m	Aerated Concrete Block density ≤ 1920.00kg/m^3 min. thickness 0.1000m	
C	**Y**	Aerated Concrete Block density > 1920.00kg/m^3 min. thickness 0.1500m	min. 0.050m max. 0.075m	Aerated Concrete Block density > 1920.00kg/m^3 min. thickness 0.1500m	
D	**Y**	Hollow Clay Block min. thickness 0.075m	min. 0.050m max. 0.075m	Aerated Concrete Block density > 1920.00kg/m^3 min. thickness 0.1500m **or** Brick work min. thickness 0.1000m **or** Aerated Concrete Block density ≤ 1920.00kg/m^3 min. thickness 0.1000m	**(i)** **(ii)** **(iii)**
E	**Y**	Cellular/Aerated Concrete Block min. thickness 0.075m density ≤ 1600.00kg/m^3	min. 0.050m max. 0.075m	Aerated Concrete Block density > 1920.00kg/m^3 min. thickness 0.1500m **or** Brick work min. thickness 0.1000m **or** Aerated Concrete Block density ≤ 1920.00kg/m^3 min. thickness 0.1000m	**(i)** **(ii)** **(iii)**

APPENDIX 4A - BUILDING CONTROLS FOR WALL CONSTRUCTION OF COMMON CONSTRUCTION METHODS IN NON-DOMESTIC BUILDING STOCK

F	X	Timber Stud Frame min. thickness 0.075m	min. 0.050m max. 0.075m	Aerated Concrete Block density > 1920.00kg/m^3 min. thickness 0.1500m **or**	**(i)**
				Brick work min. thickness 0.1000m **or**	**(ii)**
				Aerated Concrete Block density ≤ 1920.00kg/m^3 min. thickness 0.1000m	**(iii)**
		STUD WALL LINING Fibreboard ≥ 0.0125m thick **or** Insulating Gypsum Plaster ≥ 0.0095m thick			
G	Y	Compressed Straw Slabs min. thickness 0.075m	min. 0.050m max. 0.075m	Aerated Concrete Block density > 1920.00kg/m^3 min. thickness 0.1500m **or**	**(i)**
				Brick work min. thickness 0.1000m **or**	**(ii)**
				Aerated Concrete Block density ≤ 1920.00kg/m^3 min. thickness 0.1000m	**(iii)**
H	Y	Hollow Clay Blocks min. thickness 0.075m	min. 0.050m max. 0.075m	Hollow Clay Blocks min. thickness 0.075m	
I	Y	Cellular/Aerated Concrete Blocks density ≤ 1600.00kg/m^3 min. thickness 0.075m	min. 0.050m max. 0.075m	Cellular/Aerated Concrete Blocks density ≤ 1600.00kg/m^3 min. thickness 0.075m	

SOLID WALL CONSTRUCTION

	PLASTER	WALL MATERIAL	DENSITY	MINIMUM THICKNESS	
J	**Y**	Cellular/Aerated Concrete Block	$\rho \leq 1440.00kg/m^3$	0.2000m	**(i)**
			$1440.00kg/m^3 < \rho \leq 1600.00kg/m^3$	0.2500m	**(ii)**
			$1600.00kg/m^3 < \rho \leq 1760.00kg/m^3$	0.3000m	**(iii)**
K	**Y**	Stone/Conrete Wall with		0.3500m	**(i)**
		Internal backing of C/A Concrete Block	$\rho \leq 1440.00kg/m^3$	0.1000m	**(ii)**

APPENDIX 4A - BUILDING CONTROLS FOR WALL CONSTRUCTION OF COMMON CONSTRUCTION METHODS IN NON-DOMESTIC BUILDING STOCK

CONTROL PERIOD – 1977-1984 – Building Regulations 1976 - Statutory Instruments No. 1676
No use of Wall Thickness charts – Building Regulations stipulate minimum wall thickness by fire, sound and basic thermal insulation levels.

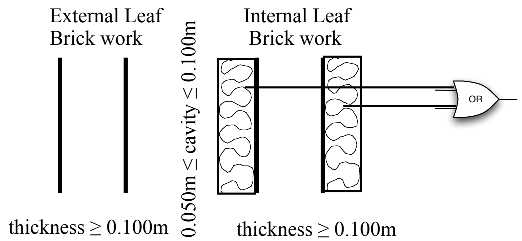
U-value (when surface resistances are taken as 0.18) ≤ 1.0 W/m².K
SMALL BUILDING – Not greater than 12m in height with a maximum bearing load of 3kN/m² . - **Schedule 7 of S.I No. 1676 (values given in Metric units)**
Solid Brick/Block Wall – Up to 3.5m in height, maximum wall length 12m **minimum wall thickness of 0.1900m**

- Between 3.5m to 9m in height
  - Wall length <= 9m, **minimum wall thickness of 0.1900m**
  - Wall length > 9m, **minimum wall thickness of 0.2900m for 1st storey, 0.1900m above**
- Between 9m to 12m in height
  - Wall length <= 9m, **minimum wall thickness of 0.2900m for 1st storey, 0.1900m above**
  - Wall length > 9m, **minimum wall thickness of 0.2900m for first two storeys, 0.1900m above**

Thermal Insulation of External Walls controlled by **Schedule 11 of Statutory Instruments No. 1676 (values given in Metric units):**

BRICK - CAVITY - BRICK

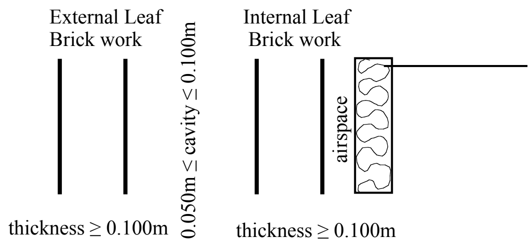
A



Insulation applied to either side of internal leaf:

(i) Compressed Straw Slab - 0.029m
(ii) Wood Wool Slab (ρ ≤ 400.00kg/m³) - 0.022m
(iii) Fibre Insulating Board - 0.016m
(iv) Corkboard - 0.012m
(v) Mineral Fibre Slab - 0.010m

B

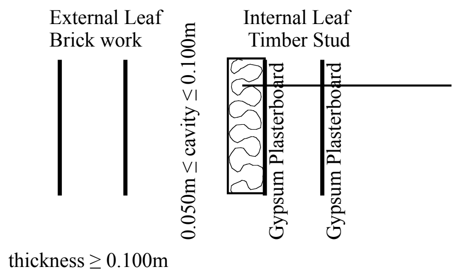


Regulated Insulation Layer:

(i) Asbestos Insulating Board - 0.013m
(ii) Wood Wool Slab (ρ ≤ 400.00kg/m³) - 0.008m
(iii) Fibre Insulating Board - 0.006m
(iv) Corkboard - 0.005m
(v) Mineral Fibre Slab - 0.003m

BRICK WALL WITH TIMBER STUD INNER LEAF

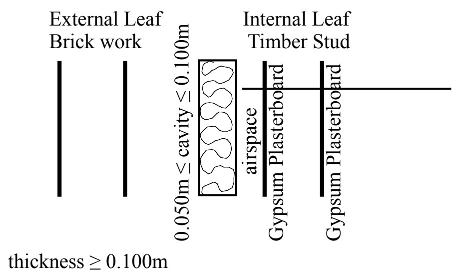
C



Insulation:

(i) Compressed Straw Slab - 0.049m
(ii) Wood Wool Slab (ρ ≤ 400.00kg/m³) - 0.037m
(iii) Fibre Insulating Board - 0.025m
(iv) Corkboard - 0.020m
(v) Mineral Fibre Slab - 0.017m

D

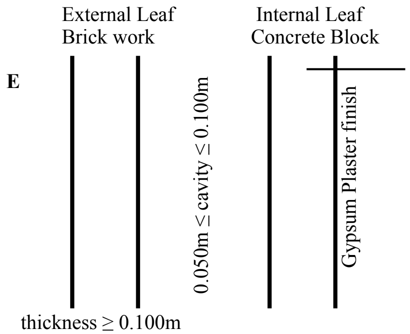


Insulation:

(i) Compressed Straw Slab - 0.031m
(ii) Wood Wool Slab (ρ ≤ 400.00kg/m³) - 0.023m
(iii) Fibre Insulating Board - 0.017m
(iv) Corkboard - 0.013m
(v) Mineral Fibre Slab - 0.010m
(vi) Polystyrene Board - 0.010m

APPENDIX 4A - BUILDING CONTROLS FOR WALL CONSTRUCTION OF COMMON CONSTRUCTION METHODS IN NON-DOMESTIC BUILDING STOCK

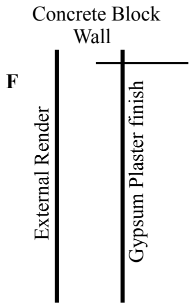
BRICK OUTER LEAF - CAVITY-CONCRETE BLOCK INNER LEAF



Insulation from concrete block:

Wall Thickness (m)	Block Density (kg/m³)
(i) 0.240	1200 < ρ ≤ 1400
(ii) 0.180	1000 < ρ ≤ 1200
(iii) 0.140	800 < ρ ≤ 1000
(iv) 0.108	600 < ρ ≤ 800
(v) 0.084	ρ ≤ 600

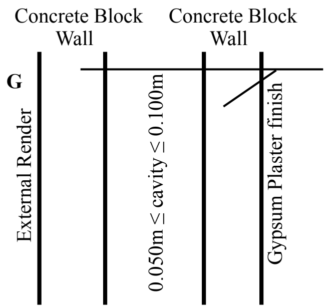
CONCRETE BLOCK WALL - SOLID



Insulation from concrete block:

Wall Thickness (m)	Block Density (kg/m³)
(i) 0.400	1200 < ρ ≤ 1400
(ii) 0.300	1000 < ρ ≤ 1200
(iii) 0.240	800 < ρ ≤ 1000
(iv) 0.190	600 < ρ ≤ 800
(v) 0.150	ρ ≤ 600

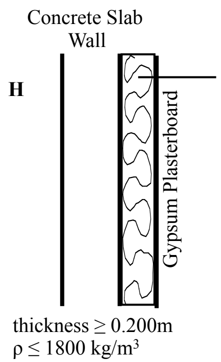
CONCRETE BLOCK CAVITY WALL



Insulation from concrete walls:

Wall Layer Thickness (m)	Block Density (kg/m³)
(i) 0.290	1200 < ρ ≤ 1400
(ii) 0.225	1000 < ρ ≤ 1200
(iii) 0.175	800 < ρ ≤ 1000
(iv) 0.140	600 < ρ ≤ 800

CONCRETE SLAB WALL



Insulation:

(i) Compressed Straw Slab - 0.049m
(ii) Wood Wool Slab (ρ ≤ 400.00kg/m³) - 0.037m
(iii) Fibre Insulating Board - 0.025m
(iv) Corkboard - 0.020m
(v) Mineral Fibre Slab - 0.017m

OR AIR SPACE BEFORE INSULATION LAYER

(i) Compressed Straw Slab - 0.031m
(ii) Wood Wool Slab (ρ ≤ 400.00kg/m³) - 0.023m
(iii) Fibre Insulating Board - 0.017m
(iv) Corkboard - 0.013m
(v) Mineral Fibre Slab - 0.010m
(vi) Polystyrene Board - 0.010m

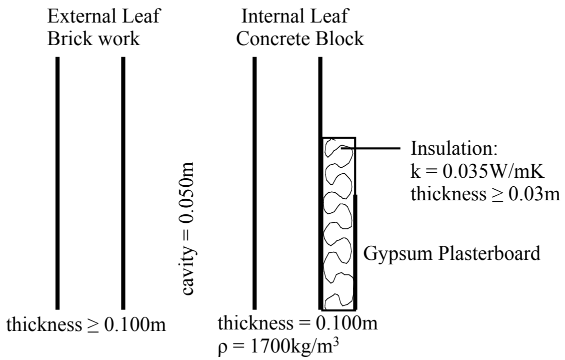
APPENDIX 4A - BUILDING CONTROLS FOR WALL CONSTRUCTION OF COMMON CONSTRUCTION METHODS IN NON-DOMESTIC BUILDING STOCK

1985-1990 PART L - BUILDING ENERGY REGULATIONS (FROM 1984 BUILDING ACT)

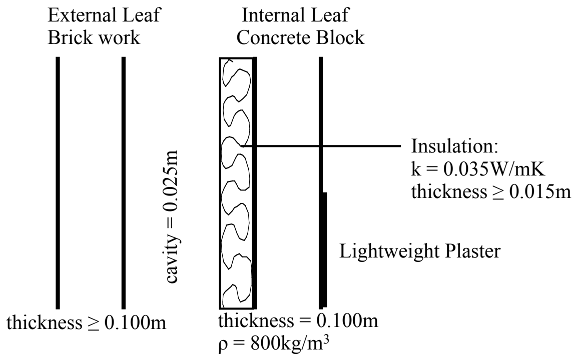
Minimum exposed wall U-value = 0.7W/m^2.K

BRICK-CAVITY-BLOCK WALLING

A



B



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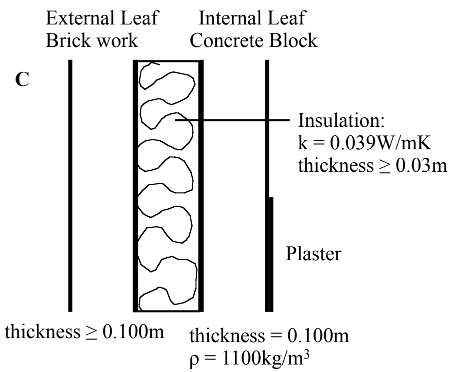
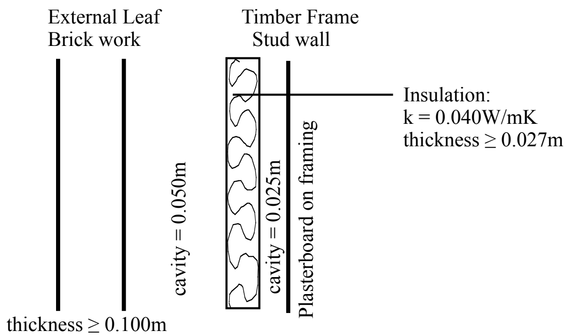
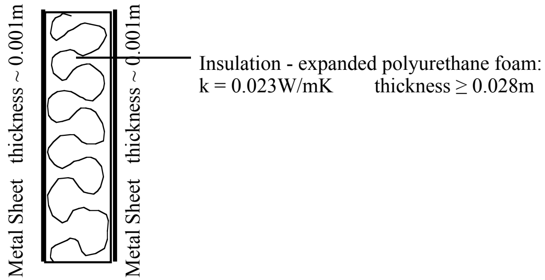


D



COMPOSITE METAL PANEL

E

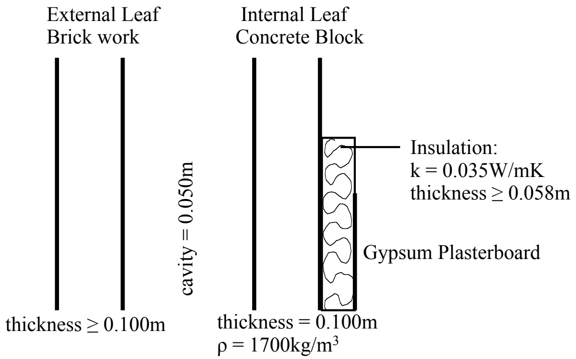


1991-1995 PART L - BUILDING ENERGY REGULATIONS and 1996-2001 PART L - BUILDING ENERGY REGULATIONS

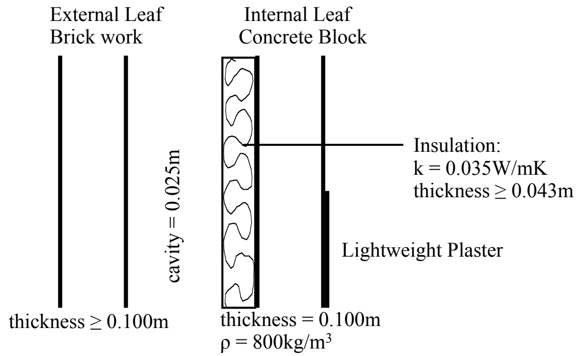
Minimum exposed wall U-value = 0.45W/m².K

BRICK-CAVITY-BLOCK WALLING

A



B



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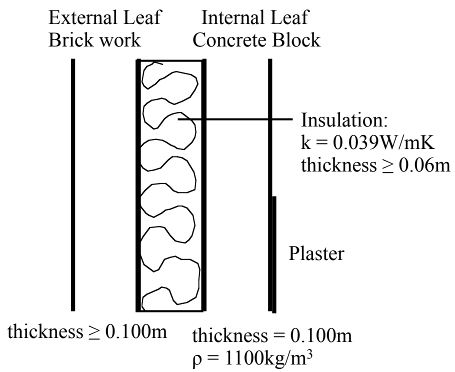

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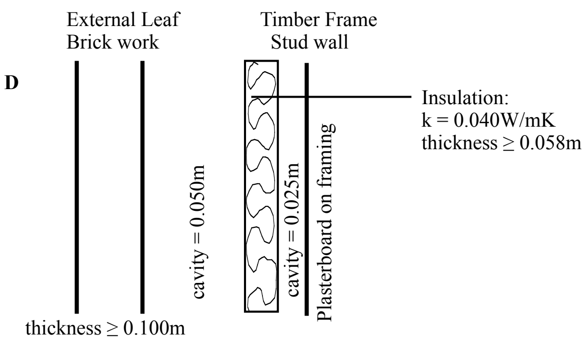
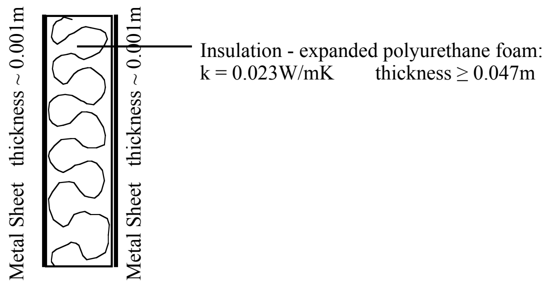


COMPOSITE METAL PANEL

E

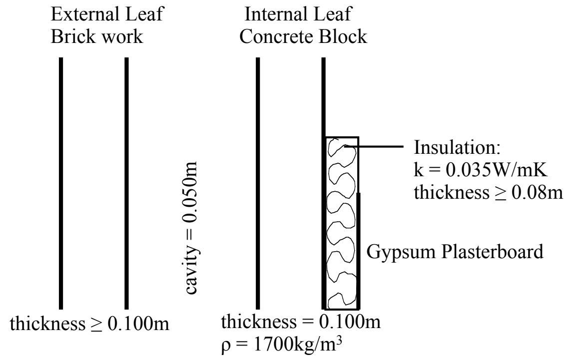


2002-2006 PART L - BUILDING ENERGY REGULATIONS and 2006-Present (2008) PART L - BUILDING ENERGY REGULATIONS

Minimum exposed wall U-value = 0.35W/m².K

BRICK-CAVITY-BLOCK WALLING

A



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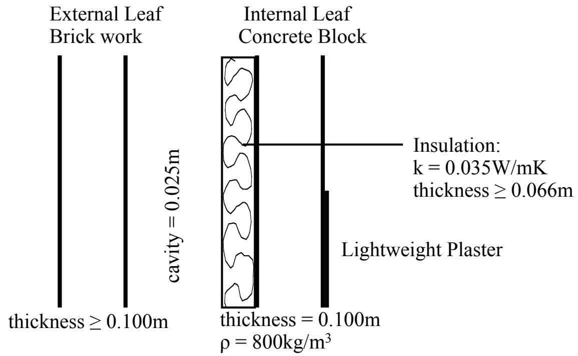

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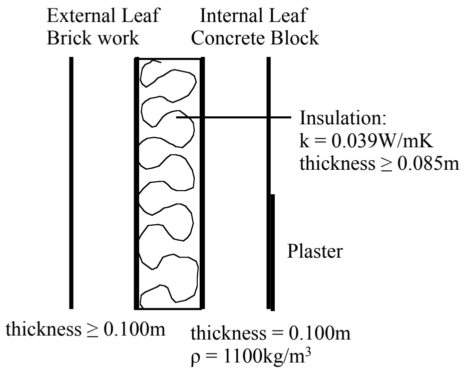

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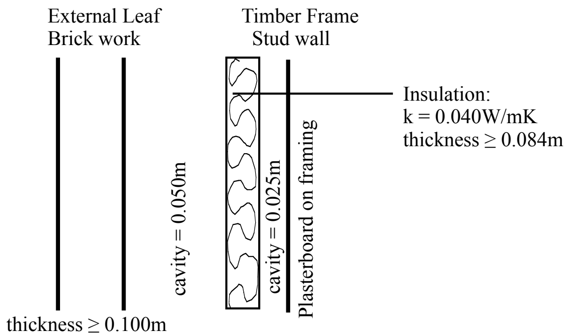
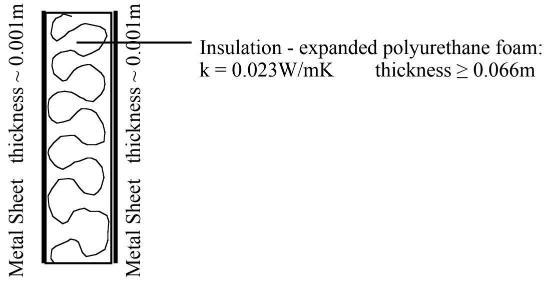


COMPOSITE METAL PANEL

E



Typical wall construction methods and variation identified in the building regulations. This is not considered exhuastive for the non-domestic building stock - further development of standard wall constructions in each Control Period would give greater scope to the model. Identifying distribution of use of these methods in the stock, by control period would give a more complete probability assessment.

Equal probability applied to each construction type identified for each control period. Post 'Wall Thickness Charts' buildings above 3 storeys assumed to be constructed as non-load bearing walls. Therefore wall construction assumed equal at each level.

Appendix C

NOTE OF CURRENT PROBABILITY MODEL USE

In all cases the model only applies logic to determine insulation thickness with insulation material conductivity (k) of 0.035W/m.K. Insulation thickness in all tables given in units of mm.

BUILDING REGULATIONS 1991 - 1995

4B-1 Solid Floor in Contact with Ground - detached building U = 0.45 W/m².K

Insulating Material Thermal Conductivity (k = W/m.K)	Greater dimension of floor (m)							
	< 10	10 -15		15 - 20			> 20	
	Lesser dimension of floor (m)							
	< 10	< 10	10 - 15	< 10	10 -15	15 - 20	< 10	≥ 10
0.025	31	25	15	22	-	-	21	-
0.03	38	30	18	26	-	-	25	-
0.035	**44**	**35**	**21**	**31**	**11**	**-**	**29**	**-**
0.04	50	39	24	35	13	-	33	-
0.045	57	44	27	40	14	-	37	-
0.05	63	49	30	44	16	-	41	-

4B-2 Solid Floor in Contact with Ground - semi-detached/end terrace building U = 0.45 W/m².K

Insulating Material Thermal Conductivity (k = W/m.K)	Greater dimension of floor (m)							
	< 10	10 -15		15 - 20			> 20	
	Lesser dimension of floor (m)							
	< 10	< 10	10 - 15	< 10	10 -15	15 - 20	< 10	≥ 10
0.025	25	21	-	19	-	-	18	-
0.03	30	25	-	23	-	-	22	-
0.035	**35**	**29**	**-**	**27**	**-**	**-**	**26**	**-**
0.04	39	33	-	30	-	-	29	-
0.045	44	37	-	34	-	-	33	-
0.05	49	41	-	38	-	-	37	-

4B-3 Solid Floor in Contact with Ground - mid-terrace building U = 0.45 W/m^2.K

Insulating Material Thermal Conductivity (k = W/m.K)	Distance between exposed edges of floor (m)	
	< 10	≥ 10
0.025	16	-
0.03	19	-
0.035	**22**	**-**
0.04	25	-
0.045	29	-
0.05	32	-

4B-4 Suspended Ground Floor - detached building U = 0.45 W/m^2.K

Insulating Material Thermal Conductivity (k = W/m.K)	Greater dimension of floor (m)							
	< 10	10 -15		15 - 20			> 20	
	Lesser dimension of floor (m)							
	< 10	< 10	10 - 15	< 10	10 -15	15 - 20	< 10	≥ 10
0.025	26	22	12	20	-	-	19	-
0.03	31	26	14	24	-	-	23	-
0.035	**36**	**30**	**17**	**28**	**-**	**-**	**27**	**-**
0.04	42	34	19	32	11	-	30	-
0.045	47	39	21	36	12	-	34	-
0.05	52	43	24	40	13	-	38	-

4B-5 Suspended Ground Floor - semi-detached/end terrace building U = 0.45 W/m^2.K

Insulating Material Thermal Conductivity (k = W/m.K)	Greater dimension of floor (m)							
	< 10	10 -15		15 - 20			> 20	
	Lesser dimension of floor (m)							
	< 10	< 10	10 - 15	< 10	10 -15	15 - 20	< 10	≥ 10
0.025	22	19	-	18	-	-	18	-
0.03	26	23	-	22	-	-	21	-
0.035	**30**	**27**	**-**	**25**	**-**	**-**	**25**	**-**
0.04	34	30	-	29	-	-	28	-
0.045	39	34	-	33	-	-	32	-
0.05	43	38	-	36	-	-	35	-

4B-6 Suspended Ground Floor - mid-terrace building U = 0.45 W/m².K

Insulating Material Thermal Conductivity (k = W/m.K)	Distance between exposed edges of floor (m)	
	< 10	≥ 10
0.025	16	-
0.03	20	-
0.035	**23**	**-**
0.04	26	-
0.045	29	-
0.05	33	-

4B-7 Exposed Ground Floor - mid-terrace building U = 0.45 W/m².K

Insulating Material Thermal Conductivity (k = W/m.K)		Allowable reduction in basic thickness (mm)		
	Basic Thickness (mm)	Base Concrete slab ≥ 30.150m	Top Screed ≥ 0.075m	Wood Block Top finish ≥ 0.010m
0.025	51	3	5	2
0.03	61	4	6	2
0.035	**72**	**5**	**7**	**3**
0.04	82	5	7	3
0.045	92	6	8	3
0.05	102	7	9	4

BUILDING REGULATIONS 1996 - 2001

Ground floor insulation determined by ratio of floor perimeter P (m) to floor area A (m^2). Concrete slab thickness equivalent to the minimum stated in 1985 regulations (0.1m). Insulation thickness given in mm.

4B-8 Solid Floor in Contact with Ground - U = 0.45 $W/m^2.K$ (insulation on inside surface)

	Insulation Thermal Conductivity (W/m.K)						
P/A	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
1	26	33	39	**46**	53	59	66
0.9	25	32	38	**44**	51	57	63
0.8	24	30	36	**42**	48	54	60
0.7	22	28	34	**39**	45	51	56
0.6	20	25	30	**35**	40	45	50
0.5	17	21	25	**30**	34	38	42
0.4	12	15	18	**21**	24	27	30
0.3	4	5	6	**6**	7	8	9
<0.27	0	0	0	**0**	0	0	0

4B-9 Suspended Timber Ground Floor - U = 0.45 $W/m^2.K$ (insulation on external surface)

	Insulation Thermal Conductivity (W/m.K)						
P/A	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
1	37	44	51	**57**	64	70	77
0.9	35	42	49	**55**	62	68	74
0.8	33	40	46	**53**	59	65	70
0.7	31	37	43	**49**	54	60	65
0.6	27	33	38	**43**	49	54	58
0.5	22	27	32	**36**	40	44	49
0.4	15	18	22	**25**	28	31	34
0.3	4	5	6	**7**	8	9	10
<0.27	0	0	0	**0**	0	0	0

4B-10 Suspended Concrete Floor - U = 0.45 W/m².K (insulation on inside surface)

	Insulation Thermal Conductivity (W/m.K)						
P/A	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
1	24	30	36	**42**	48	54	60
0.9	23	29	35	**41**	46	52	58
0.8	22	28	33	**39**	44	50	55
0.7	20	25	31	**36**	41	46	51
0.6	18	23	27	**32**	36	41	45
0.5	15	18	22	**26**	29	33	37
0.4	10	12	15	**17**	19	22	24
0.3	2	2	2	**3**	3	4	4
<0.27	0	0	0	**0**	0	0	0

BUILDING REGULATIONS 2002-2006 & 2006-Present

Ground floor insulation determined by ratio of floor perimeter P (m) to floor area A (m^2). Concrete slab thickness equivalent to the minimum stated in 1985 regulations (0.1m). Insulation thickness given in mm.

4B-11 Solid Floor in Contact with Ground - U = 0.25 $W/m^2.K$ (insulation on inside surface)

	Insulation Thermal Conductivity (W/m.K)						
P/A	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
1	61	76	91	**107**	122	137	152
0.9	60	75	90	**105**	120	135	150
0.8	58	73	88	**102**	117	132	146
0.7	57	71	85	**99**	113	126	142
0.6	54	68	82	**95**	109	122	136
0.5	51	64	77	**90**	103	115	128
0.4	47	59	70	**82**	94	105	117
0.3	40	49	59	**69**	79	89	99
0.2	26	32	39	**45**	52	58	65

4B-12 Suspended Timber Ground Floor - U = 0.25 $W/m^2.K$ (insulation on external surface)

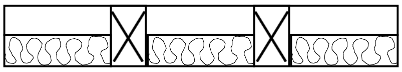
	Insulation Thermal Conductivity (W/m.K)						
P/A	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
1	93	107	121	**135**	149	162	176
0.9	92	106	119	**133**	146	160	173
0.8	90	104	117	**131**	144	157	170
0.7	88	101	114	**127**	140	153	166
0.6	85	98	111	**123**	136	148	161
0.5	81	93	106	**118**	130	142	154
0.4	75	87	99	**110**	121	132	143
0.3	66	77	87	**97**	107	117	127
0.2	49	57	65	**73**	81	88	96

4B-13 Suspended Concrete Floor - U = 0.25 W/m².K (insulation on inside surface)

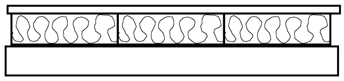
	Insulation Thermal Conductivity (W/m.K)						
P/A	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
1	62	78	93	**109**	124	140	155
0.9	61	76	92	**107**	122	138	153
0.8	60	75	90	**105**	120	135	150
0.7	59	74	88	**103**	118	132	147
0.6	57	71	86	**100**	114	128	143
0.5	55	68	82	**96**	110	123	137
0.4	51	64	77	**90**	103	116	128
0.3	46	57	69	**80**	92	103	115
0.2	36	45	54	**62**	71	80	89

Inter-Storey Floor Construction - U = 0.25 W/m².K

Timber Construction



Concrete Construction



Timber joists assumed to be 48 mm wide with 400 mm centres - accounting for 12% of floor area.

4B-14 Insulation Base Thickness (mm) for inter-storey floors - U = 0.25 W/m².K

	Insulation Thermal Conductivity (W/m.K)						
Construction	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
Timber	109	136	163	**193**	225	253	261
Concrete	75	94	112	**131**	150	169	187

4B-15 Insulation Base Thickness (mm) for inter-storey floors - U = 0.25 W/m².K
(Ignoring timber joist thermal bridging)

	Insulation Thermal Conductivity (W/m.K)						
Construction	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
Timber	80	100	120	**140**	160	180	200
Concrete	75	94	112	**131**	150	169	187

4B-16 Reduction in Base Thickness (mm) for common components

	Insulation Thermal Conductivity (W/m.K)						
Component	0.02	0.025	0.03	**0.035**	0.04	0.045	0.05
10mm plasterboard	1	2	2	**2**	3	3	3
≥19mm timber flooring	3	3	4	**5**	5	6	7
50mm screed	2	3	4	**4**	5	5	6

4B-17 Ceiling and Roof Construction - Uvalues (1966 to 2008)

Construction Period	Roof Type	Maximum U value ($W/m^2.K$)	Insulation - Minimum Thickness (m)
1966-1971 & 1972-1976	Pitched	1.42	Wood wool slabs - 0.050 Compressed straw slabs - 0.050 Gypsum Granules - 0.038 Corkboard - 0.025 Fibre insulating board - 0.025 Mineral wool* - 0.025 Expanded Polystyrene - 0.019
	Flat Solid Concrete (high density)		Wood wool slabs - 0.038 Vermiculite Concrete screed - 0.050 Cellular/Aerated Conc. screed - 0.075 Foamed Slag screed - 0.100 Fibre insulating board - 0.025 Expanded Polystyrene board * - 0.019
1977-1984	Pitched	0.6	Mineral Fibre quilt - 0.060 Mineral Fibre slab* - 0.050 Expanded Polystyrene - 0.050
	Flat Solid Concrete (high density with screed thickness ≥ 0.04m)		Corkboard - 0.050 Mineral fibre roof board - 0.043 Expanded polystyrene board* - 0.043
1985-1990	Pitched	0.6	Mineral Fibre slab* - 0.050
	Flat Solid Concrete (high density)		Expanded polystyrene board* - 0.043
1991-1995	Pitched	0.45	Mineral Fibre slab* - 0.083
	Flat Solid Concrete (high density)		Expanded polystyrene board* - 0.060
1996-2001	Pitched	0.25	Mineral Fibre slab* - 0.140
	Flat Solid Concrete (high density)	0.45	Expanded polystyrene board* - 0.060
2002-2005 & 2006-Present	Pitched	0.16	Mineral Fibre slab* - 0.220
	Flat Solid Concrete (high density)	0.25	Expanded polystyrene board* - 0.150

.1 Internal Loads

Three main groups of casual internal gains for a commercial office building were identified as:

(i) Occupants

(ii) Lighting

(iii) Electrical Equipment

The gains associated with these groups are dependent on management of internal environment, patterns of equipment use, required internal environment and occupancy patterns. The thermal loads associated with each group are uncertain when considered for a building stock.

In [3], building use is used to categorise buildings for energy assessment. The task specific occupancy patterns, equipment loads and ideal environmental conditions influence the energy demands associated with comfort control. Focusing the model on commercial office buildings, a standard pattern of occupancy and associated lighting and equipment loads were used for modelling.

.2 Occupant Load Pattern

CIBSE's Environmental design guide [108], recommends a maximum occupant density of $14m^2$ per person. For 'typical' office activity, human thermal output of 90W sensible and 50W latent heat is given. The thermal energy is emitted in equal parts by radiant and convective means.

Office hours were considered between 07:00hr to 19:00hr, with a stepped increase and decrease for the first and last hour of the 'working day', respectively. A 2 hour lunch period, between 12:00hr and 14:00hr was used in which occupant density was considered to half. Figure 2 shows the (weekday) daily pattern of occupant total heat load per unit floor area. No internal loads were applied to Saturdays or Sundays.

.3 Lighting Load Pattern

Lighting loads depend not only on the occupancy patterns of a building but also on the lighting systems and management applied in a building. Adequate light intensity depends on the tasks carried out in the lit space. The energy associated with light intensity is dependent on the lighting efficiency and required light intensity.

For office buildings, [108] suggests a light intensity in the region of 300lux to 700lux. Using current bulb efficiencies a power intensity of $15W/m^2$ is given. A 30:70 split was given to radiative and convective heat loss processes, respectively.

The lighting scheme was considered to be centrally controlled and either on or off. No account was made for reduced light requirement due to varying occupancy levels and daylight intensity. Figure 3 shows the daily (weekday only) heat load associated with lighting.

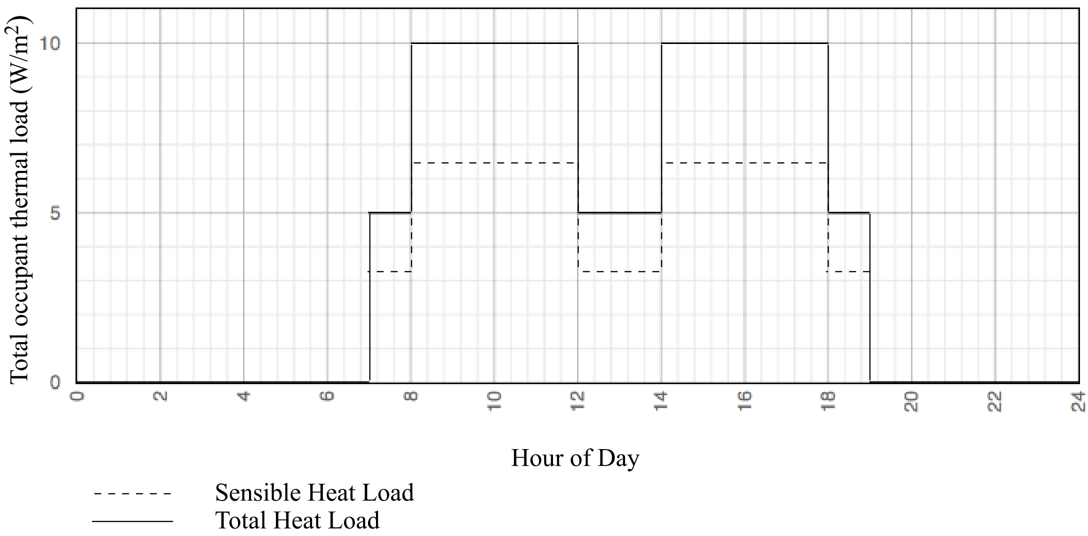


Figure 2: Total Occupant Thermal Load Pattern for Weekday - Normalised to Load per unit floor area

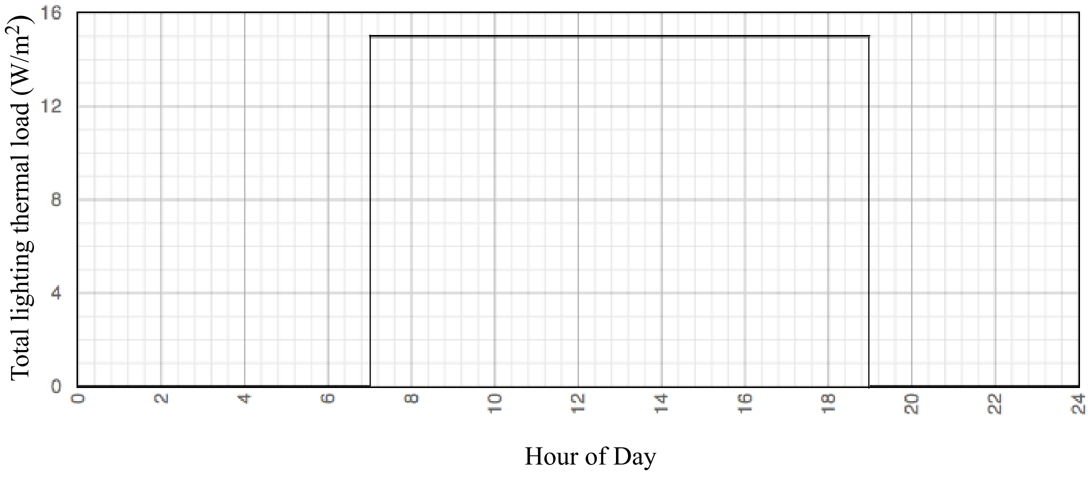


Figure 3: Normalised Lighting Heat Load Pattern for a Weekday

.4 Equipment Load Pattern

For modern office work, use of electrical equipment is common place. Based on standard power use of computing equipment in office buildings [108], a 200W equipment power rating was associated with each modelled occupant. Figure 4 shows the resulting equipment heat load pattern for weekdays.

Electrical equipment utilise fans for limiting operating temperatures. As such a 20:80 split was given to radiative and convective heat loss processes, respectively as an approximation to values given in [108].

Figure 4: Normalised Equipment Heat Load Pattern for a Weekday

.5 Base Level Thermal Loads - Heating and Cooling

The heating and cooling requirements of a building result from the inability of the building structure to maintain an internal temperature deemed comfortable by the occupants. The heating and cooling load of a building is, therefore, determined by the set temperature range to which the internal environment is maintained.

From [108] recommended temperature ranges for buildings of different activity are provided for heating and cooling design. For office buildings the comfort range of 21°C to 24°C is given, with a peak summer temperature of 28°C representing no more than 1% of the annual occupied period in non-air conditioned spaces.

No account is made in the modelling of the heating and cooling systems. The model simply provides or extracts the minimum amount of energy required to maintain the air node temperature of each zone in the model at the stated internal temperature limits. These values do not reflect the actual energy use of a building as efficiency and Coefficients of Performance of heating/cooling systems and associated distribution systems are not modelled. The thermal loads represent the base level thermal loads required by the building.

For all models the temperature range used was 20°C to 26°C at occupied times (weekdays only) and for unoccupied periods limits were set to 10°C to 30°C. The control of internal temperature for unoccupied periods assumed building management aims to limit extremes in temperature to avoid damage to sensitive equipment and avoid large start-up costs/times to achieve acceptable working conditions.

For each zone large heating and cooling capacities were provided to ensure modelled conditions of each building remained within the given temperature limits - regardless of zone size and associated thermal loads. Air humidity control was not accounted for in modelling.

Figures 5 and 6 show how internal temperature was kept within the specified temperature ranges (for cooling and heating seasons respectively). Temperature peaks are flattened as the model injects (heat requirement) or extracts (cooling requirement) thermal energy to/from the indoor air node. Inspection of the period typical models showed this behaviour occurred as expected within all zones of all modelled periods.

The model applies heating and cooling thermal loads when the modelled indoor temperature would otherwise fall outside the given temperature range. The thermal energy input at the given time-step is the minimum amount required to maintain the internal air node temperature to the nearest extreme of the set temperature range.

The model does not reflect real thermal control, where a single control point temperature is used to maintain indoor temperature within a given temperature range. Actual building thermal energy demands are dependent on the heating and cooling systems and sensor controls deployed within a building. As the models made no account of heating and cooling systems, the calculated thermal loads provide a measure of a base measurement that represents the inability of the building structure to passively control internal temperature within the given range.

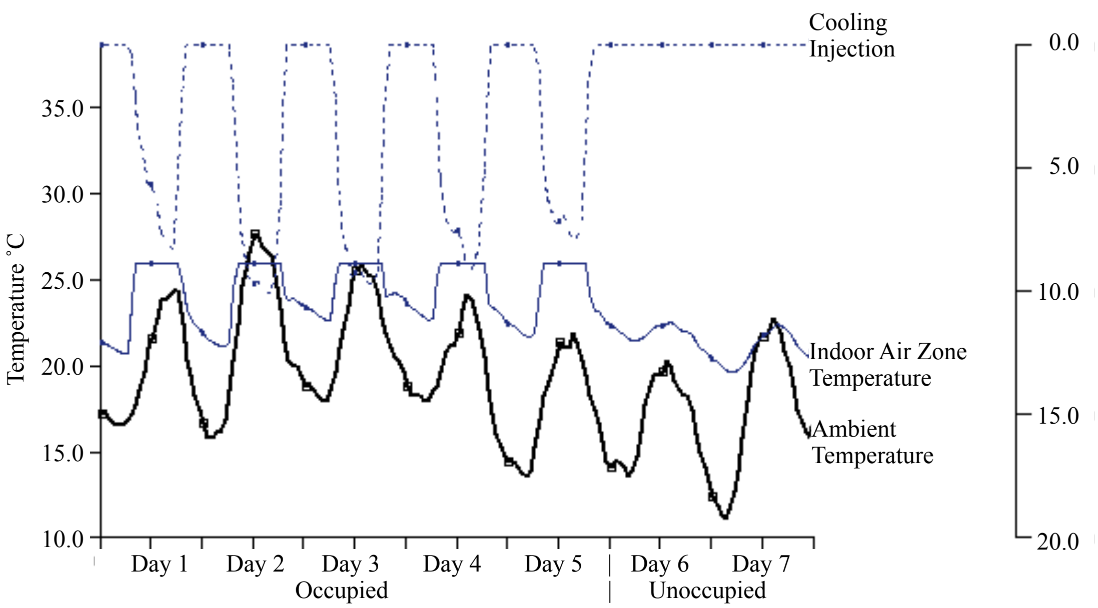


Figure 5: Example temperature and thermal load profiles - cooling season

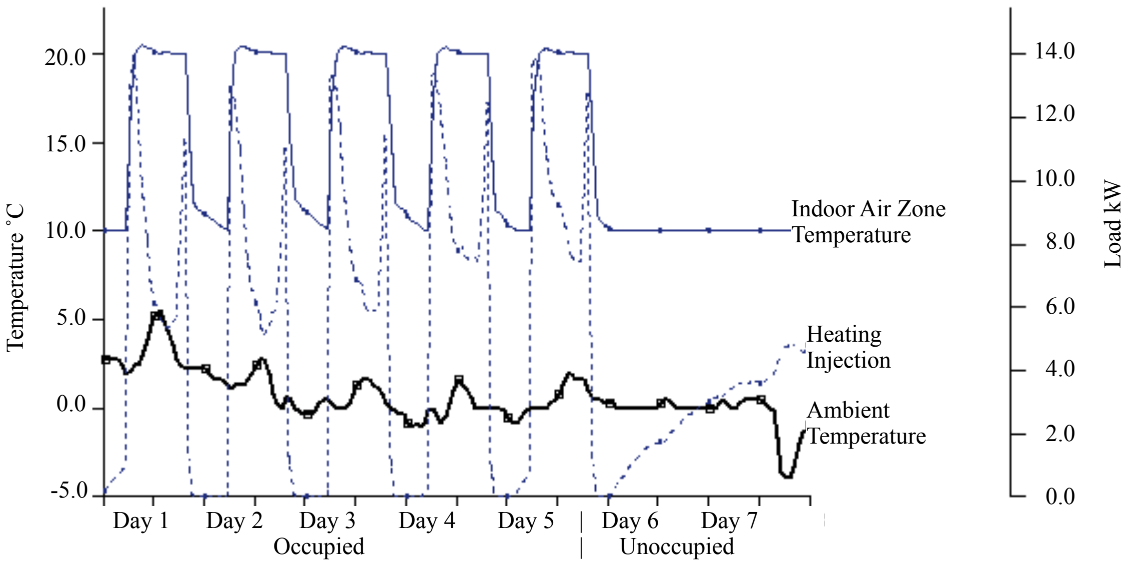


Figure 6: Example temperature and thermal load profiles - heating season

.6 Ventilation for Indoor Air Quality

The ventilation rate required to maintain acceptable indoor air quality will effect thermal loads, due to differences in internal and external air temperature. For office buildings an air replacement rate of $0.01\text{m}^3.s^{-1}$.per person is recommended in [108]. This rate was applied to all building models. This 'ideal' ventilation rate is independent of whether purposeful ventilation is supplied by mechanical or natural methods.

The model did not account for additional purposeful ventilation, such as that applied by opening of windows or variable rate mechanical ventilation systems. Addition of such ventilation would add further uncertainty in building thermal performance, especially for occupant controlled ventilation measures.

Appendix E - Summary of Parameter Uncertainties

Table 15: Summary of Parameter Uncertainties

Parameter	Range	Percentage Variation from Base Case Load									
		1915- 1938	1938- 1952	1953- 1965	1966- 1971	1972- 1976	1977- 1984	1985- 1990	1991- 1995	1996- 2001	2002- 2008
	HEATING										
Open Plan Base Case	(kWh/m^2/year)	67.35	62.58	64.2	74.77	73.71	67.67	64.97	60.22	22.14	7.45
Wall Construction	**	2.3 to -9.9	2.58 to -10.24	2.47 to -9.30	1.73 to -6.67	1.6 to -6.25	0.75 to -3.07	0.43 to -1.36	0.20 to -0.57	0.38 to -1.13	0.40 to -1.32
Number of Storeys	1 to 8	22.47 to -31.41	25.59 to -35.94	22.96 to -35.34	11.83 to -22.92	12.86 to -23.22	19.15 to -25.37	23.22 to -26.81	29.43 to -28.96	58.23 to -30.01	176.67 to -48.11
Length Width Ratio	1:1 to 5:1	0 to 27.2	0 to 26.85	0 to 27.14	0 to 25.25	0 to 25.13	0 to 24.4	0 to 24.45	0 to 23.61	0 to 35.30	0 to 39.08
Floor Construction	Conc. Solid/Wood Suspd	0 to -1.16	0 to -1.2	0 to -0.36	0 to 1.43	0 to 1.86	0 to 1.19	0 to 2.90	0 to 1.37	0 to 2.06	0 to -0.56
Climate File	*	-5.14 to 27.59	-5.22 to 27.72	-5.28 to 27.34	-5.44 to 28.34	-5.49 to 28.32	-5.56 to 28.85	-5.55 to 28.18	-5.52 to 28.67	0.07 to 42.70	-1.87 to 51.90
Latitude	51-54	0.33 to -1.19	0.32 to -1.18	0.32 to -1.17	0.38 to -1.35	0.38 to -1.35	0.38 to -1.36	0.38 to -1.33	0.37 to -1.34	0.63 to -2.28	0.67 to -2.20
Cellular Base Case	(kWh/m^2/year)	79.7	74.03	75.55	84.36	83.21	76.86	73.58	68.64	28.83	10.69
Cellular Length Width Ratio	1:1 to 5:1	0 to 33.18	0 to 32.63	0 to 32.68	0 to 31.74	0 to 31.60	0 to 31.12	0 to 30.87	0 to 30.42	0 to 45.0	0 to 57.53
	COOLING										
Open Plan Base Case	(kWh/m2/year)	28.28	28.67	28.11	36.51	37.24	38.6	39.86	40.67	64.96	92.22
Length Width Ratio	1:1 to 5:1	0 to -10.20	0 to -9.80	0 to -10.07	0 to -3.13	0 to -2.39	0 to -1.59	0 to -0.40	0 to -0.17	0 to 3.47	0 to 8.82
Latitude	51-54	-0.21 to 0.55	-0.19 to 0.50	-0.19 to 0.50	-0.39 to 0.87	-0.39 to 0.85	-0.37 to 0.82	-0.37 to 0.80	-0.36 to 0.78	-0.48 to 1.05	
Climate File	*	-19.18 to 23.40	-19.02 to 22.60	-18.11 to 23.21	-20.10 to 22.22	-20.14 to 21.77	-20.74 to 20.11	-19.97 to 19.98	-20.16 to 18.98	-20.56 to 10.28	
Floor Construction	Conc. Solid/Wood Suspd	0 23.48	0 23.45	0 23.70	0 36.30	0 37.59	0 37.25	0 36.78	0 35.61	0 20.39	
Number of Storeys	1 to 8	-70.65 to 28.73	-70.77 to 32.50	-69.48 to 31.34	-71.30 to 21.73	-71.01 to 21.51	-72.03 to 23.21	-72.20 to 24.23	-73.48 to 26.20	-84.41 to 25.63	-84.09 to 25.31
Wall Construction	**	0 to -5.74	0 to -5.83	0 to -5.10	0 to -3.31	0 to -2.86	0 to 9.24	0 to 8.34	0 to 5.74	0 to 0.30	0 to -1.85
Cellular Base Case	(kWh/m^2/year)	20.78	21.01	20.52	30.61	31.09	32.26	33.28	34.11	55.49	77.37
Cellular Length Width Ratio	1:1 to 5:1	0 to -2.95	0 to -3.04	0 to -3.47	0 to 8.58	0 to 8.98	0 to 9.58	0 to 10.65	0 to 11.16	0 to 14.15	0 to 15.01

*default clm67, birmingham (base case), finningley, hemsby, gatwick **Brick-Cavity-Block, Brick-Cavity-Brick, Solid Brick, Composite Cladding

Appendix F

.1 Expert Knowledge - Building Stock Questionnaire

.1.1 Introduction

The following questionnaire was designed to provide a **qualitative credibility** to a stochastic modelling approach that investigates the influence of **period of construction** on the **base level thermal loads** of non-domestic buildings. The modelling work applied a theoretical analysis of historical building regulations, laws and other published data sources to identify probable variability in building construction, building form parameters, and other characteristics considered to influence thermal energy performance of a building. The process focused on non-domestic office buildings. This process was undertaken as a relatively efficient method (compared to large scale survey) of capturing the range and probable uncertainty of building characteristics (at stock level).

For clarity of the investigation and intended impact of this questionnaire an explanation of **'qualitative credibility'**, **'period of construction'** and **'base level thermal loads'** follows.

Qualitative Credibility - The model provides a probability distribution of annual thermal loads of a building according to date of construction. Quantitative validation of the model is not considered possible with current stock level data and certain levels of abstraction built into the model. In light of no comparable data, the model cannot be truly validated. Relying on expert knowledge, however, the questionnaire is intended to provide a qualitative judgement on whether the approach taken is credible. This will compare the expert bodies understanding of the stock level probable distributions of energy influencing parameters to those theoretically derived.

Period of Construction - Building regulations, historical laws and standards have been assessed to understand variation in probable building component form. Review of these documents offered a method of categorising buildings according to the control laws in force at the time of construction. As a result 10 different 'Periods of Construction' were identified for the non-domestic stock between 1900 to the present day.

Base Level Thermal Loads - The modelling method allows for a level of abstraction that is difficult to achieve by empirical methods. In essence the base level thermal load is the total thermal load requirement to maintain a specified thermal comfort (e.g. a fixed internal temperature). This takes no account of heating and cooling system types, efficiencies, or management strategies, and standardises internal load patterns. The base level thermal loads can be considered as a measure of a building's inability to passively control thermal comfort.

.1.2 Question Structure

The questionnaire is split into sections relating to different structural parameters of a building. Each section asks for a considered likelihood to be associated with discrete bands of possible component values, within the component's entire value range. This should represent the expert opinion of your institute on probable distributions of the considered building characteristics at stock level. The likelihood values, should be given as a proportion of 1, with the sum of all likelihood equalling 1. Please refer to the example given in figure 7.

Window Wall Ratio	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
0 - 0.1	0	0.01													
0.1 - 0.15	0.33	0.05	m												
0.15 - 0.2	0.15	0.08													
0.2 - 0.25	0.1	0.1													
0.25 - 0.3	0.08	0.15													
0.3 - 0.35	0.07	0.3													
0.35 - 0.4	0.065	0.16													
0.4 - 0.45	0.05	0.07													
0.45 - 0.5	0.04	0.03													
0.5 - 0.55	0.04	0.02													
0.55 - 0.6	0.035	0.02													
0.6 - 0.65	0.02	0.01													
0.65 - 0.7	0.01	0.01													
0.7 - 0.75	0.01	0													
0.75 - 0.8	0	0	m												
0.85 - 0.9	0	0													
0.9 - 1.0	0	0													
Total Probability	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7: Example for answering the probable distribution of building characteristic values for multiple periods

As the model separates the stock into periods of construction (see the introduction), the first step is for you to identify building periods which you perceive to be significantly different to other periods when considering typical characteristics and energy performance. The distribution in the considered building characteristic should be presented for each building period that you have identified. Please refer again to figure 7. The questionnaire allows for up to 15 building periods to categorise the non-domestic building stock.

Each question provides an opportunity to redefine the building periods, as relevant to the building characteristic being examined. It is not necessary to restate the periods if the same as the previous section.

The modelling method within the research is focused on buildings built between 1900 to Present day, so it is requested that focus is given to the building stock post-1900. Consideration of the non-domestic building stock pre-1900 is considered as 'added value' rather than required.

When answering the question you are asked to only use the knowledge base held within your research institute. A further comment section is provided for you to offer insight into how you arrived at the given distribution and provide a measure of confidence in the knowledge used to come to your results. If in some instances there is no knowledge/data which can be used to answer a question, please state this in the comment section with any further comments felt necessary.

If a probable distribution cannot be given, but the range in possible values can, then only the minimum and maximum of the range need be filled in with 'm'. See figure 7, Period 3 column.

.2 Questionnaire

The questionnaire is split into four sections - (i) Building Component Form, (ii) Air Leakage, (iii) Sky View Factor and (iv) Further Comments. The first section is split into subsections relating to different building components.

Each section and subsection allows for building periods to be defined in relation to the considered building variable. If this is the same as the previous section periods, then it can be left blank for ease.

.2.1 Building Component Form

Wall Construction Types

The method of wall construction is considered as an influence on U-value (for earlier building periods) and latterly (i.e. when U- value has been regulated) influencing the dynamic thermal response of the building. The model, therefore, provides a database of different wall construction types according to building period.

This section requires an identification of different construction types for external walls according to building period. A probable proportion of the non-domestic (office) building stock using each construction type is then requested.

Example: Period A has 4 distinct construction types - solid brick wall, brick-cavity-block wall, light-weight panelling and reinforced concrete panelling. The two tables below demonstrate how this data should be represented.

Construction Type	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
A	Solid Brick														
B	Brick - cavity - block														
C	Light-weight panel														
D	reinf. conc. panel														
E															
F															

Type Distribution	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
A	0.3														
B	0.5														
C	0.15														
D	0.05														
E															
F															
Total Probability															

Figure 8: Demonstration of Construction Type Assessment

Construction Type	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
A															
B															
C															
D															
E															
F															
G															
H															
I															
J															
K															
L															
M															
N															
O															
P															
Q															

Type Distribution	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
A															
B															
C															
D															
E															
F															
G															
H															
I															
J															
K															
L															
M															
N															
O															
P															
Q															
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

Floor/Ceiling Construction - Typical Methods

The model looks at two basic floor construction methods - suspended wood floor and solid concrete flooring. Each type considered a variation in construction as according to building regulations, etc.

Based on these two basic constructions a distribution of applicability in a building is required. A comments and period definition section are also provided.

The table provides a repeat of the two basic floor types. This allows ground floor construction to be considered separately to inter-storey floor construction distributions. If considered separately, please indicate which is ground floor and which is inter-storey floor construction.

Floor Construction	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Suspended Wood															
Concrete Solid															
Suspended Wood															
Concrete Solid															
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

Roof Pitch

The building energy model proved to only be sensitive to roof pitch, given consistent construction. As a result the model divides roof type into flat and pitched roof, to which different construction types were identified. The table below allows for different bands of roof pitch to be assessed in terms of distribution. The comments section should be used to discuss any considerations made about roof construction in relation to roof pitch.

Roof Pitch	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

Window/Glazing Concerns

The glazing types are (for simplicity in this questionnaire) split into single glazed, double glazed and triple glazed. A distribution of window-to-wall ratio for each glazing type, by period, is to be considered here. If a glazing type is not applicable to a period of building construction then the column should be left blank.

Single Glazed

Window Wall Ratio	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Double Glazed

Window Wall Ratio	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Triple Glazed

Window Wall Ratio	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

Storey Height

Storey Height can be considered to impact thermal loads per m^2 of floor area by changing the volume of thermally controlled space in relation to floor area. Identifying trends in storey height where considered necessary. The table below requires a distribution (by building period) for bands of storey height to be presented.

Storey Height	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

.2.2 Air Leakage

Recognised as a difficult (and potentially very influential) consideration for a building stock a model for predicting probable air leakage rates by building components was developed. If data exists within your 'knowledge group' that provides information on air leakage rates within the non-domestic building stock (and different construction periods) then it is requested that the table below be filled in.

The values should be given as either a measure of air flow rate through the building envelope in $m^3.s^{-1}.m^2$ at 50Pa or as a typical Air Change Rate per hour (ACH). Please state in the comments which measure is used.

Air Infiltration	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

.2.3 Sky View Factor

If completed, please state whether the data used in developing this knowledge is a measure in the vertical plane (i.e. for a building's wall) or a measure in the horizontal plane at street level.

Sky View Factor	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12	Period 13	Period 14	Period 15
Total Probability															

Comments

Period	Period Dates
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

.2.4 Further Comments

This section is available for any further comments on the state of knowledge of the non-domestic building stock in general and in relation to periods of building construction.

COMMENTS:

.1 Parameter Distributions - Modelled and Expert Knowledge

.1.1 Distribution Results

The first set of tables provide a summary of the distributions presented by the responding expert body. The second set of tables are the probabilities that the model gives for the discrete bands as set by the expert body. It is these two distribution sets that have been compared for assessing model credibility.

Table 16: Tables of distribution data from responding expert body (IESD)

Period	Wall Construction Type							
	Solid Brick	brick-cavity-brick/block	concrete panel	lightweight panel (no insulation)	insulated cavity brick/block	lightweight panel (insulated)	concrete panel (insulated)	block/brick, insulation, platerboard
pre-1900	1	0	0	0	0	0	0	0
1900-1930	0.9	0.1	0	0	0	0	0	0
1930-1950	0.1	0.8	0.1	0	0	0	0	0
1950-1980	0	0.9	0.1	0	0	0	0	0
1980-2002	0	0	0	0	0.2	0.4	0.4	0
2002-	0	0	0	0	0	0.1	0.5	0.4

	Ground Floor Construction		Inter-Storey Floor Construction		Roof Type			
	Suspended Wood	Concrete	Suspended Wood	Concrete	Tiled Pitched	Clad Pitched	Concrete Flat	Board Flat
pre-1900	0.7	0.3	0.8	0.2	1	0	0	0
1900-1930	0.7	0.3	0.75	0.25	0.95	0	0.05	0
1930-1950	0.5	0.5	0.4	0.6	0.55	0.1	0.1	0.25
1950-1980	0.1	0.9	0.1	0.9	0.1	0.1	0.2	0.6
1980-2002	0	1	0.05	0.95	0.25	0.4	0.15	0.2
2002-	0	1	0.05	0.95	0.25	0.5	0.15	0.1

	WWR - Single Glazed				WWR - Double Glazed				WWR - Triple Glazed			
	<10%	10-20%	20-40%	40-100%	<10%	10-20%	20-40%	40-100%	<10%	10-20%	20-40%	40-100%
pre-1900	0	0.25	0.65	0.1	0	0	0	0	0	0	0	0
1900-1930	0.1	0.2	0.55	0.15	0	0	0	0	0	0	0	0
1930-1950	0.15	0.15	0.55	0.15	0	0	0	0	0	0	0	0
1950-1980	0.1	0.2	0.45	0.25	0	0.2	0.5	0.3	0	0	0	0
1980-2002	0.1	0.2	0.5	0.2	0.1	0.2	0.5	0.2	0	0	0	0
2002-	0	0	0	0	0.1	0.15	0.65	0.1	0	0.1	0.8	0.1

	Storey Height		Air Leakage (ACH)				SVF
	<2.8m	>2.8m	2+	1 - 2	0.5 - 1	<0.5	N/A
pre-1900	0.1	0.9	0.8	0.2	0	0	N/A
1900-1930	0.1	0.9	0.7	0.3	0	0	N/A
1930-1950	0.4	0.6	0.5	0.5	0	0	N/A
1950-1980	0.7	0.3	0.1	0.8	0.1	0	N/A
1980-2002	0.65	0.35	0	0.8	0.2	0	N/A
2002-	0.65	0.35	0	0	0.1	0.9	N/A

.1.2 Expert Comments

Some of the key comments given in the questionnaire response are presented below.

The end section of further comments are presented first.

.. a difficult excercise .. not at all confident about the numbers.

..confidence is highest for up to 1930, followed by part 2002, the former because of a more standard form of construction and the latter due to regulations constraining design, and some things having gone out of fashion, e.g. flat roofs.

Table 17: Tables of distribution data from research of building regulations, *a priori*

Period	Wall Construction type							
	Solid Brick	brick-cavity-brick/block	concrete panel	lightweight panel (no insulation)	insulated cavity brick/block	lightweight panel (insulated)	concrete panel (insulated)	block/brick, insulation, platerboard
1894 - 1938	0.44	0.56	0	0	0	0	0	0
1939 - 1952	0.25	0.58	0.17	0	0	0	0	0
1953 - 1965	0.27	0.54	0.19	0	0	0	0	0
1966 - 1971	0.27	0.54	0.19	0	0	0	0	0
1972 - 1976	0.27	0.54	0.19	0	0	0	0	0
1977 - 1984	0	0.29	0.21	0	0.22	0	0.14	0.14
1985 - 1990	0	0	0	0	0.55	0.17	0.14	0.14
1991 - 1995	0	0	0	0	0.53	0.21	0.13	0.13
1996 - 2002	0	0	0	0	0.51	0.2	0.14	0.15
2002 - Present	0	0	0	0	0.54	0.17	0.14	0.15

	Ground Floor Construction		Inter-Storey Floor Construction		Roof Type			
	Suspended Wood	Concrete	Suspended Wood	Concrete	Tiled Pitched	Clad Pitched	Concrete Flat	Board Flat
1894 - 1938	0.5	0.5	0.5	0.5	0.51	0	0.25	0.24
1939 - 1952	0.5	0.5	0.5	0.5	0.51	0	0.25	0.24
1953 - 1965	0.5	0.5	0.5	0.5	0.51	0	0.25	0.24
1966 - 1971	0.5	0.5	0.5	0.5	0.51	0	0.25	0.24
1972 - 1976	0.5	0.5	0.5	0.5	0.51	0	0.25	0.24
1977 - 1984	0.5	0.5	0.5	0.5	0.26	0.25	0.49	0
1985 - 1990	0.5	0.5	0.5	0.5	0.26	0.25	0.49	0
1991 - 1995	0.5	0.5	0.5	0.5	0.26	0.25	0.49	0
1996 - 2002	0.5	0.5	0.5	0.5	0.26	0.25	0.49	0
2002 - Present	0.5	0.5	0.5	0.5	0.26	0.25	0.49	0

	WWR - Single Glazed				WWR - Double Glazed				WWR - Triple Glazed			
	<10%	10-20%	20-40%	40-100%	<10%	10-20%	20-40%	40-100%	<10%	10-20%	20-40%	40-100%
1894 - 1938	0.02	0.21	0.67	0.1	0	0	0	0	0	0	0	0
1939 - 1952	0.01	0.17	0.73	0.09	0	0	0	0	0	0	0	0
1953 - 1965	0.02	0.15	0.71	0.12	0	0	0	0	0	0	0	0
1966 - 1971	0.01	0.03	0.76	0.2	0	0	0	0	0	0	0	0
1972 - 1976	0.01	0.04	0.75	0.2	0	0	0	0	0	0	0	0
1977 - 1984	0.01	0.04	0.77	0.18	0	0	0	0	0	0	0	0
1985 - 1990	0.01	0.07	0.92	0	0	0	0.28	0.72	0	0	0	0
1991 - 1995	0	0.05	0.95	0	0	0	0.28	0.72	0	0	0	0
1996 - 2002	0	0	0	0	0	0.02	0.49	0.49	0	0	0	1
2002 - Present	0	0	0	0	0	0.03	0.47	0.5	0	0	0	1

	Storey Height		Air Leakage (ACH)				SVF
	<2.8m	>2.8m	2+	1 - 2	0.5 - 1	<0.5	N/A
1894 - 1938	0.47	0.53	0.4	0.2	0.1	0.3	N/A
1939 - 1952	0.66	0.34	0.4	0.2	0.1	0.3	N/A
1953 - 1965	0.74	0.26	0.4	0.2	0.1	0.3	N/A
1966 - 1971	0.76	0.24	0.4	0.2	0.1	0.3	N/A
1972 - 1976	0.76	0.24	0.4	0.2	0.1	0.3	N/A
1977 - 1984	0.72	0.28	0.4	0.2	0.1	0.3	N/A
1985 - 1990	0.75	0.25	0.4	0.2	0.1	0.3	N/A
1991 - 1995	0.74	0.26	0.4	0.2	0.1	0.3	N/A
1996 - 2002	0.75	0.25	0.4	0.15	0.1	0.35	N/A
2002 - Present	0.76	0.24	0	0	0.01	0.99	N/A

Wall Construction Types

.. assumed number of buildings used to present probable parameter distribution at stock level - Rather than floor area, volume or premises.

This keeps the data inline with the considered model distributions. No understanding of variation in the identified forms is provided.

Roof Pitch

.. this was very difficult, particularly types of flat roof and for later periods.

.. no distinction between pitched roof with loft void and with sloping ceilings.

Window/Glazing Concerns

.. assumed glazing relates to as built. In some instances, where $\Sigma p = 1$ *for all cases even if numbers are very small.*

.. ignored rooflights so instances of no wall glazing but rooflighting comes under <10%.

.. again very difficult, especially for later periods.

In relation to triple glazing for the latter periods .. *extremely few non-domestic buildings.*

Sky View Factor

....unable to estimate